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A Conceptual Framework for Exploring the Scalable Integration of Roadmapping and Innovation System Functions for Industrial Emergence

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Abstract

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paths that may help technology ventures to navigate towards successful business development.

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A Conceptual Framework for Exploring the Scalable Integration of Roadmapping and Innovation System Functions for Industrial Emergence

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ABSTRACT

Roadmapping is a graphical technique that supports communication within and between organisations for a variety of purposes in the context of strategic planning and innovation management, enabling alignment and synchronisation between different elements of the innovation system. Previous studies show that the use of roadmapping is empirically well acknowledged as flexible at various levels and adaptable to many applications. However, there seems to be relatively little research on the theoretical underpinnings of roadmapping in the context of strategy and innovation. On the other hand, in the literature of innovation system functions, over the past decade the functional analysis of the dynamics of innovation systems to identify system failures has been increasingly popularised. However, comparatively little focus has been given to practical implications at the firm level. This provides an opportunity to further explore theoretical and practical contributions if the different research domains of roadmapping and innovation system functions can be integrated in a scalable manner by unifying dimensions and units of analysis. To address the research gap, this paper presents a conceptual framework for exploring how the scalable integration could be realised by utilising insights derived from the literature on economics, management, innovation studies and systems engineering. This research explores how innovation system functions-based roadmapping could provide a new perspective and useful insights on the theory and practice of both roadmapping and innovation system functions. It also provides an opportunity to develop a theoretically underpinned structured approach to identify, select and communicate the essence of possible emergence paths that may help technology ventures to navigate towards successful business development.

Keywords: Roadmapping; Industrial Emergence; Innovation System Functions; Strategy; Innovation.

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1. BACKGROUND

Roadmapping is a graphical technique that supports communication within and between organisations for a variety of purposes in the context of strategic planning and innovation management (Garcia and Bray, 1997, Phaal et al., 2004), enabling alignment and synchronisation between different elements of the innovation system (Phaal et al., 2005). The roadmapping approach has been increasingly utilised since the initial development by Motorola in 1980s for supporting the alignment of the development of technology and product (Willyard and McClees, 1987), thereafter being adopted (and adapted) first in large technology-intensive firms, and then widely disseminated to many other sectors and applications (Phaal and Muller, 2009). Previous studies show that the use of roadmapping is empirically well acknowledged as being flexible at various levels in terms of dynamic range, granularity and user level for many applications (Garcia and Bray, 1997, Kostoff and Schaller, 2001, Petrick and Echols, 2004, Lee and Park, 2005, Kajikawa et al., 2008, Phaal et al., 2009, Phaal and Muller, 2009, Gerdsri et al., 2009) and as being flexible to integrate with other management tools in a scalable manner (Phaal et al., 2012, Kerr et al., 2013, Mortara et al., 2014).

Industrial 'Emergence Mapping' approach, developed by Phaal et al. (2011), provides a qualitative structured diagrammatic framework and a series of mapping exercises with interview and workshop-based methods to explore, from functional perspectives, the patterns of key events, milestones, activities and processes in the emergence of new technologies and industries, depicting how business organisations succeed or fail over time (Probert et al., 2013). Further research and practice on the industrial emergence mapping approach has become one of the research themes at the Centre for Technology Management (CTM)[1] and the Centre for Science, Technology and Innovation Policy (CSTI)[2] of the University of Cambridge in the UK, aiming to contribute to the theory and practice of roadmapping for strategy and innovation at both firm and sector levels (Ford et al., 2010, Phaal et al., 2011, Routley et al., 2013, Ho and O'Sullivan, 2013, Ho, 2014).

As a result of preliminary exploratory study of this doctoral research, which has the primary research focus on technology management, the following research focus has been identified: to explore further theoretical and practical contributions by examining the integration opportunities between roadmapping and innovation system functions (Hekkert et al., 2007, Hekkert and Negro, 2009). As these two approaches have similarities and commonalities in terms of the innovation system context focus, functional perspectives and dynamic analysis, it is expected that exploring the integration opportunities will provide a new perspective and useful insights on the theory and practice of both roadmapping and innovation system functions.

The existing literature on innovation system functions have limited practical implications from the viewpoint of firms, meaning innovation system functions are not yet scalable (and adaptable) to firm level innovation application, while the roadmapping approach, while demonstrably useful, has limited theoretical underpinning in the literature. The scalable and flexible nature of the roadmapping approach may provide initial confidence for realising this integration by considering roadmapping as the 'receptor'

[1] See http://www.ifm.eng.cam.ac.uk/research/ctm/industrial-emergence/
[2] See http://www.ifm.eng.cam.ac.uk/research/cstip/themes/science-technology-industrial-emergence/

providing a practical method and process, and innovation system functions as the ‘donor’, theoretically underpinning the roadmapping approach. However, roadmapping and innovation system functions define dimensions and units of analysis differently, as they are in different research domains. It is worth carefully investigating how the integration between these two approaches could be realised.

This paper presents a conceptual framework as an early progress of the doctoral research, for exploring how the integration of roadmapping and innovation system functions could be realised. The remainder of this paper is as follows. Section 2 reviews the literature on roadmapping and innovation system functions. A conceptual framework and potential future research directions of this doctoral research are presented in Section 3.

2. LITERATURE REVIEW

2.1 Roadmapping

Roadmapping is a graphical technique that often involves a workshop-based method and process, which could be considered as a socially facilitated mechanism consisting of the process of cogitation, articulation and communication among the participants producing ‘roadmap’ as an output (Kerr et al., 2012). The process and product of roadmapping are supported by the use of roadmap templates, based on an underlying ‘roadmap architecture’, used in the roadmapping workshop for the purpose of structured visual representation of strategy. While many types of roadmap architecture exist in practice and management literature, the most frequently used is a multi-layered time-based format, providing a common structured visual language for strategy development (Phaal et al., 2010). There are a growing number of empirical contributions in the literature of roadmapping, however, there is relatively little research on the theoretical underpinnings of roadmapping in the context of strategy and innovation (Phaal and Yoshida, 2014). This section briefly reviews the literature on roadmapping to explore the nature and characteristics of the roadmapping approach including the description of the industrial emergence mapping approach.

Scalability of Roadmapping

Previous studies show that the roadmapping approach is flexible at various levels and can support a variety of aims in the context of strategic planning and innovation management. For instance, Figure 1 below shows examples of the types of roadmap often seen in industry (Phaal et al., 2004). The roadmapping approach can be considered as being purpose-driven, with the format and features of roadmap architecture varying depending on the needs of the organisations. For instance, (a) product planning, (d) long-range planning and (h) integration planning, indicated in Figure 1, use a simple format representing technology and/or product to explore specific developments such as technological convergence and system integration. On the other hand, (b) service/capability planning, (c) strategic planning, (e) knowledge asset planning, (f) program planning and (g) process planning, also shown in Figure 1, utilise a multi-layered format to explore the alignment of the developments of various elements of the innovation system. On top of the layered formats, roadmap can also be depicted in a graphical form such as bars, tables, graphs, pictorial representations, flow charts and texts (Phaal et al., 2004).

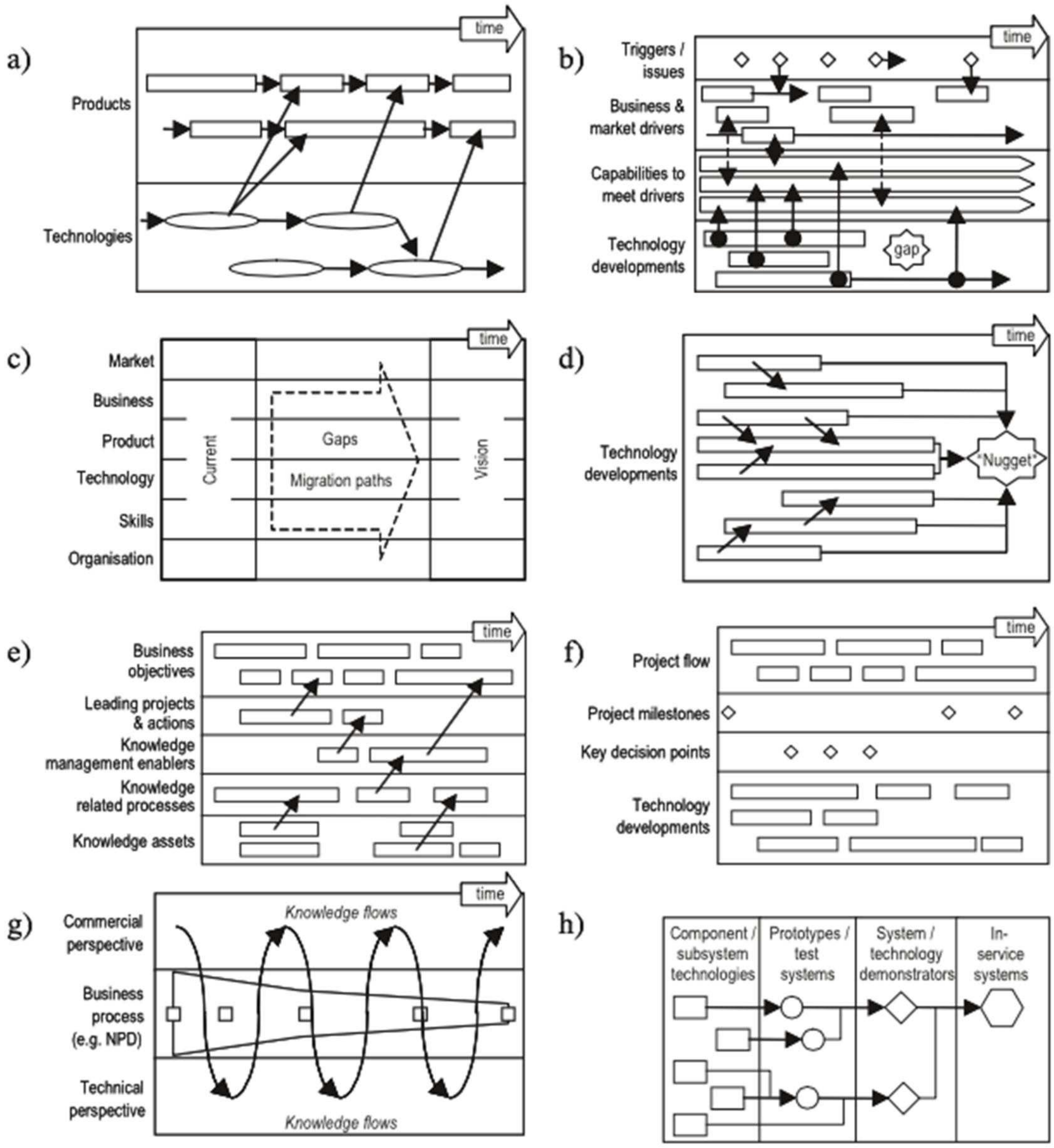

Figure 1: Examples of technology roadmap architecture types (Phaal et al., 2004).
(a) product planning; (b) service/capability planning; (c) strategic planning; (d) long-range planning;
(e) knowledge asset planning; (f) program planning; (g) process planning; (h) integration planning.

As well as purpose and format, there exist other dimensions that underpin the scalable nature of roadmapping. For example, ‘dynamic range’ that roadmap can cover is very diverse in terms of scale and complexity of the system (Phaal and Muller, 2009). Figure 2 shows the abstraction hierarchy and number of details that roadmapping can cover from scientific foundation to sector levels. It suggests that as the magnitude of information that can be contained in a single roadmap could be tremendous, the key initial step is to define the focus, scope and aims of roadmapping by identifying relevant perspectives to represent in order to understand and map the system dynamics (Phaal and Muller, 2009).

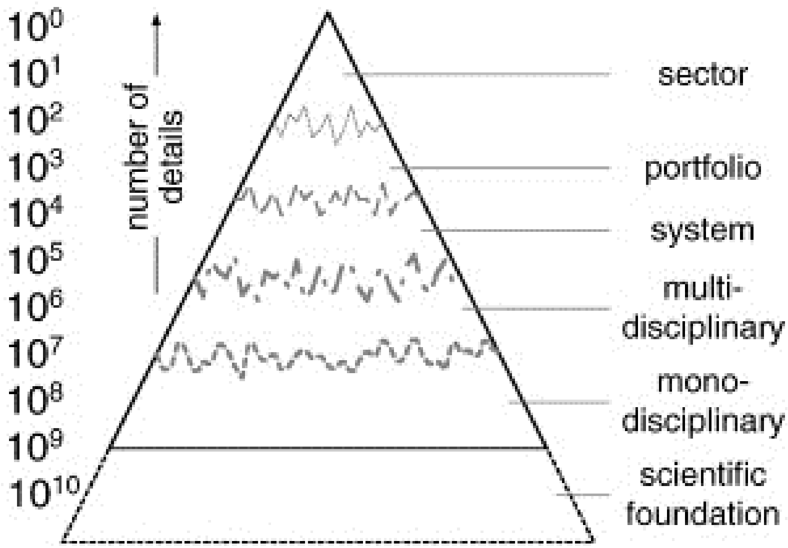

Figure 2: Abstraction hierarchy that roadmap can cover (Phaal and Muller, 2009).

Generalised Roadmapping Framework

A generalised roadmapping framework has been produced by Phaal et al. (2003) which enables the roadmapping users to design the timeframes, structure of information, process and graphical format of roadmapping, by covering the following six fundamental questions underpinning the process of roadmapping: 1) where do we want do?, 2) where are we now?, 3) how can we get there?, 4) why do we need to act?, 5) what should we do?, and 6) how should we do it?

Figure 3 below shows the generalised roadmapping framework that can be adapted to many contexts and scales. As shown in Figure 3, the generic form of the roadmap architecture is based on a time horizon, and multiple (hierarchical) layers representing functional and stakeholder perspectives, enabling systems thinking to be applied to the alignment and synchronisation between different elements of the innovation system. At the highest level of roadmap architecture, there are three broad layers corresponding to the following knowledge dimensions (Phaal et al., 2010): 1) top layer as know-why (purpose) dimension of knowledge, covering overall trends and drivers, regulations and standards, industrial dynamics and application market or customers, which corresponds to ‘Market’ and ‘Business’ in Figure 3, 2) middle layer as know-what (delivery) dimension of knowledge, covering tangible systems such as development of product, service, infrastructure, engineering systems and organisational capabilities, which corresponds to ‘Product’, ‘Service’ and ‘System’ in Figure 3, and 3) bottom layer as know-how (resource) dimension of knowledge, covering internal and external resources such as finance, facilities, enabling technologies, skills, organisation, management and process, partnerships and networks and demand side enablers, which corresponds to ‘Technology’, ‘Science’ and ‘Resource’ in Figure 3. The set of functional perspectives enables the roadmapping approach to be scalable at various levels and adaptable to many applications.

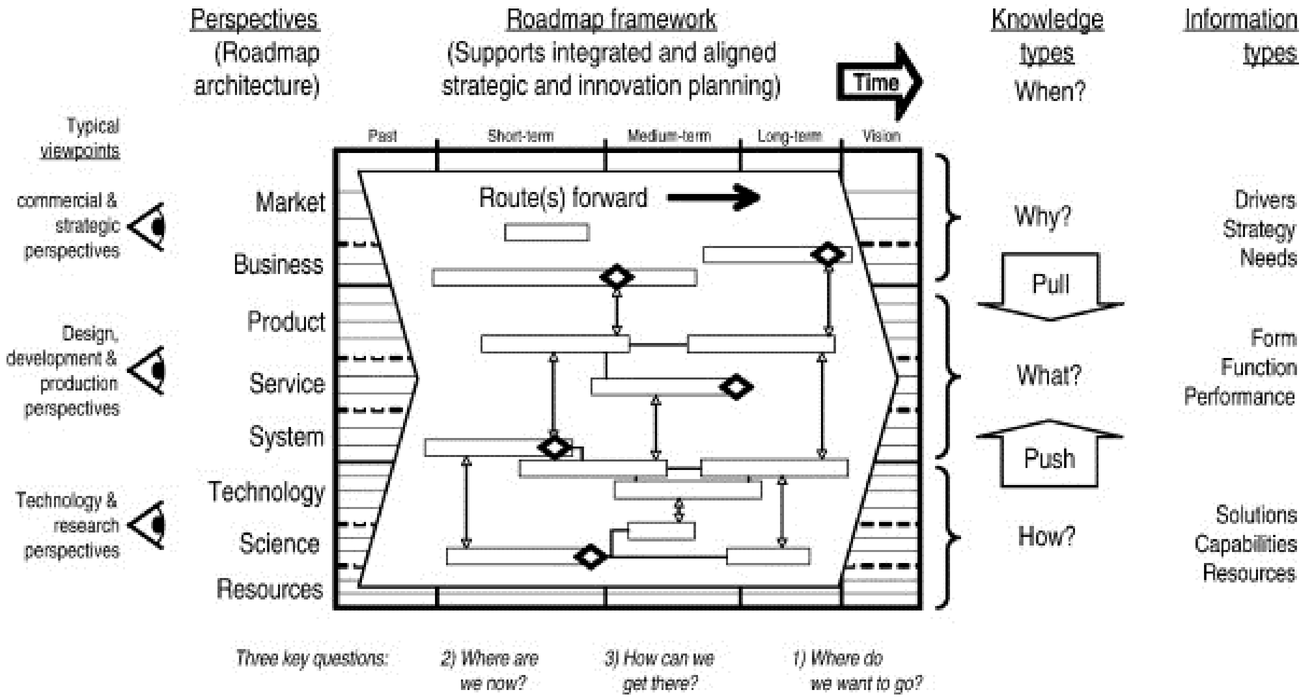

Figure 3: Generalised roadmapping framework (Phaal and Muller, 2009).

Industrial 'Emergence Mapping' Approach

One of the most recent developments derived from the generalised roadmapping framework is the so-called industrial 'Emergence Mapping' approach, developed by Phaal et al. (2011). This provides a qualitative structured diagrammatic framework and a series of mapping exercises with interview and workshop-based methods to explore from functional perspectives, the patterns of key events, milestones, activities and processes in the emergence of new technologies and industries, depicting how business organisations succeed or fail over time (Phaal et al., 2011). The research outcomes are expected to benefit technology managers and policymakers when deciding which technological areas to target for their investment and what kind of strategic options could be developed for implementation (Phaal et al., 2012). This sub-section describes the background of industrial emergence mapping based on the work by Phaal et al. (2011) and Probert et al. (2013).

The industrial emergence mapping approach is based on lifecycle concepts (i.e. inclusion of phases and transitions of industrial evolution). According to Phaal et al. (2011), there are six phases and three stages in the lifecycle of industrial emergence: 1) precursor phase where the emergence is driven by science base, 2) science-technology transformation stage, 3) embryonic phase where the emergence is driven by technological development, 4) technology-application transformation stage, 5) nurture phase where the emergence is driven by application, 6) growth phase where the emergence is driven by market, 7) application-market transformation stage, 8) maturity phase and 9) decline and/or renewal phase. Figure 4 shows the diagram illustrating the phases, transitions, milestones and trajectories of technology-intensive industrial emergence, adopted from Phaal et al. (2011).

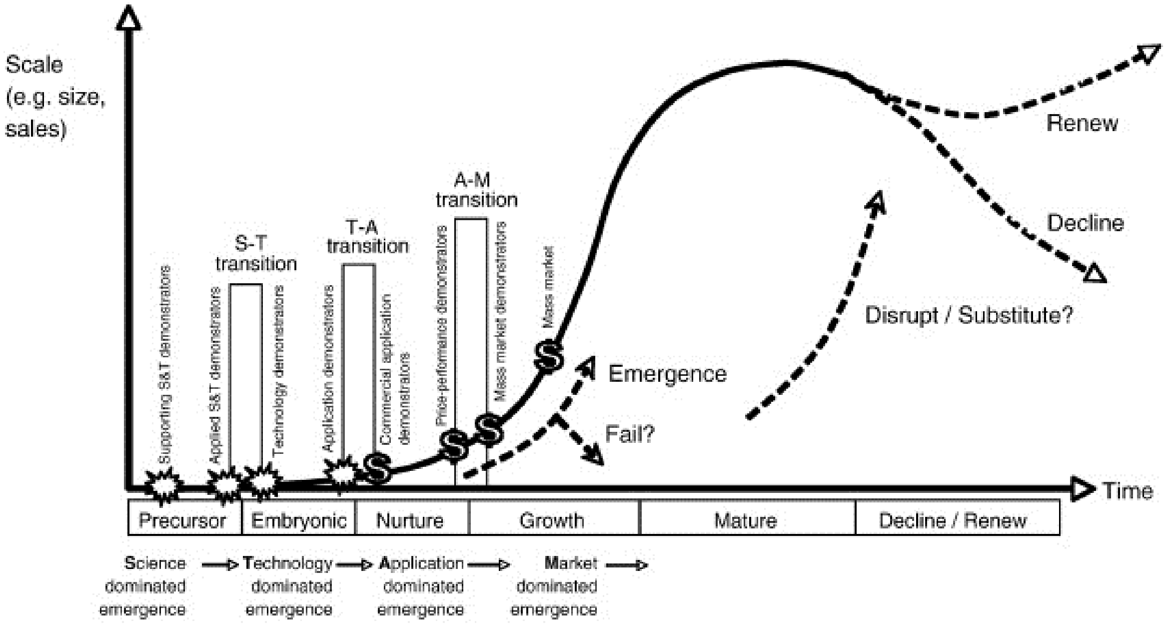

Figure 4: Phases, transitions, milestones and trajectories of technology-intensive industrial emergence (Phaal et al., 2011).

The co-dynamics and interactions of key actors, market and technological events and achievements are examined from functional perspectives by mapping the key events and milestones with three layers: 1) value context, which includes macro-level indicators that drive the evolution of industrial emergence such as government policy and industrial dynamics, 2) value capture, which includes processes and activities relating to business model, strategies and distribution system delivering products and services to customers for revenue generation, and 3) value creation, which includes activities of organisations and the internal and external resources, and capabilities they utilise to generate novel scientific and technological knowledge (Probert et al., 2013). Figure 5 shows the thematic representation of the industrial emergence mapping framework, adopted from Phaal et al. (2011).

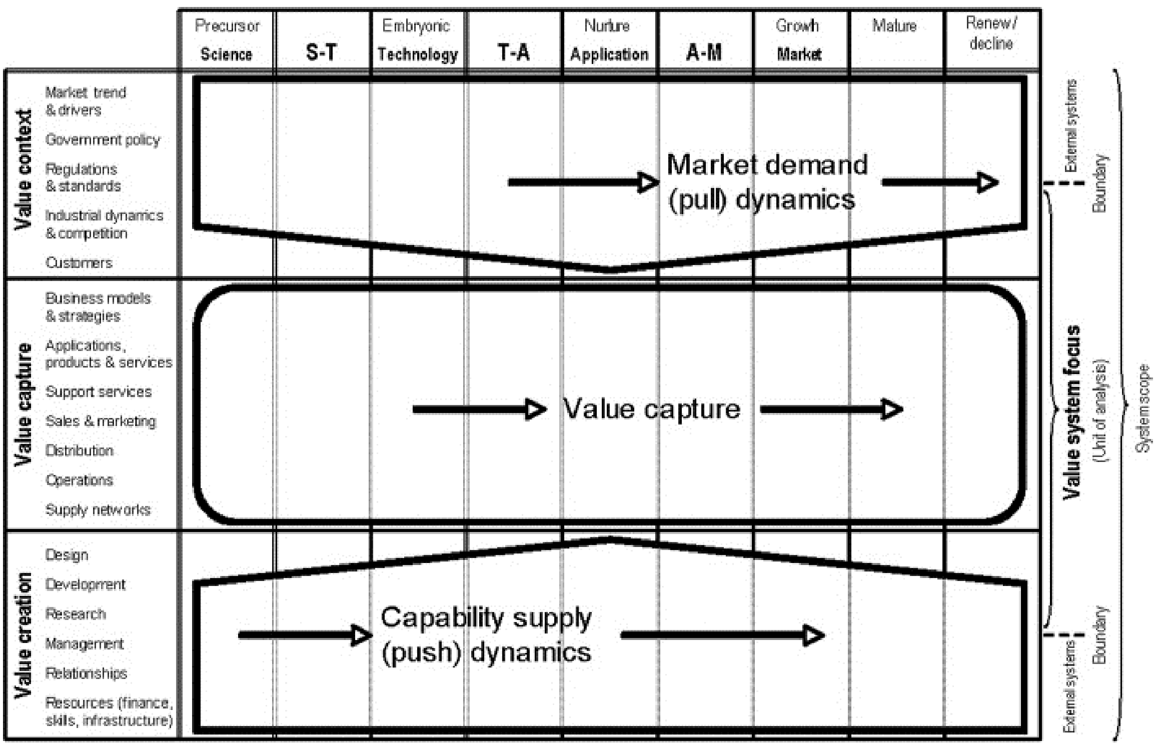

Figure 5: Industrial emergence mapping architecture (Phaal et al., 2011).

The importance of identifying demonstrator milestones in the emergence of new technologies industries is also addressed by Phaal et al. (2011). These events are important because they are considered to delineate the phases and transitions, signalling key events and/or achievements that attract potential investments in subsequent stages (Phaal et al., 2011). A number of demonstrator types are defined in the emergence processes involving science, engineering and large-scale industrialisation. According to Phaal et al. (2011), identifying the demonstrators would significantly contribute to the analysis and simplification rather than identifying every single stage or actor involved at the defined system boundary. Furthermore, the characteristics of different activities and processes in the emergence of new technologies and industries have been identified: precursor market activity, specialist markets, early adopter market, market stimuli, technological stimuli, enablers, barriers and regional perspectives. These factors are important for evaluating the nature and characteristics of industrial emergence. Furthermore, according to Phaal et al. (2011), they have identified at least five patterns of industrial emergences at system-level based on more than 25 emergence maps in diverse sectors, context and unit of analysis of historical industrial evolution. The patterns of industrial emergence identified by Phaal et al. (2011) are: 1) funnel-like patterns of emergence, 2) transitions as key characteristics of industrial emergence, 3) push-pull 'engine' of industrial emergence, 4) importance of initial conditions, and 5) catalytic events.

With regard to the practicality of the industrial emergence mapping approach, four practical tools have been suggested by Probert et al. (2013). Three of the tools support the identification of patterns, enablers and barriers in the historical evolution and development of industrial systems. Industry Scan (IS) is the first tool, mapping the historical industrial emergence to explore and communicate the understanding of patterns, enablers and barriers in the evolution of the industrial system. Expert Scan (ES) is the second tool, designed as an analytical tool to examine personal perspectives of historical industrial emergence through an interview-based mapping method. The outcomes from ES can be utilised to support strategy and policy development, by combining the findings with the patterns, enablers and barriers identified in IS (Probert et al., 2013). Organisation Scan (OS) is the third tool, a workshop-based method to capture, map and communicate the knowledge and experience of historical industrial emergence. According to Probert et al. (2013), the outcomes from these three tools can be utilised to support strategic planning activity of organisations, which is the focus for the fourth tool: Emergence Roadmap (ER), which is a workshop-based roadmapping method to help organisations navigate technology-based industrial emergence.

2.2. Innovation System Functions

In the literature of innovation system functions over the past decade, the functional analysis of the dynamics of innovation systems has been increasingly popularised (Truffer et al., 2012). The innovation system functions-based approach traces its origin back to the theoretical foundation of 'system of innovation' introduced by Lundvall (1985), which has been influenced by the original conceptual idea of the 'national system of political economy' presented by List and Colwell (1856). Drawing upon the early work by Lundvall (1985) and Freeman (1995), the main assumption of innovation system theory has been emphasised by Suurs and Hekkert (2009b, p.670) that "determinants of technological change are not (only) to be found in individual firms or in R&D networks, but also in a broader social structure in which the firm as well as R&D networks are embedded". A major early empirical contribution to the theory of innovation system was observed in 1988 where the success of the Japanese economy from the perspective of national innovation system was examined (Freeman, 1995). Since then, there have been a growing number of theoretical and empirical contributions in the literature of innovation studies, which have enabled the innovation system analysis to be adaptable to various dynamic ranges and geographical levels such as technological, local, sectoral, regional and national innovation systems.

Out of these different innovation system approaches, the innovation system functions-based approach is unique in that it focuses on the analysis of the dynamics of emerging industries from functional perspectives (Truffer et al., 2012), aiming to identify system failures by comparatively evaluating the nature and rate of technological change in terms of actors, structure and system functions (Hekkert et al., 2007, Hekkert and Negro, 2009). Previous studies show that there are a growing number of theoretical and empirical contributions in the literature of innovation system functions. However, comparatively little focus has been given to practical implications at the firm level, which is the key perspective employed in the roadmapping approach, relating to the origins of the method. This section briefly reviews the literature on innovation system functions to explore the nature and characteristics of the approach.

Functionality of Innovation Systems

The functions of innovation systems approach assists an holistic and systematic evaluation of innovation system performance by investigating how specific functions of innovation systems emerge and develop over time. Functions here refer to all activities contributing to the development, diffusion, and utilisation of innovations (Johnson, 2001, Bergek et al., 2008a). According to Hekkert et al. (2007), there are seven system functions to be evaluated: entrepreneurial activities, knowledge development, knowledge diffusion, guidance of the search, market formation, resource mobilisation, and creation of legitimacy. The functional approach to analyse innovation systems is a very important approach to examine the emergence of new technologies and industries because this approach allows investigations to focus on the early-stage processes of how system structures emerge and develop over time (Truffer et al., 2012). Table 1 below shows the summary of the functions of innovation systems, where the definitions are adopted from Hekkert et al. (2007) and Hekkert and Negro (2009), the short descriptions are adopted from Suurs et al. (2010), and the suggested indicators for each function are adopted from van Alphen et al. (2010).

Table 1: Definitions, descriptions and suggested indicators of innovation system functions (adopted from Hekkert et al. (2007), Hekkert and Negro (2009), Suurs et al. (2010) and van Alphen et al. (2010))

Functions	Descriptions	Suggested Indicators
Function 1. Entrepreneurial Activities	At the core of any innovation system are entrepreneurs. These risk takers exploit business opportunities and perform innovative commercial and/or practice-oriented experiments.	Number and degree of variety in entrepreneurial experiments; number of different types of applications; breadth of technologies used and characteristics of the complementary technologies employed; number of new entrants and diversifying established firms.

Function 2. Knowledge Development	Technological research and development (R&D) are a source of variation in the system and are therefore prerequisites for innovation processes to occur. Non-technological knowledge is also of key importance. 'Learning by searching' and 'learning by doing' are the key process of this function.	Number and degree of variety in R&D projects; type of knowledge (scientific, applied, patents) that are created and by whom; competitive edge of the knowledge base; mismatch between the supply of technical knowledge by universities and demand by industry.
Function 3. Knowledge Diffusion	The typical organisational structure of an emergent innovation system is the knowledge network, primarily facilitating information exchange. Network activity can be regarded as a precondition to 'learning by interacting'. When user producer networks are concerned, it can also be regarded as 'learning by using'.	Amount and type of collaborating between actors in the innovation system; kind of knowledge that is shared within these existing partnerships; amount, type and weight of official gatherings (e.g. conferences, platforms) organised; configuration of actor-networks (homo or heterogeneous set of actors).
Function 4. Guidance of the Search	This system function represents the selection processes necessary to facilitate a convergence in development.	Amount and type of visions and expectations about the technology; belief in growth potential; clarity about the demands of leading users; specific targets or regulations set by the government or industry.
Function 5. Market Formation	New technologies often cannot outperform established ones. In order to stimulate innovation it is necessary to facilitate the creation of (niche) markets, where new technologies have a possibility to grow.	Phase of the market and its (domestic & export) potential; users of the technology and how their demand is articulated; institutional stimuli for market formation; uncertainties faced by potential project developers.
Function 6. Resource Mobilisation	Financial, material and human factors are necessary inputs for all innovation system developments.	Availability of human capital through education, entrepreneurship or management; availability of financial capital (seed and venture capital, government funds for R&D); availability of complementary assets (complementary products, services, network infrastructures); level of satisfaction with the amount of resources.
Function 7. Creation of Legitimacy	The emergence of a new technology often leads to resistance from established actors. In order for an innovation system to develop, actors need to raise a political lobby that counteracts this inertia, and supports the new technology.	Public opinion towards the technology and how is the technology depicted in the media; main arguments of actors pro or against the development of the technology; legitimacy to make investments in the technology; activity of lobby groups active in the innovation system (size and strength).

Evaluation of the functions of innovation systems depends on spatial and historical context by applying the event-based approach, or otherwise called event history analysis, whereby development and technological transition processes are conceptualised as sequences in the form of events, identifying the pathway and process by investigating the stream of events through which they unfold (Hekkert et al., 2007). Empirical studies suggest that this method offers a practical approach in a systematic manner. It also offers analysis of qualitative historical data for narratively analysing the functions of innovation systems by relating them to events (Suurs et al., 2009). Diagnostic questions for each function are suggested by (Hekkert et al., 2011) which enable the event history analysis to search for relevant events in the innovation system functions context.

On top of the event history analysis, some scholars have integrated a standardisation index by putting all the investigated events into the equally weighted index: '+1' for a positive event and '-1' for a negative event occurring in the defined innovation systems. The sum of standardised scores is then sorted out by year to examine the functional development of innovation systems for the defined time span. Theoretical and empirical studies have included the case of hydrogen and fuel cell (Suurs et al., 2009), automotive natural gas (Suurs et al., 2010) and carbon capture storage (van Alphen et al., 2010). In contrast, van Alphen et al. (2010) used an interview-based method to gather information and experience from experts, and rated the level of their satisfaction against fulfilment of functions of innovation systems, Lai et al. (2012) utilised a survey method for key actors and stakeholders to assess the perceived fulfilment of the functions of innovation systems, and Breukers et al. (2014) combined a participatory method to provide in-depth insights of the functionality of innovation systems to support future planning.

Functional Pattern Recognition

An increasing number of scholars contributing to the development of innovation system functions-based approach have started to evaluate the emerging technology dynamics in terms of functional patterns, or otherwise called cumulative causation. The notion of cumulative causation comes from virtuous and vicious cycles, a complex chain of events that reinforce itself through positive feedback loops (Barash and Webel, 2013). Evaluating the cumulative causation of innovation systems is expected to gain insights into how particular emerging technologies successfully diffuse (i.e. virtuous cycle) or fail to do so (i.e. vicious cycle) over time in terms of functional patterns (Jacobsson and Bergek, 2004, Negro and Hekkert, 2008, Bergek et al., 2008a, Bergek et al., 2008b). Suurs (2009) has elaborated this subject area further by exploring different types of 'motors' that may be occurring in the emergence of innovation systems. Suurs (2009) claims that a series of different functional patterns can be identified based on several stages in the emergence of innovation systems, where each stage involves different drivers, barriers and structural impacts on the innovation system, accelerating the 'motors' of the functional patterns (Suurs et al., 2009, Suurs et al., 2010, Suurs and Hekkert, 2009a). According to Suurs (2009), four types of motors have been identified in the emergence of typical innovation systems: science and technology push motor, entrepreneurial motor, system building motor, and market motor. The empirical studies on this area showed that motors involve self-reinforcing dynamics with formative stages necessary to establish a broad diffusion of emerging technologies into the existing technological system (Suurs et al., 2010).

2.3 Summary of the Literature Review

The brief review on the roadmapping literature above shows that the roadmapping approach is scalable at various levels, flexible for application in many contexts covering a broad range of elements including those found in the innovation system, and compatible with other management techniques for tool integration. However, the review of the literature on innovation system functions above indicates that the existing literature on innovation system functions has limited practical implications from the perspective of individual firms surrounded by the innovation system, which is the key perspective employed in the roadmapping approach. This indicates that the integration of roadmapping and innovation system functions is not yet practically useful at the firm level, unless the sector level notion of innovation system functions can be adapted for application at the firm level with which the roadmapping framework is primarily associated.

3. CONCEPTUAL FRAMEWORK

This section presents a conceptual framework, depicted in Figure 6, for exploring how the scalable integration of roadmapping and innovation system functions could be realised, by utilising insights from economics, management, innovation studies and systems engineering. Potential future research directions are discussed in this section: scaling down of innovation system function to the firm level, development of innovation system function-based roadmapping, and utility level improvement through an action research at the firm level.

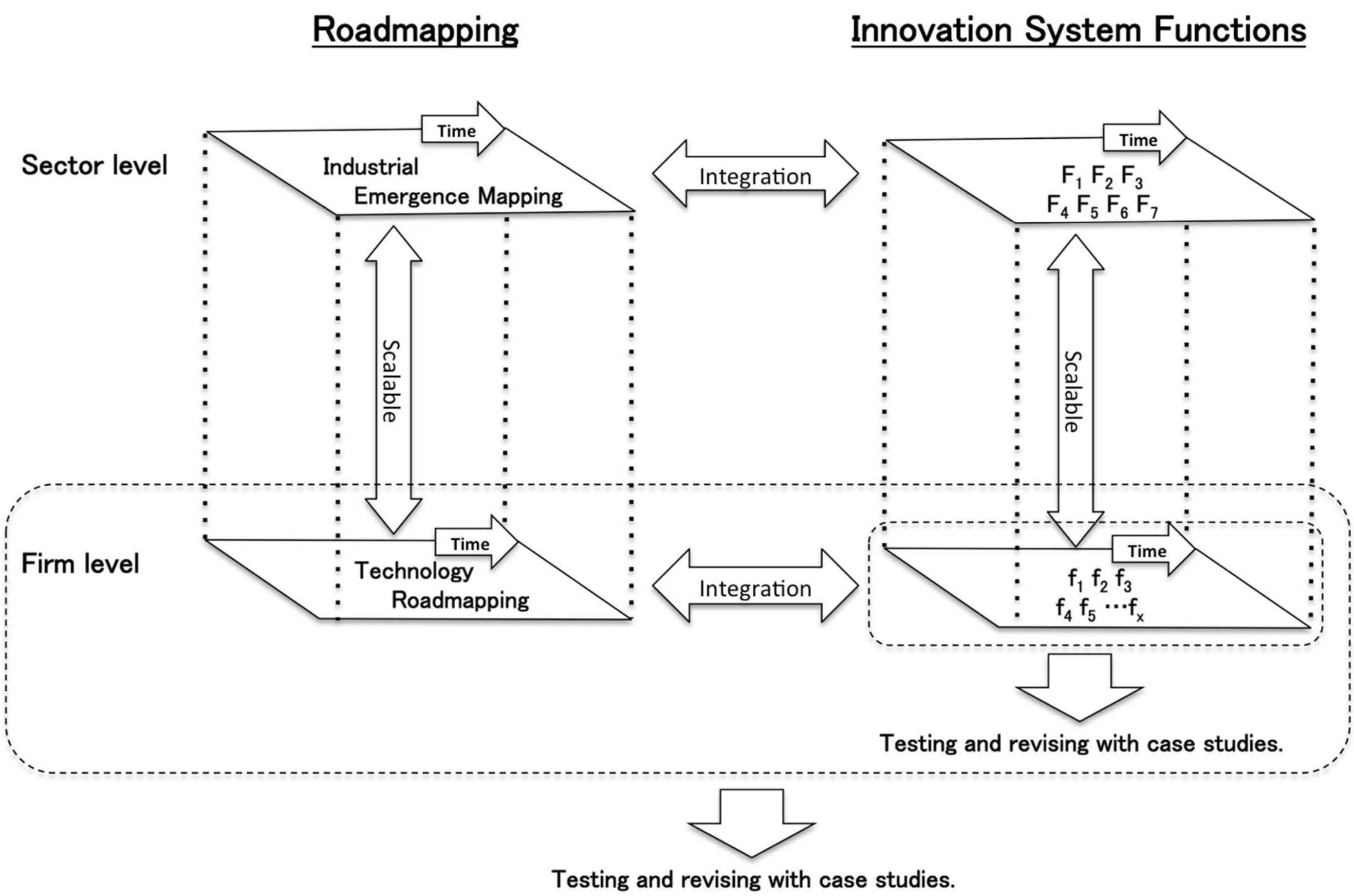

Figure 6: A conceptual framework for exploring the scalable integration of roadmapping and innovation system functions

Scaling Down of Innovation System Functions to the Firm Level

It is hoped that scaling down of innovation system functions to the firm level perspective can provide a solid theoretical underpinning of the roadmapping approach in the context of strategy and innovation. One possible approach to scaling down would be to holistically transform the sector level notion of innovation system functions to the firm level perspective, by undertaking qualitative case studies at the firm level, utilising the 'systems engineering' approach (Kapurch, 2010, Muller, 2011). It is planned that the transformed firm level functions will be developed by contrasting insights derived from the existing literature relating to the theories of the firm, which has been a growing trend in the relevant literature (Garrouste and Saussier, 2005). Since the evolutionary approach explicitly suggested by Nelson and Winter (1982), the use of evolutionary perspective for analysing economic change and technological innovation have been increasingly popularised. Many scholars have contributed to this subject area by applying various perspectives to build new concepts including, but not limited to, path dependence (David, 1985, Arthur, 1989, Arthur, 1990), knowledge-based theory of the firm (Foss, 1996), and dynamic capabilities (Teece et al., 1997).

In the relevant literature, Galbrun and Kijima (2009) examined the hierarchical deployment of the innovation system concept at the firm level, aiming to develop an holistic approach to explore the dynamic interaction between various actors in the innovation system context. However, they did not address the role of innovation system functions, and did not explicitly define any dimensions of the firm dynamics that explain the early growth of the firm. One of the potential conceptual foundations similar to innovation system functions is 'complexity and the functions of the firm' introduced by Wang and von Tunzelmann (2000). They explored the 'depth' and 'breath' of the firm from a complexity perspective, by considering the existence of firms as agents to enable the process of converting technologies into products. By taking into account the broader aspects of the firms' processes and its surrounding environment, the functions of the firm were defined as follows: technologies, markets, products, production processes and administrative management processes (Wang and von Tunzelmann, 2000). However, this approach fails to explicitly take into account the time dimension and the dynamics of the early firm growth. As also observed in other research in the relevant literature, most of the work has assumed that firms are already in existence with the established operations (Garnsey, 1998), and research on the early growth processes of the firm have not been explored extensively in the literature (Garnsey and Heffernan, 2005, Garnsey et al., 2006). Moreover, many scholars have often considered firms and industries separately in their analysis, neglecting the evolving role of the dynamic interaction between them in the process of economic growth and development (Bloch and Finch, 2010). It is expected that scaling down of innovation system functions to the firm level perspective will provide an opportunity for further theoretical contributions to the study of the early growth of the firm.

Development of Innovation System Functions-based Roadmapping

After developing the set of innovation system functions at the firm level, the next step would be to develop innovation system functions-based roadmapping as a structured approach. There would be two steps. Firstly, how to incorporate the scaled innovation system functions onto the architecture of roadmap would need to be explored. As the features of roadmap architectures used in current practice and literature are defined from functional stakeholder perspectives, the scaled innovation system functions at the firm level may result in producing the same, or at least similar, set of functional perspectives. It is expected that contrasting innovation system functions-derived functional perspectives and the ones defined in the generalised roadmapping framework will deepen understanding of the theoretical underpinnings of the roadmapping approach in the context of strategy and innovation, and will provide a new perspective and useful insights on the theory and practice of roadmapping. The second step would be to develop recommendations on the design of roadmap architectures and process steps based on insights derived from the scaled innovation system functions, aiming to guide the participants' strategic dialogue in the roadmapping workshop. It is important to note that too much guidance on roadmap architectures and process steps may lead to an over-controlling structure for the participants that might limit their thinking, exposing the process to the risk of psychological anchoring constraints. On the other hand, too little structure and guidance in the roadmap architecture would provide the participants with too much freedom so that their strategic dialogue would depend on the participants' communication style and biases, and would not be conducted efficiently. To overcome the anchoring issues of the developed roadmap architecture, it would be required to improve the utility level of the approach by conducting further research, which is described in the next sub-section.

Utility Level Improvement through an Action Research at the Firm Level

The ultimate goal of this doctoral research is to develop a theoretically underpinned structured approach to identify, select and communicate the essence of possible emergence paths that may help firms such as technology ventures to navigate towards successful business development. To overcome the anchoring issues and develop 'innovation system functions-based roadmapping' as a practical approach, it would be required to stabilise the utility level of the developed roadmap architecture, method and process. This doctoral research plans to utilise the process approach (Platts, 1993, Maslen and Lewis, 1994, Phaal et al., 2006) through an action research at the firm level to test and refine the developed approach.

Concluding Remarks

This paper has presented a conceptual framework as an early progress of this doctoral research, for exploring how the integration of roadmapping and innovation system functions could be realised. The following potential future research directions are identified: 1) scaling down of innovation system function to the firm level, 2) development of innovation system function-based roadmapping, and 3) utility level improvement through an action research at the firm level. This doctoral research explores how innovation system functions-based roadmapping could provide a new perspective and useful insights on the theory and practice of both roadmapping and innovation system functions. The ultimate goal of this doctoral research is to develop a theoretically underpinned structured approach to identify, select and communicate the essence of possible emergence paths that may help firms such as technology ventures to navigate towards successful business development.

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REFERENCES

ARTHUR, W. B. 1989. Competing technologies, increasing returns, and lock-in by historical events. *The Economic Journal*, 116-131.

ARTHUR, W. B. 1990. Positive feedbacks in the economy. *Scientific American,* 262, 92-99.

BARASH, D. P. & WEBEL, C. P. 2013. *Peace and conflict studies,* Thousand Oaks, California, USA, Sage Publications.

BERGEK, A., HEKKERT, M. & JACOBSSON, S. 2008a. *Functions in innovation systems: A framework for analysing energy system dynamics and identifying goals for system-building activities by entrepreneurs and policy makers,* Cheltenham, UK, Edward Elgar Publishing.

BERGEK, A., JACOBSSON, S., CARLSSON, B., LINDMARK, S. & RICKNE, A. 2008b. Analyzing the functional dynamics of technological innovation systems: A scheme of analysis. *Research Policy,* 37, 407-429.

BLOCH, H. & FINCH, J. 2010. Firms and industries in evolutionary economics: lessons from Marshall, Young, Steindl and Penrose. *Journal of Evolutionary Economics,* 20, 139-162.

BREUKERS, S., HISSCHEMOLLER, M., CUPPEN, E. & SUURS, R. 2014. Analysing the past and exploring the future of sustainable biomass. Participatory stakeholder dialogue and technological innovation systems research. *Technological Forecasting and Social Change,* 81, 227-235.

DAVID, P. A. 1985. Clio and the Economics of QWERTY. *The American Economic Review*, 332-337.

FORD, S., ROUTLEY, M. & PHAAL, R. The dynamics of industrial emergence. Proceedings of the International Conference of the Portland International Center for Management of Engineering and Technology (PICMET), 2010, Phuket, Thailand. IEEE, 1-8.

FOSS, N. J. 1996. Knowledge-based approaches to the theory of the firm: Some critical comments. *Organization Science,* 7, 470-476.

FREEMAN, C. 1995. The National System of Innovation in Historical-Perspective. *Cambridge Journal of Economics,* 19, 5-24.

GALBRUN, J. & KIJIMA, K. Fostering innovation system of a firm with hierarchy theory: Narratives on emergent clinical solutions in healthcare. Proceedings of the 53rd Annual Meeting of the International Society for the Systems Sciences (ISSS), 2009, Brisbane, Australia. 1-23.

GARCIA, M. L. & BRAY, O. H. 1997. *Fundamentals of technology roadmapping,* New Mexico, USA, Sandia National Laboratories.

GARNSEY, E. 1998. A theory of the early growth of the firm. *Industrial and Corporate Change,* 7, 523-556.

GARNSEY, E. & HEFFERNAN, P. 2005. Growth setbacks in new firms. *Futures,* 37, 675-697.

GARNSEY, E., STAM, E. & HEFFERNAN, P. 2006. New firm growth: Exploring processes and paths. *Industry and Innovation,* 13, 1-20.

GARROUSTE, P. & SAUSSIER, S. 2005. Looking for a theory of the firm: Future challenges. *Journal of Economic Behavior & Organization,* 58, 178-199.

GERDSRI, N., VATANANAN, R. S. & DANSAMASATID, S. 2009. Dealing with the dynamics of technology roadmapping implementation: A case study. *Technological Forecasting and Social Change,* 76**,** 50-60.

HEKKERT, M., NEGRO, S., HEIMERIKS, G. & HARMSEN, R. 2011. Technological innovation system analysis: A manual for analysts. Faculty of Geosciences, Utrecht University, Utrecht, The Netherlands.

HEKKERT, M. P. & NEGRO, S. O. 2009. Functions of innovation systems as a framework to understand sustainable technological change: Empirical evidence for earlier claims. *Technological Forecasting and Social Change,* 76**,** 584-594.

HEKKERT, M. P., SUURS, R. A. A., NEGRO, S. O., KUHLMANN, S. & SMITS, R. E. H. M. 2007. Functions of innovation systems: A new approach for analysing technological change. *Technological Forecasting and Social Change,* 74**,** 413-432.

HO, J.-Y. 2014. Standardization roadmapping: Cases of ICT systems standards. *STI Policy Review,* 5**,** 1-33.

HO, J.-Y. & O'SULLIVAN, E. 2013. Evolving roles of standards in technological innovatiom - Evidence from photovoltaic technology. *35th DRUID Celebration Conference.* Barcelona, Spain: DRUID.

JACOBSSON, S. & BERGEK, A. 2004. Transforming the energy sector: the evolution of technological systems in renewable energy technology. *Industrial and Corporate Change,* 13**,** 815-849.

JOHNSON, A. 2001. Functions in innovation system approaches. *DRUID's Nelson and Winter Conference.* Aalborg, Denmark: DRUID.

KAJIKAWA, Y., USUI, O., HAKATA, K., YASUNAGA, Y. & MATSUSHIMA, K. 2008. Structure of knowledge in the science and technology roadmaps. *Technological Forecasting and Social Change,* 75**,** 1-11.

KAPURCH, S. J. 2010. *NASA Systems Engineering Handbook,* Washington D. C., DIANE Publishing.

KERR, C., FARRUKH, C., PHAAL, R. & PROBERT, D. 2013. Key principles for developing industrially relevant strategic technology management toolkits. *Technological Forecasting and Social Change,* 80**,** 1050-1070.

KERR, C., PHAAL, R. & PROBERT, D. 2012. Cogitate, articulate, communicate: the psychosocial reality of technology roadmapping and roadmaps. *R & D Management,* 42**,** 1-13.

KOSTOFF, R. N. & SCHALLER, R. R. 2001. Science and technology roadmaps. *IEEE Transactions on Engineering Management,* 48**,** 132-143.

LAI, X. J., YE, Z. H., XU, Z. Z., HOLMES, M. H. & LAMBRIGHT, W. H. 2012. Carbon capture and sequestration (CCS) technological innovation system in China: Structure, function evaluation and policy implication. *Energy Policy,* 50**,** 635-646.

LEE, S. & PARK, Y. 2005. Customization of technology roadmaps according to roadmapping purposes: Overall process and detailed modules. *Technological Forecasting and Social Change,* 72**,** 567-583.

LIST, F. & COLWELL, S. 1856. *National system of political economy,* Philadelphia, USA, J.B. Lippincott & Company.

LUNDVALL, B.-Å. 1985. *Product innovation and user-producer interaction,* Aalborg, Denmark, Aalborg University Press.

MASLEN, R. & LEWIS, M. Procedural action research. Proceedings of the British Academy of Management Conference, 1994, University of Lancaster, Lancaster, UK.

MORTARA, L., PHAAL, R., KERR, C., FARRUKH, C. & PROBERT, D. Tool fingerprinting: Characterising management tools. International Conference of the Portland International Center for Management of Engineering and Technology (PICMET), 2014, Kanazawa, Japan. IEEE, 102-117.

MULLER, G. 2011. *Systems Architecting: A Business Perspective,* Boca Raton, Florida, USA, CRC Press.

NEGRO, S. O. & HEKKERT, M. P. Dynamics of Technological Innovation Systems: Empirical Evidence for Functional Patterns. Proceedings of the 5th International Conference on Innovation & Management, 2008, UNU-MERIT, Maastricht, The Netherlands. 195-208.

NELSON, R., R. & WINTER, S., G. 1982. *An evolutionary theory of economic change,* Cambridge, MA, Harvard University Press.

PETRICK, I. J. & ECHOLS, A. E. 2004. Technology roadmapping in review: A tool for making sustainable new product development decisions. *Technological Forecasting and Social Change,* 71**,** 81-100.

PHAAL, R., FARRUKH, C. J. & PROBERT, D. 2010. *Roadmapping for Strategy and Innovation: Aligning technology and markets in a dynamic world,* Cambridge, UK, Institute for Manufacturing, University of Cambridge.

PHAAL, R., FARRUKH, C. J. P., MILLS, J. F. & PROBERT, D. R. 2003. Customizing the technology roadmapping approach. *Technology Management for Reshaping the World***,** 361-369.

PHAAL, R., FARRUKH, C. J. P. & PROBERT, D. R. 2004. Technology roadmapping - A planning framework for evolution and revolution. *Technological Forecasting and Social Change,* 71**,** 5-26.

PHAAL, R., FARRUKH, C. J. P. & PROBERT, D. R. 2005. Developing a technology roadmapping system. *Technology Management: A Unifying Discipline for Melting the Boundaries***,** 99-111.

PHAAL, R., FARRUKH, C. J. P. & PROBERT, D. R. 2006. Technology management tools: concept, development and application. *Technovation,* 26**,** 336-344.

PHAAL, R., FARRUKH, C. J. P. & PROBERT, D. R. 2009. Visualising strategy: a classification of graphical roadmap forms. *International Journal of Technology Management,* 47**,** 286-305.

PHAAL, R., KERR, C., OUGHTON, D. & PROBERT, D. 2012. Towards a modular toolkit for strategic technology management. *International Journal of Technology Intelligence and Planning,* 8**,** 161-181.

PHAAL, R. & MULLER, G. 2009. An architectural framework for roadmapping: Towards visual strategy. *Technological Forecasting and Social Change,* 76**,** 39-49.

PHAAL, R., O'SULLIVAN, E., ROUTLEY, M., FORD, S. & PROBERT, D. 2011. A framework for mapping industrial emergence. *Technological Forecasting and Social Change,* 78**,** 217-230.

PHAAL, R. & YOSHIDA, S. Architecting strategy: Visual form and function of roadmaps. International Conference of the Portland International Center for Management of Engineering and Technology (PICMET), 2014, Kanazawa, Japan. IEEE, 2960-2971.

PLATTS, K. W. 1993. A process approach to researching manufacturing strategy. *International Journal of Operations & Production Management,* 13**,** 4-17.

PROBERT, D. R., FORD, S. J., ROUTLEY, M. J., O'SULLIVAN, E. & PHAAL, R. 2013. Understanding and navigating industrial emergence. *Proceedings of the Institution of Mechanical Engineers Part B-Journal of Engineering Manufacture,* 227**,** 781-793.

ROUTLEY, M., PHAAL, R. & PROBERT, D. 2013. Exploring industry dynamics and interactions. *Technological*

Forecasting and Social Change, 80**,** 1147-1161.

SUURS, R. A. 2009. *Motors of sustainable innovation: Towards a theory on the dynamics of technological innovation systems.* PhD thesis, Utrecht University, Utrecht, The Netherlands.

SUURS, R. A. & HEKKERT, M. P. 2009a. Cumulative causation in the formation of a technological innovation system: the case of biofuels in the Netherlands. *Technological Forecasting and Social Change,* 76**,** 1003-1020.

SUURS, R. A. A. & HEKKERT, M. P. 2009b. Competition between first and second generation technologies: Lessons from the formation of a biofuels innovation system in the Netherlands. *Energy,* 34**,** 669-679.

SUURS, R. A. A., HEKKERT, M. P., KIEBOOM, S. & SMITS, R. E. H. M. 2010. Understanding the formative stage of technological innovation system development: The case of natural gas as an automotive fuel. *Energy Policy,* 38**,** 419-431.

SUURS, R. A. A., HEKKERT, M. P. & SMITS, R. E. H. M. 2009. Understanding the build-up of a technological innovation system around hydrogen and fuel cell technologies. *International Journal of Hydrogen Energy,* 34**,** 9639-9654.

TEECE, D. J., PISANO, G. & SHUEN, A. 1997. Dynamic capabilities and strategic management. *Strategic Management Journal,* 18**,** 509-533.

TRUFFER, B., MARKARD, J., BINZ, C. & JACOBSSON, S. 2012. A literature review on Energy Innovation Systems: Structure of an emerging scholarly field and its future research directions. *Radar Paper, Strategic research alliance for energy innovation systems and their dynamics (EIS), Denmark in global competition.* Technical University of Denmark, Kongens Lyngby, Denmark.

VAN ALPHEN, K., HEKKERT, M. P. & TURKENBURG, W. C. 2010. Accelerating the deployment of carbon capture and storage technologies by strengthening the innovation system. *International Journal of Greenhouse Gas Control,* 4**,** 396-409.

WANG, Q. & VON TUNZELMANN, N. 2000. Complexity and the functions of the firm: breadth and depth. *Research Policy,* 29**,** 805-818.

WILLYARD, C. H. & MCCLEES, C. W. 1987. Motorola's technology roadmap process. *Research Management,* 30**,** 13-19.