Dimensions of Standards for Technological Innovation – Literature Review to Develop a Framework for Anticipating Standardisation Needs

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Abstract

With the prosperity of information technology, there has been an increasing awareness that standards play critical roles in supporting certain activities of technological innovation. However, because of the dual nature of standards that may both inhibit and promote innovation depending on circumstances, careful and systematic consideration of various dimensions relevant to standards is essential for managing standardisation activities to support technological innovation more effectively. Despite such renewed attention as well as various efforts by academic scholars and practitioners on systematic analysis of standardisation, our understandings of important dimensions of standards are relatively poor, due to complex dynamics and interactions between these various aspects of standards in modern technologies. In order to overcome such challenges, this paper provides a comprehensive review of literature on standards and standardisation, offering a coherent and integrated list of important dimensions of standards in the context of technological innovation. With ability to capture most of these factors in a holistic and integrated manner, a strategic roadmap-based framework is proposed as a potential framework that can represent these dimensions more systematically. The paper concludes with discussion on how such roadmap-based framework can be used to help standards organisations and policymakers in anticipating standards needs and developing relevant strategies for more effective management of standardisation activities, supporting overall technological innovation.

Introduction

Until the last decades of the 20^{th} century, there had been little academic literature that addresses standards and standardisation in a broad context of innovation. As de Vries (2001) notes, previous academic research on standards generally focused on single technical topic or particular aspect of standardisation, often economic aspect. Their views on standards have also been limited to dominating market and maximising efficiency in trade, not addressing their interplay with innovation activities in rapidly evolving technologies (Branscomb & Kahin 1995). In general, despite important roles of standards in supporting innovation activities (as noted by Tassey 2000, for example), previous literature on standards and standardisation has been presented in a less systematic way, compared to the development of academic literature on technological innovation and innovation systems.

More recently, awareness of standards and their strategic importance for innovation has been increasing with the prosperity of information technology and associated challenges presented by it. Due to the proliferation of various technical components that need to be interoperable when integrated within larger systems, 'pre-market entry' standards, such as compatibility standards, during the earlier stages of R&D have been found to play critical roles in enabling innovation and diffusion of new technologies. Such renewed attention given to the strategic importance of standards in early phases of innovation is in contrast to that of the industrial age, where standardisation needs were generally identified to limit technological options of products already existing in the market (ISO/IEC 1990). Egyedi (1999) also confirms that before the advent of standards related to information technology, the most common form of standards used to be variety reduction ex post; whereas in the 1980s, ex ante standards attracted the attention of Standards Developing Organisations (SDOs), as standardisation in early phases of technological maturity was seen to be effective to achieve interoperability.

More and more studies have been carried out since then, suggesting a variety of important roles of standards in supporting various activities of technological innovation, including: defining and establishing common foundations upon which innovative technology may be developed; codifying and diffusing state of the art technology and best practice; and allowing interoperability between and across products and systems, stimulating both innovation and diffusion of new technologies (Allen & Sriram 2000; Tassey 2000; Blind & Gauch 2009; Swann 2010; NSTC 2011a). However, inappropriate standards may impose certain constraints in innovation systems, by increasing irreversibility and decreasing interpretative flexibility of the technologies (Hanseth et al. 1996). They may also result in problems of lock-in to inferior standards or the risks of monopoly, which are potentially detrimental to innovation (Swann 2000; CIE 2006). Due to such dual nature of standards, we face the paradox that "standards are critical to market development but, once accepted by the market, standards may threaten innovation, inhibit change, and retard the development of new markets," as noted by Branscomb & Kahin (1995).

Because of such complex dynamics between standards and technological innovation, timely and appropriate development of standards is critical in facilitating innovation. Thus, there is an increasing awareness among standards experts and policymakers that carefully strategized and implemented standards are crucial to effectively support technological innovation (EXPRESS 2010; NSTC 2011a; European Commission 2011; Lord Heseltine 2012). Accordingly, there have been a number of efforts to carry out strategic foresight analyses for anticipation and management of standardisation activities, especially in emerging technology areas. For example, National Institute of Standards and Technology (NIST) in the US took a number of initiatives to coordinate the development of standards in various domains with standards-related opportunities, including smart grid, cloud computing, and additive manufacturing (NIST 2010; NIST 2011; NIST 2013). Standards organisations in Germany also adopted a systematic view of the roadmapping approach as a way of anticipating standards needs in a variety of interdisciplinary areas, such as electric vehicles, smart grid, and smart manufacturing (NPE 2012; DKE 2012; DKE 2014). SASAM's (2014) additive manufacturing standardisation roadmap is another example focusing on identification of necessary standards and formulation of strategies to develop them, in order to support the additive manufacturing industry through effective management of standardisation.

As can be seen from the above examples, there is an increasing realisation for the importance of anticipation and management of appropriate standards to effectively support technological innovation. Yet, there has only been a few academic literature addressing anticipation or foresight issues of standardisation, such as a study by Goluchowicz & Blind (2011) discussing their experiences with identifying future fields of standardisation. Such limited understanding on anticipation and strategy development for standardisation needs is probably due to complex dynamics involved in standards as well as innovation; there is thus a lack of careful and systematic consideration of various dimensions relevant to standards, which is critical for such foresight exercises that aim to anticipate standardisation needs.

Since 1990s, various academic and practical literature have been struggling to define important dimensions and aspects of standards that need to be considered for their active and constructive roles in technological development (for example, Branscomb & Kahin 1995; Baskin et al. 1998; Sivan 1999). However, such efforts have been quite challenging, because of diverse uses of 'standards' in innovation systems; there are varying levels of technical details associated with standards, various roles they play in technological innovation, and different stakeholders leading or participating in standardisation, all of which evolve over time as innovation progresses, complicating these dynamics further (Allen & Sriram 2000; Tassey 2000; Sherif 2001; Wang & Kim 2007; Swann 2010; Blind et al. 2010). For example, from their case study of photovoltaic technology, Ho & O'Sullivan (2013) provide empirical evidence which suggests that different types of standards with different roles and functions, developed by different SDOs engaging different set of stakeholders, emerge across different stages of technological innovation and development.

Because of such diversities and complexities, existing frameworks identifying key dimensions of standards are somewhat limited to explicate relationships and dynamics between standardisation and innovation; they are neither consistent nor comprehensive enough, emphasising only certain aspects of standards (for example, Sivan 1999; Tassey 2000; Blind & Gauch 2009; Hatto 2013). Baskin et al. (1998) present a more systematic framework for standardisation in terms of answers to six questions – why, what, when, who, how, and where – but it focuses on standards related to telecommunications technology only. Sivan (1999) provides a theoretical framework applicable to more general technological domains, consisting of five dimensions – level, purpose, effect, sponsor, and stage – of standards, but its high generality inevitably results in the lack of applicability of some of the dimensions to some cases, especially in the context of complex technological innovation which is the focus of our current discussion.

Such challenges in comprehensive and systematic analysis of standards for effective future-oriented standardisation activities are even more increasing with current trends in technological developments. As most technology-based industries are becoming more interdisciplinary, integrated, and rapidly evolving at the same time, it is difficult to anticipate how each aspect and dimension of standards may be related to overall innovation systems. Yet the growing importance of information technology in a variety of industrial areas – including smart grid and internet of things, just to name a few – call for more anticipatory and effective standardisation strategies (Blumenthal & Clark 1995; Jakobs et al. 2011). In addition, the increasing complexity of modern technologies – especially their system characteristic with interdisciplinary nature – makes such activities even more challenging, as it requires a large infrastructure of standards to allow integration of new technologies, with coordination of various stakeholders from the growing number of industry sectors involved (Blumenthal & Clark 1995; NPE 2012; Tassey 2014).

Consequently, even though many scholars and practitioners attempted at presenting various frameworks for standards in the context of innovation, our understandings of important dimensions of standards are relatively poor, considering complexities associated with modern technologies as well as consequent development of academic literature on innovation systems. Yet, there is an increasing awareness in the policy arena of the importance of standardisation activities in a systematic and comprehensive way to support innovation in emerging technology areas, as previously discussed (NIST 2010; European Commission 2011; NSTC 2011b; Scapolo et al. 2013; SASAM 2014). Therefore, there are needs for a framework systematically representing important dimensions and aspects of standards, that need to be considered for more effective and future-oriented standardisation activities.

In order to inform the design of a framework for anticipating standardisation needs in support of innovation, the key dimensions and characteristics of standards related to technological innovation need to be first understood. In this regard, this paper offers a coherent and integrated list of various dimensions of standards, through a comprehensive review of literature on a variety of ways of classifying or categorising different types of standards. It particularly focuses on issues that are relevant to technological innovation (as opposed to those related to process or service innovation), given the importance and urgency of the issue in emerging technology areas, as well as increased challenges with current technological landscape. Although different categories and aspects would need to be highlighted for different domains of technologies, the paper aims attention at important dimensions and issues that apply to a broad range of technological domains in general. Based on insights generated from the literature review, a practical framework for anticipating standardisation needs and developing relevant strategies is to be proposed, systematically capturing important dimensions and aspects that need to be considered for effective management of standardisation activities in supporting technological innovation.

Dimensions of Standards – a Literature Review

In order to review existing literature on various dimensions of standards in a more systematic and coherent way, a number of frameworks for standards that have been previously developed by other academic scholars has been studied. Verman (1973) is one of the first to propose a three-dimensional space as a way to systematically look at the phenomenon of standards. With each point in the space representing a potential question that one can ask about the subject of interest, the space assists in describing and analysing various domains of standards. Using Verman's dimensional approach, Sivan (1999) proposes a more verbal framework composed of five dimensions of standards: level, purpose, effect, sponsor, and stage. Although it overcomes limitations of the spatial approach which involves only three dimensions, the framework also has the inherent limitations of highlighting only parts of the terrain, potentially failing to capture other dimensions that may be important. In order to completely describe various domains of standards in the field of communications technology, Baskin et al. (1998) asked six questions that are often used to describe any forms of human activity: what, why, when, how, who, and where. It appears that the list of six questions reasonably covers all important aspects of standards and standardisation comprehensively, hence is adopted as the format of this literature review (the question of 'where' is later eliminated, as it seems to overlap with other dimensions such as 'what' and 'who'). Each question corresponds to the dimension of technology elements, roles and functions, time, level and form of consensus, and participating stakeholders, respectively. Details of these dimensions and categories of standards, as presented in existing literature, are discussed in the following sections.

1. Technology Elements: *'What'* Technology Elements to Standardise

One of the most important categories of standards that are relevant to technological innovation is types of technology elements that standards are associated with. Tassey (2014) argues that standards have different strategic and marketplace roles depending on categories of technology involved, hence different rationales for and the processes by which standards are set. Therefore, it is important to differentiate between standards for different categories of technology elements, before discussing their roles and functions.

According to Tassey (2000, 2014), standards can basically be delineated between product and nonproduct standards, which are distinctly different in terms of their relationships to product structure and public good content. **Product-element standards** typically involve one of the key attributes of a product, conveying direct competitive advantage to the owner of the technology producing those attributes. They can be related to either generic or platform technologies, i.e. the fundamental technical concepts derived from basic science for specific product innovations, or proprietary technologies, i.e. actual market applications developed by companies derived from platform technologies. **Nonproduct standards**, on the other hand, derive from a different technical base from that of product's attributes; so called infratechnologies – that provide varied and critical technical infrastructure support for the development of generic and proprietary technologies – for such standards have large public good content, hence require both industry and government investment. Measurement and test methods, interface standards, scientific and engineering databases, and standard reference materials are examples of infratechnologies frequently embodied in nonproduct standards; they tend to be competitively neutral, yet critical to the entire industry's efficiency. These product and nonproduct standards at the product level interact with each other to create a system composed of various technology elements, as depicted by Tassey (1997).

Along with these standards for various categories of technology elements, Tassey (2000) describes how subsequent production, commercialisation, and market development are all affected by standardisation, as shown in Figure 1. In addition, he notes that as technologies are becoming increasingly complex, system design will also drive standardisation simultaneously with standardisation at the product level. Therefore, standards are "ubiquitous technical infrastructure affecting all stages of technology-based activity," with complex interactions between and across various types of technology elements (Tassey 2014).

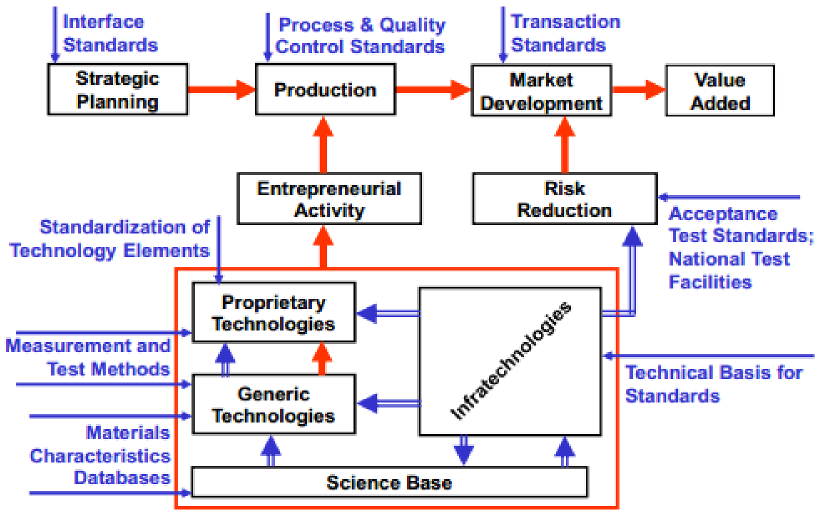

Figure 1. Roles of Standards in Technology-based Industries (Tassey 2000)

It is also important to note that such interactions between standards and technology elements should not be understood as linear or static, but more of dynamic processes. With new technologies continuously being introduced and system elements evolving at different rates, standards also need to be revised for updated interfaces at different points in time (Tassey 2014). Therefore, it is a dynamic, living process with a constant dialog about technology elements and how limited common implementations of technology may be useful to spur innovation and market development (Branscomb & Kahin 1995). As a result, such interactions and activities are also influenced by when standards are developed and introduced, as well as why standards are needed to support technological innovation, which will be discussed in the following section.

2. Roles and Functions: *'Why'* Standards are Needed

It appears that different types of standards with different roles and functions are needed for different categories of technology elements to achieve their efficient development and utilisation. Although standards have been often considered as homogeneous collection of decisions regarding economic activities, there are in fact, different standards developed for various, even multiple or contradictory, purposes, depending on the type of technical knowledge they codify (Tassey 2000). It is therefore necessary to define various types of standards according to their basic roles and functions in innovation, in order to discuss mechanics of each generic function along with their complex interactions with technology and other innovation activities.

Table 1. Standards with Various Roles and Functions (adopted from Tassey 2014)

Types	Examples	Knowledge Diffusion	Economic Impacts
Terminology and semantic standards	- Definitions of key concepts and attributes	- From basic to oriented-basic and applied research	- Increased communication efficiency among various stakeholders
Measurement and characterisation standards	- Measurement and test methods - Science and engineering databases, standard reference materials	- From basic to applied research	- Increased research efficiency through more accurate research inputs and verifiable results - Higher productivity / quality through better process control
Quality and reliability standards	- Performance metrics, such as minimum quality levels - Procedures, such as equipment calibrations	- From pilot products into mass markets	- Expand market share through performance assurance and reduction in transaction costs
Compatibility and interface standards	- Interconnection among system components - Portability of software across implementation of a computer system	- From applied research to experimental development of new products - From pilot products into mass markets	- Achieve network externalities and thereby expand value / cost ratios - Facilitate open systems and thereby enable more competition at component and subsystem levels
Variety reduction standards	- Microprocessor architecture - Size of silicon wafers	- From pilot products into mass markets	- Achieve economies of scale and compatibility across components

According to numerous literature, standards can be categorised into five basic types according to their roles and functions. **Terminology and semantic standards** define common language and definitions to facilitate efficient communication among various stakeholders (Blind & Gauch 2009; BERR 2008). **Measurement and characterisation standards** specify methods for describing, quantifying and evaluating product attributes for efficient R&D (Blind & Gauch 2009; Hatto 2010). **Quality and reliability standards** specify acceptable performance criteria along dimensions such as functional levels, efficiency, and health and safety (BERR 2008; Tassey 2000). **Compatibility and interface standards** specify properties that a technology must have in order to be compatible (physically or functionally) with other products, processes or systems (Blind & Gauch 2009; BERR 2008). **Variety reduction standards** are designed to limit a certain range or number of characteristics such as size or quality levels, for economies of scale and users' confidence (Swann 2010; Hatto 2010; Tassey 2000).

It is interesting to note that these various types of standards also play an important function of knowledge diffusion between different innovation actors. Transferring new knowledge between and across various stages of technological innovation (Blind & Gauch 2009), standards "help bridge the gap between research and marketable products (European Commission 2011, p.6)." The Expert Panel for the Review of the European Standardisation System (EXPRESS 2010, p.16) also notes that "standardisation converts new knowledge from scientific research into market" through various types of standards. Table 1 is adopted from Tassey (2014), summarising examples, knowledge diffusion roles, and economic impacts of various types of standards with different roles and functions.

3. Time: *'When'* to be Standardised

According to Blind & Gauch (2009), standards with different roles and functions are needed at different times and stages of innovation processes. Based on the linear process of technological innovation and development, they propose a framework which distinguishes various roles of different types of standards at different phases of the innovation from basic research to diffusion into market (see Figure 2).

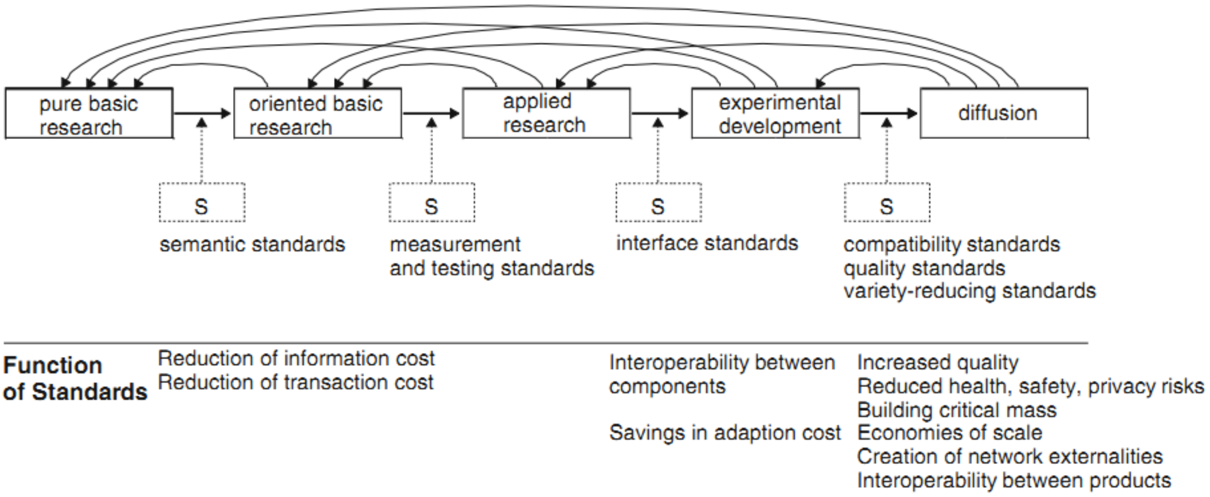

Figure 2. Various Types of Standards in the Innovation Process (Blind & Gauch 2009)

Many other academic literature have also note the importance of appropriate timing of the development and introduction of standards, in order for them to perform intended purposes. Early standardisation forestalls diversity, but precludes experience with the alternatives, limiting the ability to further innovate; whereas late standardisation allows further technical improvements, but may yield confusion, making it more difficult to achieve economies of scale and scope (Lehr 1995; Libicki 1995; Egyedi 1999; Tassey 2014). Lehr (1995, p.122) proposes that standardisation is a “complex dynamic of the trade-off between waiting for a better technology against the costs of delaying the benefits of adoption.” Therefore, standardisation on a timely basis is crucial for effectively supporting technological innovation; due to cumbersome procedural requirements of formal standards organisations and fast pace of modern technology development, anticipation and strategic planning of standardisation in a timely manner is essential to achieve this.

In order to meet the expected needs of users appropriately, successful standards should consider both real-time and timing relative to technology lifecycles. Sherif (2001) proposes a model that describes the timing relationship between standards and technology lifecycles, using the technology S-curve (see Figure 3). Although it is difficult to understand more than a posteriori relationship between standards and market development, intrinsic capabilities of the technology help us observe what types of standards may or should appear at different stages of the technology lifecycle throughout the innovation journey.

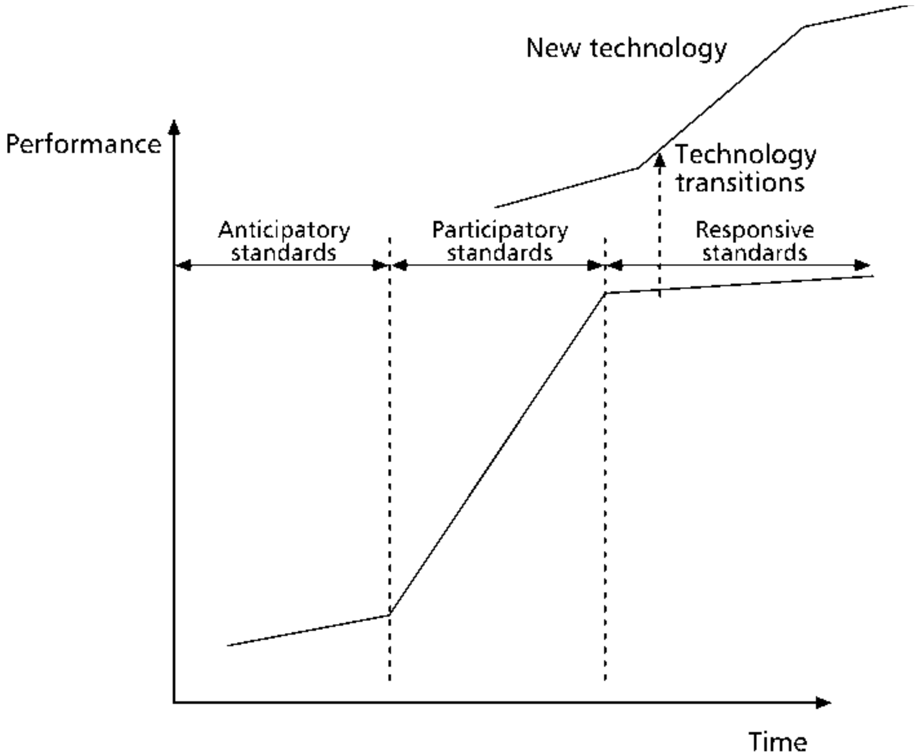

Figure 3. Timing of Standards in Relation With the Technology S-curve (Sherif 2001)

According to his framework, **anticipatory standards** are generally specified at the introduction of the technology. As they define new concepts, features, components, and tools needed to proceed with trial implementations, anticipatory standards are essential for widespread acceptance of a device or service. They are also crucial for the interoperability of communication systems, hence there are many anticipatory standards related to Information and Communication Technologies (ICT); examples of anticipatory standards in ICT include ISDN (Integrated Services Digital Network), Bluetooth, and UMTS (Universal Mobile Telecommunications Service) for voice and data. However, anticipatory standards may include irrelevant details leading to increased complexity, particularly when the market requirements are unclear or ill defined. Therefore, for anticipatory standards to be effective, their scope and objectives should be well-defined, offering a minimum set of features to stimulate the market. (Sherif 2001; Egyedi & Sherif 2008)

Participatory standards proceed in lock step with implementations for refinements and definitions of the product systems that embody the technology; hence, they are often generated while the performance of the innovation is improving, the technical knowledge is diffused, and initial products are commercialised. Examples of participatory standards can be standards specifying the behaviour of application systems to ensure a flexible evolution of the whole ensemble to a new state of operation (e.g. speech and voiceband coding algorithms of ITU Recommendations, V.90 recommendation for modems at 56Kbit/s). Participatory standards can spur incremental innovation, and a widespread interactive environment, such as the Internet, is helpful for their development. (Sherif 2001; Egyedi & Sherif 2008)

Finally, **responsive standards** are developed towards the tail of technology lifecycles, as they relate to the manifestation of a "completed and connected set of transformational technology systems used in communicating and transacting operations within and between producer / customer / supplier networks" (Betz 1993, p.361). They codify a product or service that has already been sold with some success, or define the expected quality of a service and performance level of the technology; hence, offer a systematic way to distil scientific information and provide avenues for sharing best practice technical know-how. However, waiting too long for responsive standards may encompass the danger of incompatibility and difficulty of reaching consensus, as happened with the multiplicity of television transmission standards. (Sherif 2001)

It is difficult to draw a clear-cut line between anticipatory, participatory, and responsive standards; a large number of standards are typically a mixture of two or more. For example, GSM (Global System for Mobile communications) specifications was developed partly as anticipatory in that they pre-defined a platform for future growth for both service operators and manufacturers, and partly as participatory in that they were defined with feedback from the market (Egyedi & Sherif 2008). Such characteristics make management of standardisation activities even more challenging. It is also important to note that there may be multiple technology lifecycles for multiple component technologies that make up larger technological systems, or even new technology lifecycles replacing those of old technologies or systems (as shown in Figure 3). Hence, the issue of timing relative to technology lifecycles should be distinguished from timing of standards in terms of real-time.

4. Level and Form of Consensus: *'How'* to Standardise

Along with the timing issue, content and flexibility of standards are also important factors for the efficient innovation and market penetration of technologies, as initial standards can be hard to modify or update due to time and cost requirements as well as installed-base effects (Branscomb & Kahin 1995). Therefore, it is essential to carefully consider the level of risks and uncertainties to be managed by standardisation; there are various standards options to strategically manage such risks, according to the level of consensus and form of specification.

For standards developed by formal SDOs, there are a number of different types of deliverables depending on the level of consensus achieved in standardisation as well as the level of uncertainty in technical solutions. **European Norms (EN)** and **International Standards (IS)** are developed for topics with the highest level of maturity and a high degree of consensus among various member countries. For topics that meet certain criteria, but are still underdevelopment or which have not reached a sufficient consensus, documents such as **Technical Specifications (TS)**, **Publicly Available Specifications (PAS)**, or **International Workshop Agreements (IWA)** are generated. (Hatto 2013)

Depending on the form of specifications, standards can also be distinguished between performance standards and solution-describing standards. **Performance standards** specify desired outcomes or performance levels, allowing flexibility in product or service design while still meeting the performance requirements of the standard; for example, minimum standards of quality and safety for products may be specified to promote greater consumer protection. On the other hand, providing detailed descriptions or precise specifications for exactly how designs or solutions could achieve these outcomes, **solution-describing** (also called prescriptive- or design-based) standards are much more restrictive and can inhibit certain innovation activities to a greater degree; for example, much of compatibility and interface standards for information and communications systems are of this type. (Tassey 2000; de Vries 2001; BERR 2008)

5. Stakeholders: *'Who'* is Involved in Standardisation

Finally, standards can be also categorised by who is leading or involved in standardisation activities. Before discussing the issue of stakeholders, it is necessary to first distinguish standards between de facto standards and de jure standards, according to their origins in the market place or the strategic efforts of recognised SDOs. **De facto standards** are usually driven by market forces, either voluntarily formed from widespread consensus or established through standard battles (Tassey 2014). On the other hand, **de jure standards** are generally developed and approved by recognised standard bodies (SDOs) through the formal consensus-based process (although some people prefer to limit de jure standards to legal mandates, standards emerging as formal published documents enjoy the legitimacy of the traditional formal processes, thus are appropriate to be classified as de jure standards rather than de facto standards) (Branscomb & Kahin 1995; Allen & Sriram 2000; Wang & Kim 2007; Hatto 2010). Nowadays, the distinction between de facto and de jure standards seems to be blurred in many domains of technologies especially in ICT, yet it appears that the main question arises as to whether there is an official organisation leading the formal, collective, and open process of standardisation, engaging various stakeholders involved. Summarising various published literature, Wang and Kim (2007) have developed a table comparing between de jure and de facto standards; Table 2 presents some of its highlights.

Standards can be developed by entities and organisations at different levels, with various degrees of consensus in their preparation and approval; such SDOs leading standardisation activities also have different expertise and focus, depending on their nature and characteristics. Standards that are legally mandated are often published by technical committees of official standards setting bodies that are specifically created for the purpose; they can be **national standards bodies** (e.g. BSI, DIN and AFNOR), **multinational standards bodies** (e.g. CEN, CENELEC and ETSI), or **international standards bodies** (e.g. ISO, IEC and ITU), and standards developed by them are called national, regional, or international standards, respectively. De jure (formal) standards can be also published by **non-profit (industry-driven) SDOs** (e.g. ASTM) or **professional engineering or scientific associations** (e.g. IEEE). Recently, especially in the domains of ICT, standards developed by international working groups of **industrial consortia** (e.g. W3C, OMG and IETF) or **research consortia / initiatives** (e.g. BioBricks) also tend to migrate into de jure standards. On the other hand, de facto standards, i.e. private (in the context meaning specific to an organisation) standards that have not necessarily gained consensus or approval by official bodies, are often developed by **private companies** or **trade associations**. (Coallier & Robert 2006; Hatto 2010; O'Sullivan & Brévignon-Dodin 2012)

Table 2. Comparison between De Jure and De Facto Standards (adopted from Wang & Kim 2007)

	De jure standards	De facto standards
Who governs	- Government - Official standard bodies or association (both public- and private-driven)	- Winners in market - Strategic coalitions or alliances
Standard selection	- By so called beauty contest - By permit	- By competition or battle in the market - By negotiations
Contingent conditions used	- Formal bodies and organisations - No or fewer dominant technologies	- Powerful technology leaders - Consensus in the market
Strength	- Avoid the competition costs - Selection bias	- Facilitate the technology innovation by standard competition
Weakness	- Judgment gap between decision makers and technology holders	- Risk of winner-takes-all - Privately profitable but socially undesirable technologies

The issue of who is developing standards or leading standardisation activities is also related with the issue of public intervention and the role of government in standardisation. This is because standards, as technical infrastructure with strong public good content, are considered to be powerful non-market mechanisms that governments could use to foster technological innovation (Edquist 1999; Tassey 2000). There are various modes in which the government or other public agencies can engage in standards development, including convenor, coordinator, technical leader, participant, facilitator, implementer, funder, and technical advisor (NSTC 2011a). Depending on which organisation is leading standards development, roles of the government (if any) and modes of public engagement would need to vary for effective management of standardisation activities.

Different organisations leading standards development have not only different standardisation missions and contributions, but also different participation of stakeholders. A number of literature also highlight the importance of various stakeholders involved in actually developing and writing standards, and how it evolves across different stages of the innovation process (Yoo et al. 2005; Blind & Gauch 2009). Yoo et al. (2005) argue that successful innovation is made possible only by a network of actors from industry, finance, research, and government whose interests are mediated through standards. Mapping out the standardisation landscape for nanotechnology, Blind & Gauch (2009) also highlight the large number of stakeholders interested in standards development – including various SDOs, companies, universities, as well as research organisations – and the importance of their participation at certain stages of the innovation process. There is consequently value in identifying evolving participation of various stakeholders for more effective and strategic management of standardisation activities. However, issues around stakeholders tend to be overlooked in many policy initiatives that aim to explore strategic standardisation activities for innovation.

Such issues of organisations and stakeholders involved in standardisation as well as the role of government are inherently related to the type of technology elements that has been discussed in a previous section. Besides '*what* technology elements to standardise', the issue of '*who* is leading and involved in standardisation' is also interrelated with other factors and dimensions, such as '*why* standards are needed', '*when* to be standardised', and '*how* to standardise' to support innovation. In fact, the review of literature has shown that all these dimensions and issues are not independent, but interdependent to each other, resulting in complex dynamics between various factors of standardisation activities in support of technological innovation. Therefore, in order to achieve effective anticipation and strategic planning for standardisation in support of innovation, it is imperative to be able to observe and manage complexities and dynamics between various dimensions of standards that have been identified through the above review of literature.

Developing a Framework for Anticipating Standardisation Needs

Existing literature suggests that there are a number of different ways of classifying or categorising standards, according to: categories of technology elements they are associated with (*what* technology elements to standardise), various roles and functions they play (*why* standards are necessary to support technological innovation), timing (*when* to be standardised, in terms of both real-time and relative to technology lifecycles), level and form of consensus (*how* to standardise), and stakeholders (*who* is leading and involved in standardisation). These are found to be important dimensions that influence complex dynamics between standards and technological innovation, hence need to be appropriately accounted for in managing standardisation activities to support innovation. In addition, such aspects are all interrelated to each other, and cannot be regarded as utterly separable dimensions; therefore they need to be considered holistically for effective anticipation and strategy development of standardisation. Yet more careful characterisation is needed for a number of issues in order to better understand their complex dynamics and interactions. For example, further studies need to be carried out on how different types of standards are associated with different innovation activities across different stages of innovation journey, which are briefly mentioned in various literature (for example, Blind & Gauch 2009), but not in a comprehensive or consistent way. In addition, discussions on how a variety of SDOs and diverse sets of stakeholders are involved in different standardisation activities are sparse in existing literature, hence are in need for more attention.

In order to carry out such studies more effectively, a strategic framework is needed that can systematically capture all five aspects of standards identified in previous sections. It appears that there would be a significant value in adopting a strategic roadmapping framework, a strategic framework widely adopted by many organisations in different sectors and at various levels for supporting technology management and strategic planning (Phaal et al. 2004b). Providing a coherent, holistic, and high-level integrated view of multiple aspects of technology systems, a strategic roadmap effectively displays their complex interactions between and across each other. It does so by providing a framework within which various types of data and information – including know-*why, -what, -how,* and *-when,* along with the relationships between these knowledge types – can be stored in a layered form. Hence, a roadmapping framework is able to provide a systematic view of dynamic systems, enabling "the evolution of a complex system to be explored and mapped, supporting innovation and strategy development (Phaal et al. 2009, p.287)."

Such systematic and holistic nature of a roadmapping framework potentially allows itself to effectively visualise the overall dynamics of standards in innovation systems, without losing the detail and diversity of various dimensions to be considered for effective standardisation. The framework can not only capture most of the important dimensions of standards in technological innovation – *what* technology elements to standardise, *why* standards are needed, *when* to be standardised, and *how* to standardise –, but also adequately reflect how they all interact with each other and evolve over time with a more careful level of analysis. In addition, the framework is quite flexible and adaptable that their architectures are readily reconfigurable to include any other key dimensions of innovation activities relevant to particular technology domains (Phaal et al. 2004a; Lee & Park 2005). Therefore, it can be used as a practical tool for observing and analysing complex dynamics between various aspects of standards discussed in previous sections.

Furthermore, as one of the most widely used foresight approaches for developing technology strategies, the roadmapping framework can also be used as an operational tool for anticipating standardisation needs and developing appropriate strategies for future standardisation activities. Extending the time axis to include short- and long-term vision allows future-oriented roadmapping exercises, where roadmap participants are gathered to create a common vision of the future. Bringing a consensus among various stakeholders in innovation community to anticipate standardisation needs, the framework can be potentially used to help standards organisations and policymakers make more informed decision when developing their standardisation strategies.

Therefore, a new framework is proposed in Figure 4, generally based on the roadmapping framework developed by Phaal & Muller (2009). Trying to capture all important dimensions of standards in supporting technological innovation, it essentially consists of a horizontal axis representing time (*when* to be standardised) and a vertical axis composed of a set of key activities that characterise technological innovation, represented as layers. The vertical axis, however, is modified in order for the framework to be able to capture more precisely what types of innovation activities standards support by helping knowledge diffusion between them; fundamental types of technology element activities categorised by Tassey (2000) – such as science base, infratechnologies, proprietary technologies, and production (as in Figure 1) – are adopted, composing layers of key technology element activities (*what* technology elements to standardise). These layers are sub-grouped into three colour-coded zones, according to what kind of standards the activities predominantly require: market-enabling standards, production-facilitating standards, or technology-supporting standards. As standards support knowledge diffusion between innovation activities that can be categorised into three typical perspectives – market, production, and technology perspectives, as suggested by Phaal & Muller (2009) –, standards related to certain innovation activities can be also considered to enable corresponding perspectives.

Following the strategic roadmapping convention, important innovation activities or significant events can be recorded in boxes and mapped against the two axes, with linking lines indicating interdependence between these activities. Where standards help support these activities by facilitating knowledge transfer or diffusion, a circle with an S symbol can be placed on the line, with arrows indicating the flow of knowledge and information between and across various innovation activities. This can more adequately reflect the detail and diversity of the role and function of standards in supporting technological innovation (*why* standards are needed), as suggested by various literature discussed previously. In addition to their roles and functions, the level of consensus and technical maturity as well as form of specifications (*how* to standardise) are important issues that define how standards help support technological innovation. Thus, types of deliverables as well as forms of specifications are also incorporated in the framework. Last but not least, leading organisations and stakeholders participating in standardisation activities (*who* is leading or involved in standardisation) are also critical information to be identified, hence included in the framework. The final framework thus incorporates all five important dimensions needed to be considered for effective standardisation in support of technological innovation.

The framework allows observing not only complex dynamics between standards and innovation, but also interactions between various aspects of standards. Being able to capture all critical information to be considered for standardisation, the roadmap-based framework can be also used as an operational tool for identifying where standards might be needed to help diffuse knowledge and information between particular innovation activities. Therefore, it can be used to anticipate future standards needs and develop standardisation strategies, by providing a communication venue where various stakeholders in the innovation community can be gathered to bring a consensus on future standardisation vision.

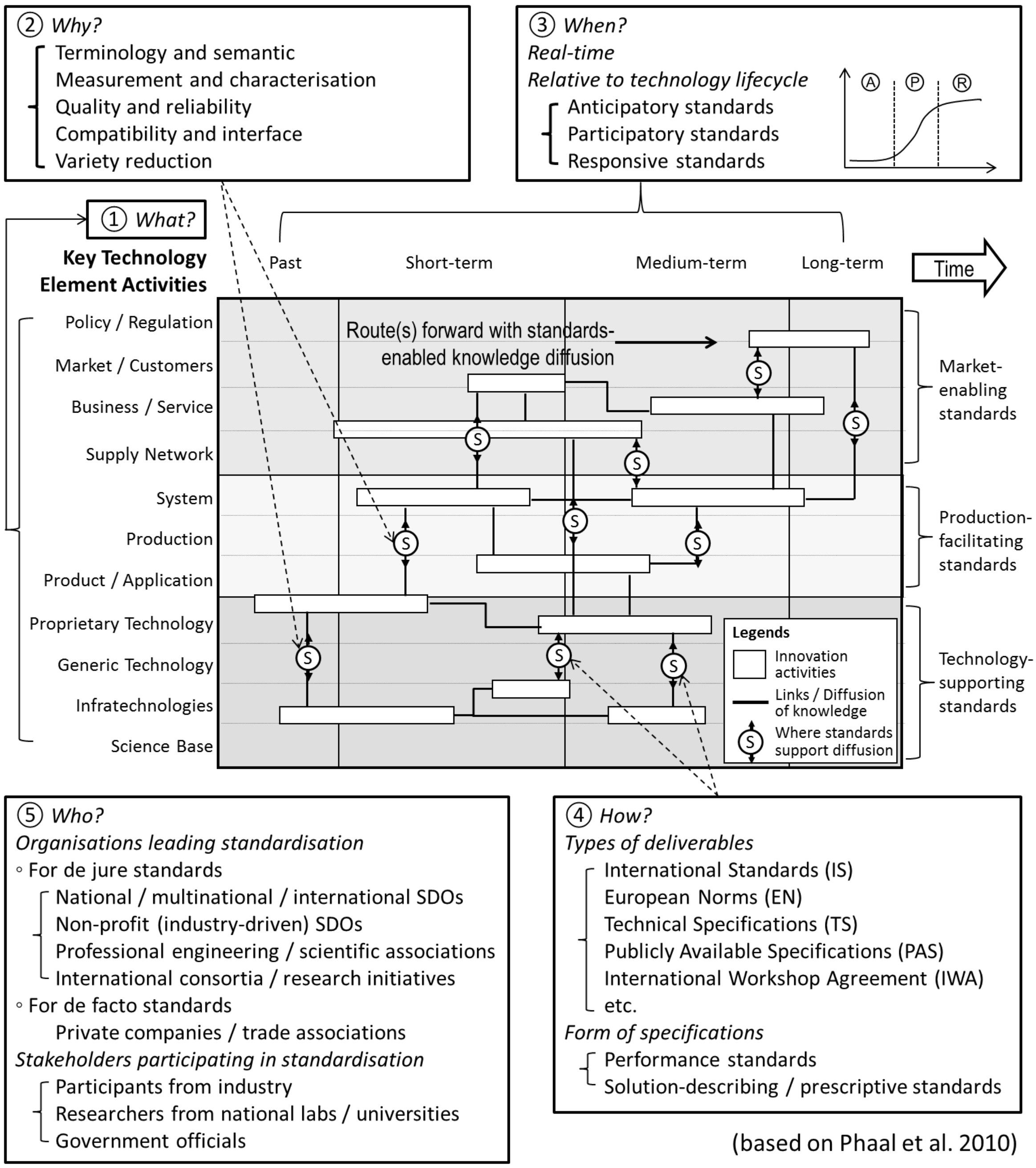

Figure 4. Proposed Framework for Anticipating Standardisation Needs

Concluding Remarks

From a comprehensive review of literature on standards and standardisation, this study explores different approaches to characterising standards relevant to technological innovation, as addressed in various academic and practical literature. By analysing their correspondence and interdependence, an integrated list of dimensions and categories of standards in the context of technological innovation is presented; technology elements (*what* technology elements to standardise), roles and functions (*why* standards are needed), time (*when* to be standardised, in terms of both real-time and relative to technology lifecycles), level and form of consensus (*how* to standardise), and stakeholders (*who* is leading and involved in standardisation), are found to be important strategic dimensions that need to be considered for effective and future-oriented standardisation activities supporting technological innovation. Capturing all these critical factors in a more coherent and systematic way, a strategic roadmap-based framework is proposed as a framework to anticipate standards needs and manage standardisation activities in support of emerging technologies that are becoming more complex, integrated, and interdisciplinary.

Similarly to the conventional roadmapping framework, the proposed framework is quite flexible and adaptable that their architectures are readily reconfigurable to suit a range of technology domains and contexts. Therefore, it can be used in various situations to help standards organisations and policymakers make more informed decisions, ensuring an anticipatory and timely management of standardisation activities. Essentially providing a canvas for mapping various types of standards with different roles and functions, according to relevant dimensions of innovation activities over time, the framework can support better articulation and visualisation of how standards-related activities can support the overall innovation system. It does so by not only helping identify future standards needs that can facilitate knowledge diffusion, but also highlighting any potential coordination, alignment and sequencing issues related to standardisation activities. Thus, the framework can be useful for both standards organisations and other organisations in policy arena, which are planning strategically around the broader spectrum of potential standards needs of emerging technologies. In particular, the utility of the framework is particularly significant to stakeholders taking a longer term strategic perspective on the potential standardisation needs of emerging technologies. In general, all these support effective anticipation and management of standardisation activities, which can support the overall innovation system.

Despite such potential advantages of a proposed roadmap-based framework for anticipating standardisation needs and developing relevant strategies, it also has a number of limitations. First, it cannot precisely visualise information about *who* is leading and involved in standardisation activities, in spite of the fact that it is a useful technique to gather information from various stakeholders and create their common visions. In addition, although it is widely recognised that such strategic roadmaps are repetitively generated drawing largely on previous roadmapping or foresight exercises, there is as yet no systematic and structured process of incorporating relevant findings from previous analyses to ensure effective planning and management of roadmapping practices. Last but not least, the current roadmap-based framework may be unable to represent systems architecture of complex technologies in sufficient details. Therefore, further research is needed to develop a more elaborated framework that can overcome these limitations, incorporating all important factors to be considered for anticipating standardisation needs in a more effective way.

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