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A technological innovation system framework to formulate niche introduction strategies for companies prior to large-scale diffusion

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ABSTRACT

Pioneering companies of radically new technological innovations often suffer from a slow uptake of their innovations and struggle to find the right introduction strategy. This paper aims to conceptualize a Technological Innovation System framework that can be applied to formulate and study niche introduction strategies from a company perspective. It combines insights from two literatures: the socio-technical systems literature and the innovation & strategic management literature. This results in a framework consisting of seven Technological Innovation System building blocks and seven influencing conditions that can influence the building blocks. The Technological Innovation System building blocks in the framework are: product performance and quality; product price; production system; complementary products and services; network formation and coordination; customers; and innovation-specific institutions. The influencing conditions in the framework are: knowledge and awareness of technology; knowledge and awareness of application and market; natural, human and financial resources; competition; macro-economic and strategic aspects; socio-cultural aspects; and accidents and events. The framework can help explore the context around an innovation during the early stages of Technological Innovation System formation and specify the scope, timing and type of niche introduction strategies that fit this context. This is illustrated with two cases: dual-clutch transmission technology and photovoltaic cells.

1. Introduction

It is remarkable how long it takes before radically new technological innovations start diffusing on a large scale. For most innovations, this takes several decades (Schnaars, 1989; Agarwal and Bayus, 2002; Ortt, 2010). Radically new technological innovations represent either an advance in technology that is so significant that attainable price/performance ratios are altered dramatically or that entirely new kinds of applications are possible (Tushman and Anderson, 1986; Garcia and Calantone, 2002). The large time interval between first introduction and the start of large-scale diffusion, the so-called adaptation phase (McIntyre, 1988; Leonard-Barton, 1988), has serious consequences for companies introducing radically new technological innovations. Introducing such innovations entails high levels of commitment by the companies over prolonged periods of time in the face of considerable levels of risk (Leifer et al., 2000; Min et al., 2006). This risk is caused by a range of issues, such as patents that expire before large-scale diffusion starts, technologies that evolve erratically, and complex patterns of competition that have to be faced. Moore (2002) describes how the diffusion in the early phases seems to contain a 'chasm' in which many pioneering companies tumble. A trial-and-error process of introducing and withdrawing different product versions by different companies, is often visible during this phase (Clark, 1985; Lynn et al., 1996). Pioneering companies first introducing radically new technological innovations often crash and burn (Tellis and Golder, 1996; Olleros, 1986; Pech, 2003). This is a serious problem both from the perspective of the companies involved and the society at large.

Various authors describe that niche strategies represent viable strategies to introduce radically new innovations (DeBresson, 1995; Gerlagh et al., 2004; Hultink et al., 1998; Meldrum, 1995). Companies adopting niche strategies are found to be relatively successful in a high-tech environment (DeBruyne et al., 2002). Niche strategies are strategies focusing on a small group of customers with specific wants and demands (Dalgic and Leeuw, 1994; Shani and Chalasani, 1993).

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These first customers are different, for example because they have wants and needs that the majority of customer do not (yet) have, because they have the resources to fulfil their wants and needs when the innovation is still very expensive and the majority of potential customers cannot afford it, or because these customers are innovative and like to experiment with new products before other customers. For companies, such niche segments of customers represent an option to introduce their innovation on a small scale and thereby limit the risks while probing the market (Lynn et al., 1996). However, for companies it is not enough to know that a niche strategy is a viable option to reduce risk when introducing an innovation into the market. In addition, companies need to know which *specific* niche strategy they could choose given the circumstances .

Two specific fields in the scientific literature are relevant when looking into the problem of specifying niche strategies: the socio-technical systems literature and the innovation and strategic management literature. We will show how these scientific fields are complementary and how combining insights from both fields is needed when investigating and specifying niche strategies. In addition, we will show how scientific knowledge gaps in both these scientific fields need to be filled in order to find out which niche strategy to use under which circumstances.

The development of socio-technical systems is explored amongst others by scholars studying transitions (Geels, 2002; Rotmans et al., 2001), technological innovation systems (Bergek et al., 2008; Jacobsson and Bergek, 2004; Hekkert et al., 2007), and strategic niche management (Kemp et al., 1998; Schot and Geels, 2008). These scholars focus mainly on sustainable innovations, a subcategory of radically new innovations, and they have two perspectives in common. Firstly, they take a systems view, meaning that innovations are perceived as part of a larger integrated system consisting of technological, social and institutional aspects. Secondly, these scholars aim to provide recommendations for policy makers on how to facilitate large-scale diffusion of radically new sustainable innovations (Jansma et al., 2018; Markard et al., 2015; Truffer, 2015). These fields consider policy intervention necessary because the free market behaviour of companies in existing markets does not always favour sustainable innovations (Kemp et al., 1998). In their view, public policies are required to arrive at societally desirable, sustainable, solutions.

The policy perspective caused a lack of attention for the strategies of companies in the socio-technical system i.e., away from the company perspective, and that is now considered a scientific gap. Company strategies represent a crucial element in socio-technical system development (Markard et al., 2015; Planko et al., 2017). “Strategies of firms and other actors or the role of strategic alliances within industries did not receive much attention in the existing body of literature on socio-technical transitions” (Markard et al., 2012, p.961). Raven et al. (2010) review the literatures on transitions and strategic niche management and argue that they lack a managerial perspective. This is a serious gap when company strategies and government policies together drive socio-technical system change (Planko et al., 2017).

Complementary to the previous literatures, the scholars in innovation and strategic management adopt a company perspective regarding introduction strategies for radically new innovations, and they can therefore potentially fill the gap in the socio-technical systems literature. The scholars in innovation and strategic management have two perspectives in common. Firstly, they take a market perspective, meaning that they see markets as the relevant system in which radically new innovations are introduced. Markets consist of actors on the supply and demand side as well as the actors and conditions governing the interplay of supply and demand (Jain, 1985; Kotler, 2009). Secondly, they take a company perspective when studying introduction strategies for radically new technological innovations. The timing of introduction strategies has evoked considerable debate (Klingebiel and Joseph, 2016; Suarez and Lanzolla, 2007; Lieberman and Montgomery, 2013). The scale of such introduction strategies is explored and companies adopting niche strategies are found to be relatively successful in a high-tech environment (DeBruyne et al., 2002).

The work of these innovation and strategic management scholars reveals another gap in the scientific literature. Although the use of niche strategies in general is proposed to introduce radically new innovations, specific types of niche introduction strategies are not distinguished and it is unknown under which market conditions to choose (specific) niche strategies. The market perspective is not helpful when completely new markets emerge. Especially in the case of radically new innovations, a wider systems perspective is required to explore the conditions that drive market formation. We therefore propose to look at the wider socio-technical system representing the context around a technological innovation, in which markets emerge and in which niche introduction strategies can be formulated.

This paper is based on a combination of both perspectives. We will address both types of scientific gaps, by taking a systems view, like the literature on socio-technical system change. But rather than a policy perspective, we will follow the management scholars in taking a company perspective to explore how radically new technological innovations can be introduced. The main aim of this paper is to identify essential actors and factors in socio-technical systems required for large-scale diffusion and to build a theoretical framework for formulating specific niche strategies based upon these insights. We will focus on a specific type of socio-technical systems, Technological Innovation Systems (TIS), because these systems include all actors and factors around a particular technological innovation (Carlsson and Stankiewicz, 1991).

This leads us to the following research questions:

1 Which actors and factors in Technological Innovation Systems (TIS-es) are required for large-scale diffusion of radically new technological innovations?
2 How can these actors and factors be combined in a framework that can aid in formulating and evaluating specific niche introduction strategies for such innovations by companies?

The paper contributes to the scientific literature by addressing two scientific gaps: (1) a lacking company perspective in the literature on (technology) innovation systems, strategic niche management and transitions and (2) the lack of specific niche introduction strategies and the lack of method to assess when to adopt which particular strategy, in the literature on innovation and strategic management.

The paper focuses on a subcategory of innovations: radically new technological innovations. This subcategory is quite broad, it encompasses widely different innovations like new materials, metals or chemical substances, electronic or mechanical systems, medicines and healthcare equipment as well as aerospace and defence systems, to name a few (for an overview see Ortt, 2010). Other types of innovations such as service innovations are not in focus but are addressed in the paper as important aspects of the socio-technical system around a technological innovation.

The remainder of the paper will consist of four sections. In Section 2, the methodology is presented, followed by a description of the framework and its use in formulating niche introduction strategies in Section 3. How the framework can be used to formulate niche introduction strategies is further illustrated for two cases of radically new technological innovations, in Section 4. The paper will end with conclusions and discussion in Section 5.

2. Methodology

The research is based on a combination of methodologies. We will first explain the steps in building up the framework and then proceed by describing how the framework is refined and validated. The details of the framework itself will be explained after that, in Section 3.

2.1. Four steps in building up the framework

Firstly, a literature research was done into a variety of research fields: strategic niche management (Kemp et al., 1998; Schot and Geels, 2008; Caniëls and Romijn, 2008), technological innovation systems (Bergek et al., 2008; Jacobsson and Bergek, 2004), and transitions (Geels, 2002; Rotmans et al., 2001). The literature research resulted in a preliminary list of so-called 'building blocks' of Technological Innovation Systems (TIS-es) around radically new technological innovations. We aimed to formulate the building blocks in such a way that a complete and compatible set of such blocks is required for large-scale diffusion. Or, to put it differently, the building blocks were formulated such that each of them, once missing, incomplete or incompatible with each other and the innovation, would form a barrier to large-scale diffusion. This paper takes a company perspective studying introduction strategies for radically new technological innovations rather than the perspective of a government that aims to formulate policies regarding important technologies. Because of the difference in perspective and goal, the preliminary subdivision of socio-technical systems as it is known in the contemporary innovation systems literature (e.g., Carlsson and Stankiewicz, 1991) needed to be adapted. This resulted in seven TIS building blocks that will be introduced and explained in Section 3.1.

Secondly, we conceptualized how knowledge of the status of these TIS building blocks can help to formulate niche introduction strategies. Specifically, we conceptualized how knowledge about barriers in the TIS building blocks can provide information that can be used to assess the timing, scope and type of introduction strategies. In addition, we used secondary material on historical cases to illustrate how different barriers were circumvented with different niche introduction strategies. Strategy formation using knowledge about the building blocks will be discussed in Section 3.2.

Thirdly, to further specify niche introduction strategies, we explored the conditions that influence TIS building blocks. These so-called 'influencing conditions' explain problems in the formation of TIS building blocks, and hence indicate causes of barriers to large-scale application of radically new technological innovations. In a second round of literature research, we explored influencing conditions with an effect on TIS building blocks. Such conditions were found in innovation management literature (e.g., Bond and Houston, 2003; Talke and Hultink, 2010; Hueske and Guenther, 2015) and in the socio-technical systems literature (e.g., Edquist, 2011; Geels, 2004; Negro et al., 2012b). To identify such influencing conditions a wider system perspective is required than a TIS or a market perspective. The wider socio-technical system also encompasses conditions, such as knowledge of technology, that can already exist prior to the formation of a TIS or a new market. We categorized influencing conditions in seven groups, which will be discussed in Section 3.3.

Fourthly, we conceptualized how the combined knowledge of the building blocks that can form a barrier to large-scale diffusion, especially the ones that are incomplete, incompatible or altogether missing, and knowledge of the causes of these barriers can be used to further specify the type of introduction strategies. The line of reasoning behind the framework and its use will be described in Section 3.4 and its application will be illustrated in Section 4.

2.2. Two steps in refining and validating the framework

The initial framework was validated, tested and improved in two steps. Firstly, four secondary historical cases were studied: Teflon, Nylon, anti-lock brakes (ABS) and the polymer exchange membrane in fuel cell electric vehicles. Based on these studies, the preliminary list of building blocks and influencing conditions was validated and complemented. In addition, a preliminary list of introduction strategies of companies during the adaptation phase was created.

Secondly, five primary contemporary cases were studied: high altitude wind energy systems, reverse osmosis water desalination technology, offshore wind turbines, direct drive generators and electric vehicles. These case studies consisted of literature reviews and in-depth interviews with managers from various companies. These interviews were semi-structured and consisted of open and closed questions. During the interviews, managers were firstly asked in an open way to describe important TIS building blocks, influencing conditions and introduction strategies for their innovation. Secondly, the managers were asked for their feedback on our lists of TIS building blocks, influencing conditions and strategies. The findings from these studies were presented and published as peer-reviewed papers at three international management of technology conferences (Kamp et al., 2015 (IAMOT 2015); Ortt et al., 2015a (ISPIM 2015); Kamp et al., 2017 (IAMOT 2017)) and at one international conference on high-altitude wind energy systems (Ortt et al., 2015b) and published as a chapter in a book on high-altitude wind energy systems (Kamp et al., 2018).

The current paper will not report these primary and secondary cases that were studied to refine and validate the framework. Instead, we will combine the experiences and illustrate in Section 4 with two new cases, namely photovoltaic cells (PV) and dual-clutch transmission technology (DCT) how the framework can be used to study niche introduction strategies. But first, we will present the full framework in Section 3.

3. The technological innovation system framework and niche introduction strategies

3.1. Seven building blocks

Several strands of literature have emerged taking a systems perspective when describing the development and diffusion of technological innovations (e.g., Hughes, 1983; Carlsson and Stankiewicz, 1991; Geyer and Davies, 2000). The socio-technical systems perspective adds to perspectives representing markets primarily in terms of (potential) customers i.e., in terms of their demand-side alone. Such a demand-side perspective can be found in diffusion literature, for example Rogers (2003) but also in parts of the management literature (Sissors, 1966; Day et al., 1979). From a company perspective, however, the market consists of various actors, both on the supply and the demand side of the market. Furthermore, markets include other actors with a direct impact on demand and supply. From this perspective, the market around the company includes network partners, customers and supporting institutions as is envisioned in the socio-technical subsystems, all of which are important in system formation around a technological innovation and need to be considered when formulating and evaluating introduction strategies for such innovations.

A Technological Innovation System is a specific representation of a socio-technical system around a technological innovation and can be defined as 'a dynamic network of agents interacting in a specific economic/industrial area under a particular institutional infrastructure and involved in the generation, diffusion, and utilization of technology' (Carlsson and Stankiewicz, 1991). From this it can be derived that a TIS consists of the following structural components (Malerba, 2002): (1) technology, (2) a network of actors, (3) supporting institutions, and (4) a demand side. We take these subsystems as a starting point and modify them to study (niche) introduction strategies from a company perspective.

The component 'technology' as derived above is too broad to cater a company perspective. Companies focus on particular radically new innovations, which apply a technological principle. Important characteristics of an innovation, especially from a company perspective, are product performance and quality, and product price. The system around such an innovation is composed of several technological components. It typically entails complementary products and services and production technologies (i.e., technologies needed to produce the product) apart from the product itself. These aspects need to be taken into account when formulating or evaluating introduction strategies for companies, and hence the socio-technical subsystem 'technology' needs to be subdivided when taking a company perspective.

These considerations result in a list of seven building blocks, to which we refer as TIS building blocks, that need to be analysed when formulating and evaluating niche introduction strategies for innovations. Each of these building blocks is essential for the emergence of a TIS and their absence, incompleteness or incompatibility with other building blocks can seriously hamper large-scale diffusion.

1 Product performance and quality;
2 Product price;
3 Production system;
4 Complementary products and services;
5 Network formation and coordination;
6 Customers;
7 Innovation-specific institutions.

The building blocks are further described below, and are summarized in the appendix in Table A1. These building blocks include technological factors (such as the product, the production system, and complementary product and services), social, economic and institutional factors (such as a network of actors, customers, the product's price and innovation-specific institutional aspects). All of these factors are elaborated below.

3.1.1. Product performance and quality

The first TIS building block is a new high-tech product with a sufficiently good performance and quality now, or in the near future, when compared to competing products (Magnusson and Berggren, 2018). Target customers should regard the product as a viable option, or as a viable alternative compared to other options. For example, in the case of many sustainable products, environmental performance can be valued highly, but early product versions may suffer from low quality and may be unable to meet the customers' requirements (Kemp et al., 1998). Hence, large-scale diffusion can be hampered.

3.1.2. Product price

Product price is an important TIS building block. Often, technological innovations are initially very expensive compared to competitive alternatives, which can hamper their diffusion (Kemp et al., 1998). The price of a product involves financial and non-financial (e.g., time and effort) costs to acquire and use the product. Acquiring products involves various costs related to selling and depreciating investments in previous products, and it also involves switching costs, i.e. costs involved in switching from one product to another, and transaction costs, i.e. costs to find the right new product and a supplier (Tsoutsos and Stamboulis, 2005). For large-scale diffusion, a product is required with a reasonable price (absolutely or relatively compared to other competitive products) (Negro et al., 2012b).

3.1.3. Production system

Another essential TIS building block is a production system that can deliver high quality products in large quantities. Over time, growing experience with the production process and the product itself will increase the product's quality and decrease its production costs (learning by doing) (Kamp et al., 2004). These effects increase the competitiveness of the product Geels (2004). Incompleteness or absence of this building block constitutes a problem for many radically new technological innovations. Creating a large production facility is not only a major investment, it may also take a considerable amount of time to develop and fine-tune such production systems (Kemp et al., 1998). A lack of production system can block large-scale diffusion.

3.1.4. Complementary products and services

A fourth TIS building block is the availability of complementary products and services supporting development, production, distribution, adoption, use, repair, maintenance and disposal of the innovation. Diffusion of the innovation can be hampered when complementary products and services are unavailable, incompatible or too expensive (Geels, 2004; Kemp et al., 1998). Development of complementary products and services can induce multiple innovations in firms that are linked together and therefore motivated to align their strategy Malerba (2002). A lack of complementary products and services can block large-scale diffusion.

3.1.5. Network formation and coordination

The network of actors in the supply chain is an important TIS building block. Multiple types of actors are vital for large-scale diffusion of an innovation. Actors can refer to suppliers of parts, actors assembling or producing the product, distributors, and actors providing complementary products and services (Kemp et al., 1998; Edquist, 2011; Kamp and Vanheule, 2015). Malerba (2002) describes the importance of coordination between these actors. This coordination not only involves actual collaboration between actors but also involves a shared vision regarding the technological innovation and the TIS surrounding it (Negro et al., 2012b). A lack of actors or a lack of coordination between them, can completely block large-scale diffusion.

3.1.6. Customers

Customers represent an important TIS building block (Kemp et al., 1998; Malerba, 2002). A customer segment needs to be identified early on (Kamp et al., 2004). Potential customers with a need for the innovation should be identified, for example through a problem solved by the innovation or because they largely benefit by using the innovation. To become actual customers, the potential customers should be aware of the innovation, see its benefits compared to other products, and have the knowledge, means and willingness to acquire and use it (Ortt et al., 2013). When innovations are developed without involving (future) customers, several customer-related issues may hamper their diffusion (Kamp et al., 2004). Potential customers may want to use a product but may lack the means to acquire it. They may lack knowledge of a product and can be uncertain about a product and hence perceive risks. Additionally, "users (..) have to integrate new technologies in their practices, organizations and routines, something which involves learning and adjustments. New technologies are sometimes said to be 'tamed' to fit in concrete routines and application contexts" (Geels, 2004, p. 902). Obviously, without actual customers there is no large-scale diffusion.

3.1.7. Innovation-specific institutions

Innovation-specific institutions form an important TIS building block (Kemp et al., 1998). These institutions refer to formal and informal rules such as government policies, laws, standards and regulations (North, 1990). Such rules can either support or block development and diffusion of an innovation (Ortt and Egyedi, 2014). Geels (2004) indicates that quality norms and property rights can produce trust. A lack of a long-term consistent policy can affect development and diffusion of innovations (Negro et al., 2012b; Vasseur et al., 2013). Stable and supporting innovation-specific institutions increase certainty for companies and investors and hence facilitate development and diffusion of innovations.

3.2. The building blocks and niche introduction strategies

3.2.1. Building blocks can provide some information about niche introduction strategies

The combination of the seven building blocks forms a Technological Innovation System (TIS). A complete system, meaning that all building blocks are complete and compatible, is required for large-scale diffusion of radically new high-tech innovations. Conversely, one or more missing, incomplete or incompatible building block(s) can hamper large-scale diffusion. In that case, such building blocks turn into a barrier. Examples of such barriers can be found in historical cases. For example, the ultra-strong poly-ethylene fibre was invented around 1964. Large-scale diffusion was hampered by the lack of a method to produce

Table 1
Examples of barriers in TIS building blocks for specific innovations, and niche introduction strategies to deal with these barriers.

TIS building block	Barrier	Niche introduction strategy	References
1 Product performance and quality	Photovoltaic cells (PV) initially lacked in performance compared to other electricity generating methods, such as fossil-based generators.	PV was first introduced as a light-measurement instrument for photography (in the 1930s), and later as a way to generate electricity for radio on satellites (in the 1950s) before it became a mainstream technology (from the late 1970s onwards) to generate electricity.	(Green, 2005)
2 Product price	The first practical two-way Video-telephony installations required a very expensive installation.	In the 1980s, EU institutions subsidized specific video telephony applications for hearing-impaired people.	(Dickson and Bowers, 1974; Ortt, 1998)
3 Production system	The initial production method to create an ultra-strong poly-ethylene fibre was not scalable.	A high-end niche strategy was used to provide hand-made Dyneema for surgery.	(Hongu and Phillips, 1997; Mulder, 1992).
4 Complementary products and services	The infrastructure for telephony, required for its widespread use, was not available at first.	Therefore, telephony was first used as a means of intra-firm communication, and as a dedicated burglar alarm, which are both stand-alone or local-area niche strategies.	(Dordick, 1990; Huurdeman, 2003).
5 Network formation and coordination	Professional sportsmen and women sometimes design and build their own equipment because suppliers lack detailed knowledge of sports to do so.	Some of these sportsmen started producing and selling these products on a small scale. Many of these innovative products, such as klapskates (for speed-skating), adapted canoes, or kite-surfing equipment, were subsequently produced on a large scale for mainstream customers.	(Herstatt and Von Hippel, 1997).
6 Customers	At first, potential customers lacked the required knowledge to use computers.	Therefore, computers were used in education to allow students to learn how to use them and the accompanying software. These students later on started to use computers in their work in organizations and in their daily life.	(Mark et al., 1985; Windrum and Birchenhall, 1998).
7 Innovation-specific institutions	In the early 20th century, the contraceptive pill was banned in the US due to the dominant Christian institutions' objections.	The product was redesigned in the 1920s, and introduced as a hormone preparation for pregnancy problems, gynaecological cancers, and other conditions, becoming an accepted contraceptive in the 1960s when Christian objections dwindled.	(Junod and Marks, 2002).

the fibre in large quantities (Mulder, 1992). At the time, the process of producing the fibres involved manually stirring with a stick in a poly-ethylene solution, forming loose fibres which could then be combined to create a small string. Such a production method could not be scaled to an industrial production process. That means that the building block ‘production system’ was incomplete and hence formed a barrier to large-scale diffusion of the innovative material. More cases illustrating barriers hampering large-scale diffusion can be found in Table 1.

Before all building blocks are in place and large-scale diffusion becomes possible, it is often possible to introduce a specific version of the innovation in a niche segment. In such cases, when some of the building blocks are in place yet a few others are missing, not yet complete or not compatible, a niche introduction strategy may be possible. Poly-ethylene fibre, for example, before it was produced on a large scale (with the tradename Dyneema) using the method of gel-spinning in the late 1980s, was already produced on a small scale and used locally for specific types of micro-surgery in the mid-1970s (Mulder, 1992). That means that a niche introduction strategy was adopted that circumvented the barrier in the ‘production system’. More examples of specific niche introduction strategies circumventing barriers in specific TIS building blocks can be found in Table 1.

The cases in Table 1 reveal a few interesting issues. It is illustrated how each of the seven building blocks (column 1), can turn into a barrier (column 2). These cases also reveal that, if a barrier blocks large-scale diffusion, small-scale niche introduction strategies can sometimes circumvent this barrier (column 3). For example, if large-scale production is not yet possible, the innovation can be produced by hand for a niche application (see row 3). Or, if the product price is too high for large-scale diffusion, government subsidy can help to make the product available in a specific niche application (see row 4). Finally, the historical cases show that, in the face of each of these barriers, different types of niche introduction strategies were adopted. Government subsidy nor hand-made production would have facilitated a niche application in any of the other cases described in Table 1. This means that each of the barriers may call for a different type of niche introduction strategy. But what then is the nature of the relationship between the TIS and its building blocks on the one hand and the introduction strategies on the other hand?

The status of the building blocks of the TIS around an innovation can be used to assess whether large-scale diffusion and hence large-scale introduction strategies are possible. If we assume that our set of building blocks constitutes a complete TIS, then large-scale diffusion becomes possible once all building blocks are complete and compatible with the innovation. Examples of large-scale introduction strategies a company can adopt are market skimming (entering the market with a high-priced product and then gradually lowering the price over time to maximize the turnover) and market penetration (entering the market with a low-priced product to increase the customer base quickly) (see for example Kotler and Keller, 2016; Porter, 2008). In contrast, when all building blocks are incomplete, missing or incompatible, then introduction of the innovative product into the market is not a viable strategic option. In such a situation, the company may decide to wait and may, in the meantime, apply other strategies to stimulate the build-up of the missing building blocks, such as networking strategies or lobbying strategies. If, however, only a limited number of the building blocks are missing, incomplete or incompatible, it is sometimes possible to adopt a niche introduction strategy that circumvents the barrier(s), meaning that a limited number of products are introduced into a specific part (or niche) of the market. So, the status of the building blocks provides information about the *timing* of an introduction strategy (when is introduction possible) and about the *scale* of the introduction strategy (large-scale introduction versus a small-scale niche introduction strategy). However, it is not clear yet which *type* of niche introduction strategy can be used. In the next subsection we will explain why more information is needed to formulate the type of niche introduction strategy.

3.2.2. Why more information is needed to formulate niche introduction strategies

If a TIS building block is incomplete, missing or incompatible, meaning that a barrier is hampering large-scale diffusion, this provides information about the timing and scale of introduction strategies. Because of the presence of the barrier, a small-scale niche introduction strategy is needed. But the *nature* of the barrier does not always provide enough information to assess the *type* of niche introduction strategy. In addition, studying the *cause* of the barrier can provide extra information that can be used to formulate a specific type of niche introduction strategy.

If, for example, the TIS building block ‘customers’ is lacking, meaning that not enough customers adopt the innovation, it is unclear what type of strategy to choose unless the cause of the lack of customers is known. Different causes are possible and knowledge of these causes is important because each of the causes may call for a different niche introduction strategy. If customers are lacking because potential customers have too limited knowledge of how to use the innovation, for example, then companies can decide to adopt a strategy in which they, through the application of the innovation, educate customers how to use it. For example, companies in the early 1980s sold personal computers to universities and students as part of their niche introduction strategy. These students introduced the use of computers in the companies where they started to work after they completed their studies. Introducing computers in the education programs of universities thereby created a snowball effect in industry. So, knowledge of the cause (in this case: lack of knowledge of potential customers) of the barrier (in this case: lack of customers) can help to formulate a niche introduction strategy.

In contrast, customers can also be lacking because potential customers have too limited financial resources to buy the innovation. A strategy to increase knowledge amongst potential customers will not be effective then. Yet companies can adopt other niche introduction strategies when the price of the innovation is too high for potential customers, for example by making a simple and relatively affordable product to lower the price. Alternatively, the company could also consider to focus on a small niche of wealthy customers. Both the factors “knowledge of how to apply the innovation” and “financial resources” are not TIS building blocks themselves but they do influence these building blocks and can be used to explain why barriers emerge in these blocks. Hence, we refer to such factors as influencing conditions.

So, knowledge of influencing conditions can be used to assess the cause of a barrier, and that cause, in turn, can be used to formulate the *type* of niche introduction strategy. That means that influencing conditions can provide important information to formulate niche introduction strategies. We added influencing conditions to our framework. In the next section we will describe some of the influencing conditions of a TIS.

3.3. Seven influencing conditions

To complete our framework, we now focus on conditions that influence the TIS building blocks. Several branches in the scientific literature inspired us in formulating such conditions. Firstly, we studied literatures that explore barriers to innovation i.e., barriers to the development, supply, adoption and implementation of radically new technological innovations. Different literatures were found to explore such barriers amongst which the innovation management literature (e.g., Bond and Houston, 2003; Talke and Hultink, 2010; Hueske and Guenther, 2015) and the socio-technical systems literature (e.g., Edquist, 2011; Geels, 2004; Geels et al., 2008; Negro et al., 2012b). Secondly, we studied literature describing mechanisms of change in innovation systems in order to explore influencing conditions (e.g., Hekkert et al., 2007; Suurs and Hekkert, 2009).

Following (Geels et al., 2008) we found three groups of conditions with an effect on system formation and hence on the TIS building blocks: (1) knowledge, (2) resources, and (3) macro-environmental conditions. These groups of conditions were formulated by these authors with an overall perspective typically held by governments, which aim to formulate policies stimulating TIS formation around strategic new technologies. The company perspective, which aims to formulate and evaluate niche introduction strategies for radically new innovations, requires a further subdivision and specification of these categories of conditions.

In a company different combinations of resources are used and hence the types of resources need to be specified. In fact, strategy formation can be referred to as applying particular combinations of resources to obtain a goal (Mintzberg, 1987). That is why we subdivided ‘resources’ into three types: natural, human and financial resources. In a company, especially high-tech companies, knowledge is of paramount importance (e.g., Bloodgood, 2019; Fagerberg et al., 2012). Different types of knowledge are required for strategy formation. We subdivided ‘knowledge’ into two types: knowledge of technology, and knowledge of application and market. A combination of both is required to successfully introduce high-tech innovations (Ortt et al., 2013). We also added new conditions, which we found to be important from a company perspective, such as competition, socio-cultural aspects and accidents and events. So, when adopting a company perspective to study strategy formation, different types of knowledge, resources and macro-environmental conditions need to be distinguished, each of which can affect one or more building blocks during TIS formation:

1. Knowledge and awareness of technology;
2. Knowledge and awareness of application and market;
3. Natural, human and financial resources;
4. Competition;
5. Macro-economic and strategic aspects;
6. Socio-cultural aspects;
7. Accidents and events.

These influencing conditions will be discussed in detail below and are summarized in Table A2.

3.3.1. Knowledge and awareness of technology

The first influencing condition ‘knowledge and awareness of technology’ refers to fundamental and applied technological knowledge. Fundamental knowledge focuses on the technological principles in components of the TIS, such as the product, the production system and complementary products. Applied technological knowledge is required to develop, produce, repair, maintain, and improve these components. Both types of knowledge are required for TIS formation. These types of knowledge can be developed through research and development or through knowledge creation and experimentation in practice (Kamp et al., 2004; Bergek et al., 2008; Edquist, 2011). Kamp (2002) refers to education and training as important mechanisms for transferring knowledge of technology across actors. A lack of relevant fundamental and applied technological knowledge by actors in the TIS can hamper TIS formation.

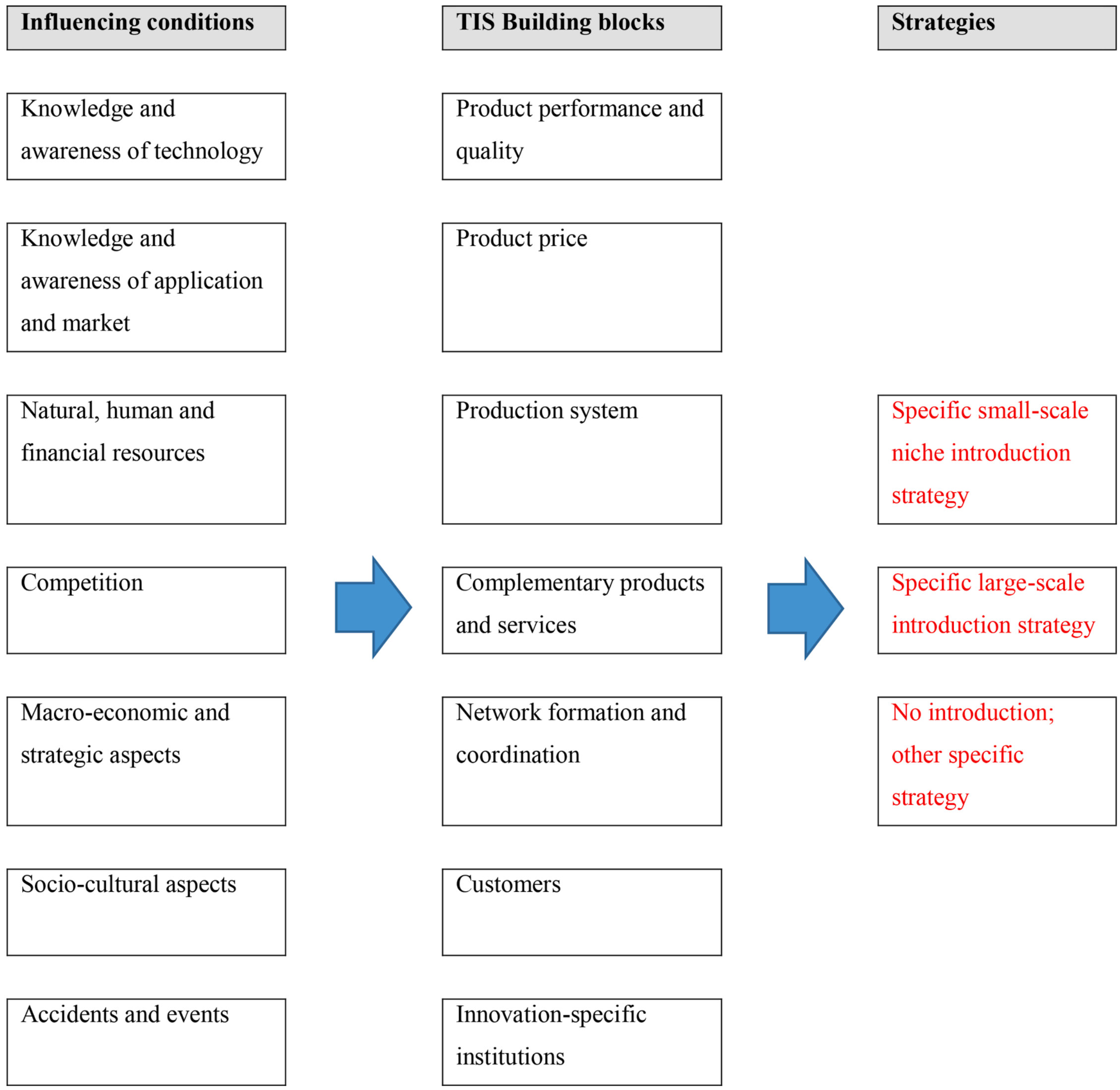

Fig. 1. Technological Innovation System (TIS) Framework.

3.3.2. Knowledge and awareness of application and market

The second influencing condition 'knowledge and awareness of application and market' refers to the knowledge how, and in which applications, the innovation can be used. It also refers to knowledge of the market structure and the relevant actors involved. This knowledge can be developed through market analysis, experimentation, learning by doing, learning by using or learning by interacting with relevant actors in the socio-technical system (Lundvall, 1992; Malerba, 2002; Kamp et al., 2004; Kamp and Bermudez-Forn, 2016). All actors in the TIS can suffer from a lack of knowledge and awareness of application and market. For example, when potential customers are not aware of the product, or do not know how and for what purpose to use a product, or when they do not know who can supply the product, then TIS formation is hampered (Kamp et al., 2004; Ortt et al., 2013). When suppliers lack knowledge of application, they cannot target a customer segment and hence TIS formation is hampered.

3.3.3. Natural, human and financial resources

Another condition influencing TIS formation is the availability of resources. Firstly, natural resources are required (Kemp et al., 1998; Malerba, 2002; Geels, 2004; Bergek et al., 2008; Vasseur et al., 2013). Natural resources to create products, production systems and complementary products can be acquired by each actor separately or by associations of organizations. Secondly, human resources with appropriate knowledge and competences, need to be mobilized (Kemp et al., 1998; Geels, 2004; Bergek et al., 2008; Vasseur et al., 2013). The appropriate knowledge and competences may be acquired via education programs or courses or in practice, via learning by doing. Thirdly, financial resources are needed for development and application of the innovation, the production system and complementary products and services (Kemp et al., 1998; Malerba, 2002; Edquist, 2011; Vasseur et al., 2013). Financial resources can come from different types of actors, such as supplying companies, investors, governmental institutions, or customers. Lack of natural, human or financial resources hampers TIS formation.

3.3.4. Competition

In practice, competition refers to an important influencing condition. Especially during TIS formation, innovations based on old technologies compete with those based on new technologies (Magnusson and Berggren, 2018). At the same time, different product versions based on a new technology may compete. When competing alternatives require different components, production systems, complementary products and services, then alternative networks of companies are formed. All of this may create a chaotic and complex pattern of competition between networks of companies. In such situations, uncertainty may increase and

TIS formation may be hampered (Shapiro and Varian, 1999). So, competition can have a large impact on several TIS building blocks. Competition for example determines the relative price and performance of a radically new innovation.

3.3.5. Macro-economic and strategic aspects

Macro-economic and strategic aspects form important influencing conditions of the TIS building blocks. An economic recession can hamper TIS formation (Bergek et al., 2008) whereas economic growth can facilitate it, for example, by providing funds for incubation activities and consultancy services (Edquist 2011). The macro-economic situation involves conditions like the market structure and the contemporary way of doing business, and these conditions are often reflected in strategic policies of countries regarding important industries. The combination of these conditions can influence the formation of TIS building blocks (Kemp et al., 1998).

3.3.6. Socio-cultural aspects

Socio-cultural aspects refer to the norms and values held by potential customers and other important stakeholders in the socio-technical system. These aspects may be more informal than the laws, rules, regulations and policies mentioned as institutions but they can have a large impact on the formation of these institutions and on the behaviour of the actors in the TIS. Socio-cultural aspects can also change over time and can thereby switch from a stimulating into a blocking factor. Socio-cultural aspects can influence the formation of TIS building blocks (Kemp et al., 1998; Geels, 2004; Bergek et al., 2008).

3.3.7. Accidents and events

Accidents can refer to accidents within the TIS, such as an accident in production or an accident by a product that fails. Accidents can also refer to accidents outside the TIS, such as wars or natural disasters. Both can have a large impact on several building blocks in a TIS (Kemp et al., 1998; Ortt et al., 2013). Some accidents may also stimulate TIS formation for radically new technological innovations. Terroristic attacks in Europe in the 1980s represent an example of accidents stimulating the development of a radically new telecommunication innovation. The threat of attacks made US civilians reluctant to travel to Europe while, at the same time, a postal strike hampered communication. This coincidence stimulated the emergence of fax machines for B-to-B communication (Coopersmith, 1993).

3.4. Using the framework in practice

Fig. 1 represents the framework showing how the combination of building blocks and influencing conditions in technological innovation systems can point at specific strategies. The connections between influencing conditions and TIS building blocks in Fig. 1 are not specified in detail although we acknowledge that some connections may be more likely than others. However, in our case studies mentioned in Section 2.2 we have found that all connections are possible. Hence, we represent all the connections by one big arrow rather than many small ones for each connection separately.

The framework is meant for a particular situation, is created with a particular perspective in mind and has a specific goal. The framework is meant for the situation in which a radically new technological innovation has been demonstrated to work (the invention), and is developed into an innovation that has *not* started to diffuse on a large scale yet. So we focus on the adaptation phase between first introduction and the start of large-scale diffusion of an innovation. The framework takes a company perspective and has the goal to aid in the formulation of niche introduction strategies, either by managers trying to commercialize their innovation or by scholars evaluating such strategies.

The entire line of reasoning behind the framework is built up step by step in the previous subsections and is now summarized in Exhibit 1.

Exhibit 1. : The line of reasoning behind the framework

- Large-scale diffusion, implementation and use of radically new technological innovations require many actors and factors, the combination of which can be seen as a Technological Innovation System (TIS).
- This system consists of technological, social and institutional actors and factors, all of which are categorized by us in seven so-called TIS building blocks.
- These building blocks represent a further subdivision of the factors often used in contemporary TIS frameworks because, in contrast to these TIS frameworks, we take the perspective of companies rather than governments. We aim to give recommendations for company strategies rather than government policies, and that requires a more fine-grained subdivision.
- Each of the building blocks, once missing, incomplete, or incompatible with the other blocks or the innovation, forms a barrier to large-scale diffusion.
- Information about the status of the building blocks can help to formulate the *timing* and *scale* of introduction strategies for radically new technological innovations.
- Additional information about the *type* of introduction strategies can be derived by studying influencing conditions with an impact on the building blocks. These factors can explain the cause of a barrier. These causes are important to formulate the specific types of niche introduction strategies because different causes of a barrier call for different strategies.

Based on this line of reasoning we can now explain how the framework can be used in practice either by scientists studying introduction strategies or by managers formulating introduction strategies for their radically new technological innovations.

When applying the framework, a manager or scholar will go through a sequence of steps which are summarized in Exhibit 2. In a first step, the status of seven building blocks needs to be explored. Information about the status of these blocks can be gathered in different ways. Some information may be available in a company, other information can be found by conducting a literature research, market research, or it can come from other sources. Subsequently it needs to be assessed to what extent each building block is complete (and compatible), partly complete (or partly compatible), or missing (or incompatible). Such a crude assessment in three categories based on various information sources, is enough to proceed. The completeness should be assessed in terms of the degree to which the building block is enabling large-scale diffusion and use of the innovation. For a radically new telecommunication innovation, for example, different situations regarding the infrastructure can be distinguished: the infrastructure is not available yet, or local area infrastructures are available, or a complete infrastructure is in place. In these situations, the building block 'complementary products and services' can be considered as missing, partly complete or complete, respectively.

In a second step, possible introduction strategies are explored. When all TIS building blocks are in place and complete, large-scale introduction strategies, such as market penetration or market skimming, are possible. In contrast, when almost no building block is complete, introduction is not even a viable option and the company may decide to wait and may, in the meantime, apply other strategies to stimulate the build-up of the missing building blocks. The situation in between these two extremes, in which one or a few building blocks is/are missing or incomplete, calls for a careful analysis to see whether a niche introduction strategy is possible. The status of the TIS building blocks thus provides information about the timing and scale of introduction.

If the TIS building blocks are partly complete, then a third step, to further specify possible introduction strategies, requires that the status of the influencing conditions, i.e. the conditions with an impact on the TIS building blocks, is explored. The status of the influencing conditions may reveal the causes of incomplete building blocks, and that knowledge can be used to specify a particular niche introduction strategy that circumvents or changes the incomplete building block and its cause.

In a fourth an last step, the status of the TIS building blocks and the influencing conditions needs to be monitored regularly because the so-called adaptation phase, being the phase between first introduction and the start of large-scale diffusion, is often turbulent and erratic (Clark, 1985; Lynn et al., 1996). A change in the situation will be reflected in the status of the TIS building blocks and/or the influencing

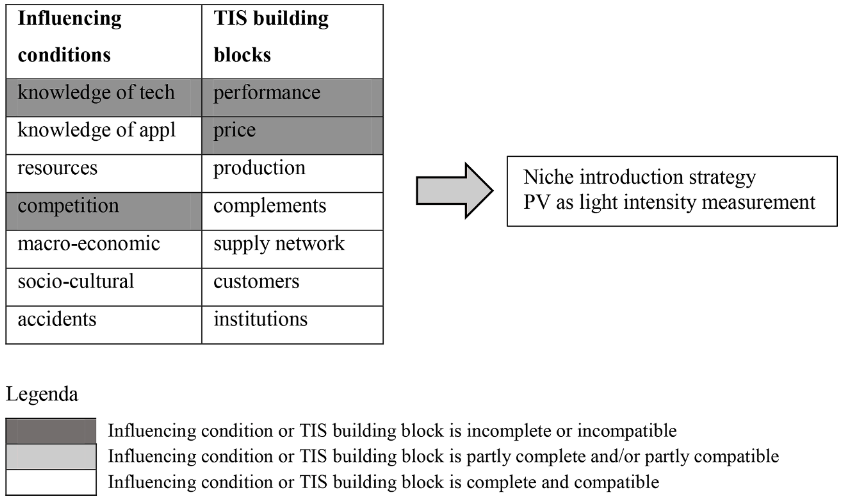

Fig. 2. Technological Innovation System (TIS) status for photovoltaic cells around 1932.

conditions and may call for a new or updated niche introduction strategy. Prior research indicated that, on average, between two and three different niche introduction strategies can be found prior to the start of large-scale diffusion of radically new technological innovations (Ortt, 2010). Once all building blocks are in place and complete, large-scale introduction becomes possible.

Exhibit 2. : Using the framework in practice

The framework is meant to study introduction strategies (goal) of companies (perspective) during the adaptation phase, the time interval before first introduction until the start of large-scale diffusion, for radically new technological innovations (situation). Steps when applying the framework:

1 Explore the status of the seven TIS building blocks.
   a Information gathering for each building block using various sources.
   b Assessment of the status of each building block (complete, partly complete or missing).
2 Explore possible introduction strategies.
   a All blocks compatible and complete: large-scale diffusion is possible
   b All blocks incomplete or missing: introduction is not a viable strategic option.
   c Some blocks are complete, some not: niche introduction strategies may be possible.
3 Explore the status of the seven influencing conditions.
   a Identify the causes of the incomplete building blocks by assessing the influencing conditions.
   b Use knowledge of the cause to further specify timing, scale and type of introduction strategy.
4 Monitor the status of the TIS building blocks and the influencing conditions regularly to assess if new strategies are possible or needed.

4. Case studies

4.1. Introduction to the case studies

We will now discuss two historical cases of radically new technological innovations: photovoltaic cells (PV) and dual-clutch transmission technology (DCT). These cases represent fundamentally different innovations in many respects, for example in terms of their industry, their sustainability and in terms of when they were first introduced: PV was first introduced in the 1930s, DCT in the 1970s.

The goal of the cases is to illustrate the use of our Technological Innovation System (TIS) framework from a company perspective, in particular how to use the framework to study niche introduction strategies. We focus on the time period between first introduction and the start of large-scale diffusion, the so-called adaptation phase. Both for PV and DCT, two episodes in this phase were selected in which we assess the status of the TIS by means of the framework. In each of the four episodes the logic of the actual historical niche introduction strategies will be discussed by referring to the framework.

For both case studies, a literature search was performed and a selection of sources was analysed in detail to derive the timing of the adaptation phase, to assess the status of the TIS building blocks and the influencing conditions within different episodes, and to find strategies of companies in these episodes. The combinations of the status of the TIS-es in different episodes and the strategies chosen by companies in these episodes were studied to illustrate how the framework can aid companies to formulate introduction strategies.

4.2. Photovoltaic cells (PV) around 1932 and around 1958

The principle of photovoltaic cells (PV) was invented in 1839 by Becquerel using two metal plates immersed in a solution and connected by a wire, creating a small electric current once light fell on it (Green, 2005). Later on, during the 19th century, early versions of the solid-state PV cells as we know them today, were created. In 1932, solid-state PV cells were first introduced for light intensity measurement in photography. Large-scale diffusion of PV cells started in the late 1970s. This means that the adaptation phase for PV lasted about 45 years, from 1932 to the late 1970s.

In 1932, a first episode marked the start of the adaptation phase. Because of the limited technological knowledge, the then available solid state PV cells had such a low efficiency (performance) and such a high price relative to competing electricity providing technologies, that they could not be used profitably for battery charging or electricity generation. However, the cells were good enough to measure light intensity, which was highly useful in the growing market of photography. This episode is interesting because it illustrates how the first niche application for PV could circumvent the limited performance and high price, in terms of electricity generation, by providing another functionality, measuring light intensity. Fig. 2 shows the status of the Technological Innovation System (TIS) for PV in 1932.

Both the price and performance of photovoltaic cells (two building blocks) further improved after the first episode but without bringing the efficiency close to competing electricity generating technologies. However, the cells had unique performance dimensions: the energy content per weight was relatively high when compared to contemporary batteries. Its ability to work for years without maintenance and interruption made PV particularly fit for use in satellites. From 1958 onwards, another episode thus emerged when PV panels were applied to power radios in satellites (Perlin (2013). The large available budgets in the US space program facilitated research to increase PV performance. The increased performance enabled other niche applications, such as energy provision for buoys at sea, which emerged before large-scale diffusion of

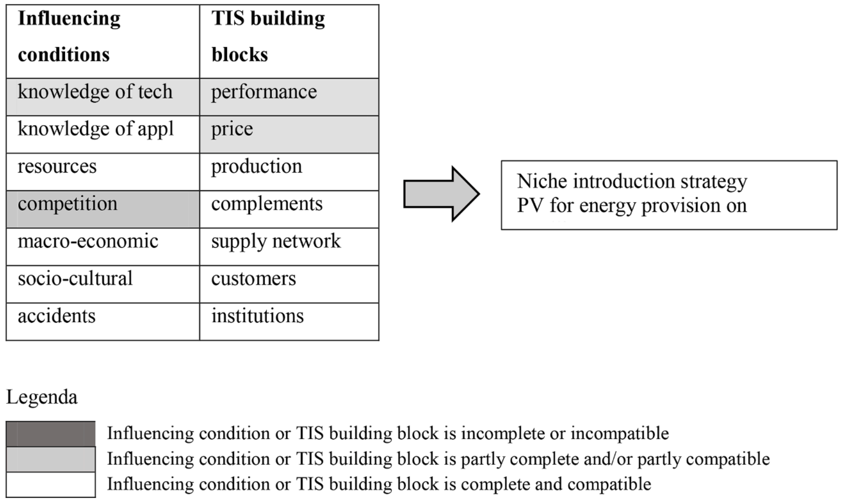

Fig. 3. Technological Innovation System (TIS) status for photovoltaic cells around 1958.

PV started in the 1980s. The second episode, around 1958, is interesting because it shows that PV had unique performance attributes in specific applications even before it could compete with other electricity generating technologies in mainstream markets. The TIS status in 1958 is shown in Fig. 3.

Fig. 3 shows that around 1958, as compared to the 1930s, similar barriers were present, but they were lowered. The lowering of the barriers and the developments in satellite communication, allowed a new niche introduction strategy, namely PV as energy provision on satellites.

Interestingly, in later PV episodes after 1958, the role of other building blocks came to the fore. For example, in the 1990s, many governments provided subsidies to stimulate the adoption of PV panels, and hence institutions became a stimulating factor. Later on, however, when some governments changed their subsidy policies unexpectedly, the same institutions turned into barriers hampering TIS formation and thus large-scale diffusion (Vasseur et al., 2013; Negro et al., 2012a).

4.3. *Dual-Clutch transmission technology (DCT) in 1983–1987 and around 2003*

Dual-clutch transmission technology (DCT) is a gear system that can put one gear into position while the other is functioning. DCT offers gentle, jerk-free changes like automatic transmissions, together with the efficiency and speed of manual transmissions. The principle of DCT was invented in 1935 by Kégresse, a former engineer from Citroën, who envisioned the system for heavy duty vehicles. The idea was good, but knowledge to create components, such as the control of the gear boxes, was lacking. The first niche application was in 1983 by Porsche. Large-scale diffusion started in 2004 in the VW Passat (Naunheimer et al., 2011; Senatore, 2009). This means that the adaptation phase lasted about 20 years, from 1983 to 2004.

Porsche started to work on DCT in the late 1970s but years of development were required before introduction was possible. Between 1983 and 1987 was a first episode when Porsche and Audi introduced DCT in race cars. At that time, computers to control gear shifts became compact enough to be installed in (race) cars. Race cars with DCT won several championships. However, the knowledge of technology regarding the electronic and hydraulic components and friction materials in DCT was still limited. The system often broke and hence DCT was still unsuited for large-scale production. In 1987 the FIA, the world motor sport federation, banned the application of DCT in racing and this episode thus ended.

The 1983–1987 episode is very interesting for various reasons. Firstly, because price was not a barrier, although several other barriers remained, Porsche adopted a niche strategy by applying DCT in racing to demonstrate and further develop the technology. This niche strategy

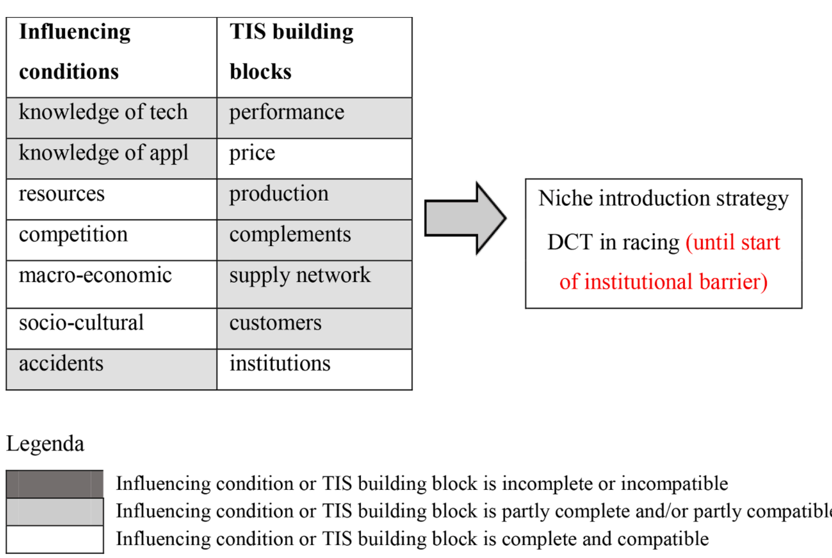

Fig. 4. Technological Innovation System (TIS) status for dual-clutch transmission technology 1983–1987.

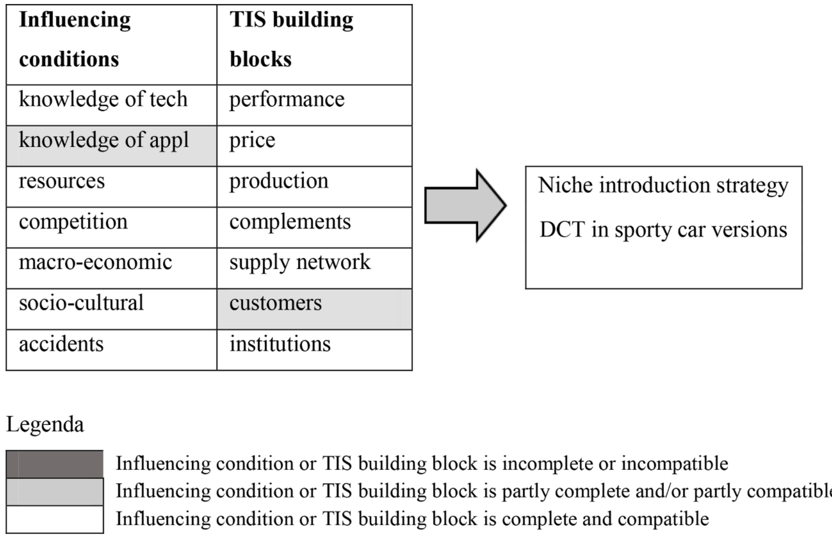

Fig. 5. Technological Innovation System (TIS) status for dual-clutch transmission technology around 2003.

could increase the company's knowledge of technology and the knowledge of application by potential customers interested in racing. So, the niche strategy could help remove some of the remaining barriers. This strategy was not without risks: the initial lack of reliability of the system might have damaged Porsche's reliable image. In practice their image was saved by the race results. Secondly, at the end of the episode another barrier emerged unexpectedly: FIA as an institution banned the use of DCT in racing because of its lack of reliability and possibly because of unequal competition that evoked lobbying by other brands to ban the technology. When this institutional barrier appeared at the end of the episode it marked the end of Porsche's niche introduction strategy. So, mostly barriers lower over time, but this episode illustrates that new barriers can also emerge over time. Fig. 4 shows a representation of the status of the TIS for DCT in the period 1983–1987.

In 2003, another episode emerged when the Volkswagen group (VAG) decided to introduce DCT in the Audi TT 3.2 Quattro and the Golf Mk4 R32. The knowledge of the technology had progressed to the point that the supplier of DCT, BorgWarner, indicated that the price of DCT was lower than competitive alternatives. VAG invested in production facilities in Kassel. So, the influencing condition 'knowledge of technology' improved and the barriers in the product performance, complementary products and services, supply network and production were removed or lowered considerably. However, customers represented a last barrier. European customers considered automatic transmission as "unsporty". VAG adopted a niche strategy to teach potential customers how smooth, fast and fuel-efficient DCT was by fitting it in their most sporty car versions in Europe. By using this niche strategy, they made the customers aware of this innovation as an interesting alternative, thereby removing the last barrier.

Interesting about this 2003 episode is that it appeared after about 15 years of silence (1987–2003) and about 25 years after Porsche acquired the technology. So, Porsche, and later VAG, kept the DCT idea in stock while tracking developments in the TIS and its environment. The knowledge of technology progressed in different ways. Continental improved the control unit and BorgWarner improved fraction materials and lubricants, together enabling a reliable DCT system. VAG developed parts of the technology but also tracked external developments. A logical last niche strategy before large-scale introduction, to remove the 'customers' barrier, was to introduce DCT in the most sporty car versions of the consumer market. Fig. 5 shows a representation of the status of the TIS for DCT around 2003.

4.4. *What do these cases illustrate?*

The cases illustrate how particular states of the Technological Innovation System (TIS), as reflected in the framework, call for specific niche introduction strategies. The cases also illustrate how information about the combined status of the building blocks and the influencing conditions can be used to formulate or evaluate niche introduction strategies.

In the PV case (see Fig. 2) the technology initially, in the 1932 episode, suffered from a relatively low performance and high price, as compared to competing technologies for electricity generation. This barrier to large-scale diffusion was caused by two influencing conditions: a lack of knowledge of technology and severe competition by alternative electricity providing technologies. The niche introduction strategy circumvented the barriers by focusing on a different functionality and market, light intensity measurement in photography. In the episode in the late 1950s, about 25 years later, the same barriers were apparent yet because of progress in the contemporary knowledge of technology, these barriers were lowered. In that episode (see Fig. 3) PV was used for electricity generation, but now in the very special context of satellites, where the still relatively low price/performance ratio could be accepted because other technologies could not provide electricity on satellites. So, a change in the TIS allows or even calls for a change in niche introduction strategy.

In the DCT case, the change of the TIS in subsequent episodes, as reflected in the barriers and their causes in the framework, is more drastic. When DCT was introduced in racing in the 1980s, a lot of barriers were in place. A racing application, however, is a typical way in the automotive industry to experiment and demonstrate new technologies. This niche introduction strategy not only circumvents barriers but also lowers them because the strategy also enhances the knowledge of the technology and of the market. The second episode, about 20 years later, showed a completely different status of the TIS and hence called for a different niche introduction strategy. In this episode the importance of knowledge of the influencing conditions is clearly illustrated. The fact that a lack of customers forms a barrier does not directly indicate what type of niche introduction strategy could be adopted. However, once the cause of the barrier was understood i.e., customers perceiving DCT as a kind of 'unsporty' automatic transmission, it was logical for the VAG corporation to introduce DCT in their very sporty car versions, the so called 'hot hatches'.

5. Conclusions and discussion

5.1. Answers to the research questions

Radically new technological innovations require a remarkably long time to start diffusing on a large scale (Schnaars, 1989; Agarwal and Bayus, 2002; Ortt, 2010). Large scale diffusion of innovations requires a system of actors and factors, comprising of, for example, production facilities, actors that supply components, and customers. In case of radically new technological innovations, such a system needs to be built up from scratch or an existing system around a previous technological innovation needs to be changed fundamentally. Building up or changing such a system, a Technological Innovation System, takes time. The first research question is: Which actors and factors in Technological Innovation Systems (TIS) are required for large-scale diffusion of radically new technological innovations? We used a combination of literature research and case-studies to derive seven groups of these actors and factors, referred to as TIS building blocks:

1 Product performance and quality;
2 Product price;
3 Production system;
4 Complementary products and services;
5 Network formation and coordination;
6 Customers;
7 Innovation-specific institutions.

Each of these TIS building blocks, if incomplete or incompatible with the innovation, can form a barrier that blocks large-scale diffusion. Conversely: when all building blocks are complete, large-scale diffusion is possible.

A fascinating phase can be distinguished prior to large-scale diffusion when the building blocks are not complete (yet). In this phase, specific small-scale niche applications are sometimes possible. This so-called adaptation phase, spans the time interval between the first introduction of the innovation and the start of large-scale diffusion. This phase is most often not just a *slow* start of large-scale diffusion; its typical length, about a decade, is too long for that (Agarwal and Bayus, 2002). Moreover, this phase is most often not just a *small* start of large-scale diffusion; the first small-scale applications are often significantly different from later mainstream applications (Lynn et al., 1996; Ortt and Schoormans, 2004) because the system is incomplete during this phase and the innovation and its applications need to be adapted to that situation.

We took a company perspective and focused on introduction strategies during this adaptation phase. Our second research question focuses on actors and factors in a TIS: How can these actors and factors be combined in a framework that can aid in formulating and evaluating niche introduction strategies for companies for radically new technological innovations? We found that the status of the building blocks can be used to assess the *timing* and the *scale* of introduction strategies. Large-scale introduction strategies are possible when all building blocks are in place. However, when most building blocks are incomplete or incompatible, and hence form barriers, then introduction is not a viable strategy. In between these two extreme situations, when some building blocks are complete and some are not, small-scale niche introduction strategies are sometimes possible that can circumvent or even lower these barriers. These niche strategies are important because they help to build up the TIS around the innovation, help to create a market for the innovation and give companies the opportunity to sell products and thereby to create revenue. So, the status of the building blocks can be used to study timing and scale of company introduction strategies for radically new high-tech innovations during the adaptation phase. During this phase companies face considerable levels of risk when entering the market (Leifer et al., 2000; Min et al., 2006). It is thus highly relevant to aid companies in specifying the right *type* of niche introduction strategies.

For that purpose, next to TIS building blocks, seven groups of influencing conditions are formulated that, additional to *timing* and *scale*, provide information to specify possible *types* of niche introduction strategies. These influencing conditions are:

1 Knowledge and awareness of technology;
2 Knowledge and awareness of application and market;
3 Natural, human and financial resources;
4 Competition;
5 Macro-economic and strategic aspects;
6 Socio-cultural aspects;
7 Accidents and events.

So, our framework is made up of a combination of seven TIS building blocks and seven groups of influencing conditions. The status of the TIS building blocks can be used to assess the timing and scale of introduction strategies. When some building blocks are incomplete and hence form a barrier to large-scale diffusion, niche introduction strategies are sometimes possible. To specify the type of niche introduction strategy, it is important to know the cause of the barriers. That is why these influencing conditions are important: they can help explain the cause of a barrier to large-scale diffusion and that, in turn, can help specify a particular niche introduction strategy that can circumvent or lower these barriers.

5.2. Discussion

5.2.1. Managerial relevance

In this paper, we focus on the time interval between first market introduction and the start of large-scale diffusion of radically new technological innovations, the so-called adaptation phase. Understanding this phase and knowing how to formulate strategies during this phase is highly important from a managerial perspective. Managers have to face the relatively high levels of risk when commercializing their radically new technological innovations (Leifer et al., 2000; Min et al., 2006; Olleros, 1986; Pech, 2003; Tellis and Golder, 1996). The risk has several causes. Introducing an innovation in the face of an incomplete Technological Innovation System (TIS) with several barriers, represents an entrepreneurial risk. Introducing an innovation in a phase when the system is built up and is changing while competing technological innovations try to establish their own system, forms an erratic situation with high levels of risk. Our framework aids in formulating and evaluating strategies in such a situation.

5.2.2. Policy relevance

Although our work takes a company perspective, it also has policy relevance. Insight in the actors and factors that are relevant for introduction of radically new technological innovations and insight in how the interplay between these actors and factors can help to formulate niche introduction strategies for companies, is relevant for policy makers as well. Policy makers may stimulate development and diffusion of a technology deemed important for society, for example because of strategic or economic reasons. Policy makers can intervene in the TIS building blocks or can intervene in the influencing conditions. Direct intervention is possible, for example, when governments start producing an innovation, when governments are amongst the first customers adopting an innovation, when governments stimulate network formation around an innovation or when institutions are altered to stimulate development and diffusion of an innovation. Policy makers can also decide to intervene indirectly by focussing on influencing conditions causing a barrier in one of the TIS building blocks. For example, innovation policy can stimulate creation of knowledge of technology by making R&D subsidies available or can increase financial resources by subsidizing potential customers.

5.2.3. Scientific contributions

Our work fills a gap in strategic management theory by proposing a framework that can aid scholars and managers in studying the timing, scale and type of niche introduction strategies for radically new technological innovations. The framework can be used to assess the status of the TIS around an innovation and can indicate in which particular conditions an early large-scale introduction strategy is possible or, conversely, which conditions call for a small-scale niche introduction strategy or which conditions require companies to wait. The framework can help to resolve an old debate in strategic management regarding the timing of introduction strategies (Klingebiel and Joseph, 2016; Suarez and Lanzolla, 2007; Lieberman and Montgomery, 2013). The debate focuses on the question whether early or late entrants in a market are more successful. The framework indicates that the right timing of entry depends on the status of a TIS around an innovation. In addition, our framework adds detail to the contemporary literature describing niche strategies as important strategies in a high-tech environment (DeBruyne et al., 2002; DeBresson, 1995; Gerlagh et al., 2004; Hultink et al., 1997; Meldrum, 1995) because the framework helps to formulate specific types of niche introduction strategies.

Our work also fills a gap in the socio-technical systems literature by taking a company perspective. Several scholars in the field of socio-technical systems have indicated that company strategies are an important factor in such systems but the company strategies are mostly lacking in contemporary socio-technical system and technological innovation system frameworks (Markard et al., 2015; Planko et al., 2017; Raven et al., 2010). Our work deliberately takes a company perspective and in doing so, adapts contemporary frameworks by adding and refining factors of a TIS. The status of TIS building blocks and the influencing conditions in our framework can aid to study introduction strategies of radically new technological innovations by companies.

Finally, our work fills a gap in diffusion theory by focusing on the early stages of diffusion. Rogers (2003) in his eminent work on diffusion of innovations, calls for more attention to the start of large-scale diffusion. Our work shows that for radically new high-tech innovations, the start of the diffusion is not always just a small and somewhat slow start of large-scale diffusion. Instead, this start of diffusion very often reveals niche applications that are significantly different from later mainstream applications. Hence the adaptation phase is not as smooth a start as diffusion models seem to imply.

5.2.4. Assumptions and limitations

Our framework, like most models and frameworks in social and management sciences, is a simplification of reality. One prominent simplification is the way in which we represent a Technological Innovation System (TIS) in terms of TIS building blocks that are influenced by influencing conditions. Other representations of innovation systems are possible, for example a system dynamics model of an innovation system to study the consequences of alternative policies (e.g., Samara et al., 2012) or a model of a TIS in terms of several key innovation functions, that can be used to aid policy makers (e.g., Hekkert et al., 2007; Bergek et al., 2008). We adopted a different simplification; the simplification is a function of the goal that we have in mind and the perspective that we take. Our goal is to study introduction strategies by companies for their radically new technological innovations at one particular moment in time during the adaptation phase. The company perspective called for an adapted set of actors and factors representing a TIS (*cf* Carlsson and Stankiewicz, 1991). The focus on a particular moment in time during the adaptation phase allowed us to work with a more static and hence simple model with building blocks. The goal (specifying timing, scale and type of introduction strategies) urged us to look at barriers in building blocks and their causes and hence led us towards describing influencing conditions.

Our framework is static; the status of the TIS building blocks and the influencing conditions should be reconsidered over time to reveal changes in the TIS that require new or adapted introduction strategies. Our framework is thus limited in terms of *understanding* the mechanisms of evolution and change in a TIS. That goal would require a more dynamic model, for example a system dynamics model. Instead, we focus on measuring the status of a TIS and showing how that status can help formulate and evaluate company strategies.

The framework of TIS building blocks and influencing conditions is a simplification in several other ways. Firstly, we assume that a TIS is made up by seven building blocks. These building blocks were based on a careful literature search and extensive testing and refining in practice. However, TIS building blocks may slightly differ per industry. We consider our building blocks as the main elements of a TIS that can be used as a starting point in studies across a variety of industries. Secondly, we assume that a TIS is influenced by several conditions. In the paper, we simplify the world by indicating seven categories of such influencing conditions. This is not a complete set, but a commonly found set that we based on a large number of case studies and used to illustrate how different causes of barriers call for different introduction strategies.

The distinction between TIS building blocks and influencing conditions, although a simplification, is important. Kemp et al. (1998) present a list of barriers for large-scale application of sustainable technologies, that is similar to our combined list of TIS building blocks and influencing conditions. Several other authors give a list of barriers in innovation and diffusion processes. We add to these inventories of potential barriers by making a distinction between TIS building blocks and influencing conditions. That means that we assume that influencing conditions can block large-scale diffusion *only* via their effect on building blocks. For example, a lack of knowledge of technology only becomes a barrier when it is limiting the performance of an innovation, a production system or complementary products and services. It is exactly this distinction that simplifies and helps to formulate and evaluate company strategies.

5.3. Future research

In our paper, we focused on niche *introduction* strategies, a subset of strategies that belong to a larger category of niche strategies. Niche strategies can be defined more broadly as company strategies stimulating growth of a TIS around a technological innovation, preparing market introduction and actually introducing a radically new innovation in the market for the first time. So, niche strategies for radically new innovations involve more than just niche *introduction* strategies. An important avenue for future research would be to explore different types of niche strategies and indicate when to adopt each of them.

The main focus in our paper was on the adaptation phase, the time between first introduction and the start of large-scale diffusion. It would be interesting to study possible company strategies in the phase prior to the adaptation phase, between invention and the first introduction. This early phase is explored over decades by the Minnesota scientists (Schröder et al., 1986; Van de Ven et al., 2008) who convincingly showed that it entails more than a standard innovation project to turn an invention into an innovation. We would like to add to this work by exploring possible company strategies during this phase. Some possible strategies in this earlier phase that can be explored, in line with the present paper, are strategies that can be used to influence the build-up of TIS building blocks. Examples might be lobbying strategies, networking strategies to build up supply networks or investing in additional R&D to improve the price/performance ratio of the innovation. Another interesting avenue for further research is related to the phase after the adaptation phase. Further research could explore how specific niche strategies during the adaptation phase can gradually and logically evolve into specific large-scale introduction strategies.

In this paper, the framework is used to assess the status of the TIS and its influencing conditions at one moment in time. In the cases of photovoltaic cells (PV) and dual-clutch transmission technology (DCT) we explored in two subsequent episodes how the TIS around these technologies changed and how that called for different niche introduction strategies. It would be interesting to extend this and track framework changes during the pattern of development and diffusion, from invention of a technology up to large-scale diffusion of innovations based on that technology. These changes would indicate how a TIS gradually changes over time. After we can *describe* such changes, it would become an exciting avenue of research to see how the building blocks and influencing conditions do interact over time, so we can begin to *explain and understand* the TIS changes over time. That would require that we release some of our assumptions.

We formulated a framework for a general TIS and its influencing conditions that can be used across industries. It would be interesting to see how a TIS needs to be adapted to specific industries. For example, in wind farms, either onshore or offshore, geographic conditions represent an important condition for large-scale implementation. The same holds for tidal and wave energy systems and solar panel farms. Geographic conditions are not part of our framework but they are important in specific industries. Most probably, more industry-specific conditions and adaptations of our general framework may be needed. Similarly, our framework is based on literature and cases that focus on European and North American countries. It would be an interesting avenue of future research to see if the framework in its current form is also valid for the situation in other types of countries, such as developing countries.

In this paper, we explored TIS formation around technological innovations. That means we focused on hardware-related innovations: technological systems, products and parts. From the perspective of that innovative hardware we looked at necessary complementary services, networks of organizations and several other aspects of the system around this hardware. In future research we would like to explore whether a similar approach can be used for radically new service innovations and if so, what types of adaptations might be needed in our framework. Can the building block of 'production system', which refers to manufacturing of hardware, be changed into something else more fitting for services? Maybe the service delivery system?

Our paper focuses attention on the fascinating early stages of TIS formation. The framework that we presented enables careful tracking of the formation and evolution of a TIS and use that information to formulate commercial strategies.

CRediT authorship contribution statement

J. Roland Ortt: Data curation; Formal analysis; Investigation; Methodology; Project administration; Supervision of (sub)projects; Validation; Visualization; Writing - original draft; Writing - review & editing. Linda M. Kamp: Data curation; Formal analysis; Investigation; Methodology; Supervision of (sub)projects; Validation; Visualization; Writing - original draft; Writing - review & editing.

Appendix

See Table A1 and Table A2

Table A1
Technological Innovation System Building Blocks.

Building blocks	Description	References
1 Product performance and quality	A product (with all subsystems including hardware and software components) is required with a sufficiently good performance and quality (absolutely or relatively compared to other competitive products). Lacking performance or quality can hamper large-scale diffusion.	(Kemp et al., 1998) (Magnusson and Berggren, 2018) (Malerba, 2002)
2 Product price	A product (with all subsystems) is required with a reasonable price (absolutely or relatively compared to other competitive products). The price of a product involves financial and non-financial (e.g., time and effort) investments to acquire and use the product. A prohibitively high price can hamper large-scale diffusion.	(Kemp et al., 1998) (Negro et al., 2012b) (Tsoutsos and Stamboulis, 2005)
3 Production system	A production system that can produce large quantities of products with sufficiently good performance and quality (absolutely or relatively compared to competitive products), is required for large-scale diffusion. A lack of production system can hamper large-scale diffusion.	(Geels, 2004) (Kemp et al., 1998)
4 Complementary products and services	Complementary products and services for the development, production, distribution, adoption, use, repair, maintenance and disposal of an innovation are required. Unavailable, incompatible or too expensive complementary products and services can hamper large-scale diffusion.	(Bergek et al., 2008) (Geels, 2004) (Kemp et al., 1998) (Malerba, 2002)
5 Network formation and coordination	Required actors and sufficient coordination of their activities to develop, produce, distribute, repair, maintain and dispose of products are required for large-scale diffusion. Coordination can be emergent and implicit (e.g., the market mechanism) or can be formal and explicit (e.g., an industry association). Coordination can involve actual collaboration and a shared vision regarding the innovation and the TIS around it. If types of actors and coordination amongst these actors are needed yet missing, large-scale diffusion can be hampered.	(Bergek et al., 2008) (Edquist, 2011) (Kamp and Vanheule, 2015) (Kemp et al., 1998) (Malerba, 2002)
6 Customers	Customer segments are required for large-scale diffusion. Potential customers with a need for the innovation should be identified. To become actual customers, they should be aware of the product, see its benefits relative to other innovations, and have the knowledge, means and willingness to acquire and use it. If actual customers are lacking, large-scale diffusion can be hampered.	(Bergek et al., 2008) (Geels, 2004) (Kamp et al., 2004) (Kemp et al., 1998) (Malerba, 2002) (Ortt et al., 2013)
7 Innovation-specific institutions	These institutions refer to formal policies, laws and regulations either describing norms and requirements regarding the product, production facilities, and complementary products and services or describing how actors (on the supply and demand side of the market) should deal with the product and system around it. Specific institutions can stimulate or hamper large-scale diffusion.	(Bergek et al., 2008) (Geels, 2004) (Kemp et al., 1998) (Malerba, 2002) (Ortt and Egyedi, 2014)

Table A2
Conditions Influencing Technological Innovation System Building Blocks.

Influencing conditions	Description	References
1 Knowledge and awareness of technology	This involves both fundamental and applied technological knowledge. Fundamental knowledge refers to the technological principles involved in components of the TIS, like the product, production and complementary products and services. Applied technological knowledge refers to the knowledge required to develop, produce, repair, maintain, and improve these components. When relevant actors lack knowledge and awareness of technology for their role, this can affect the formation of several TIS building blocks.	(Bergek et al., 2008) (Edquist, 2011) (Kemp et al., 1998) (Kamp, 2002)
2 Knowledge and awareness of application and market	This refers to knowledge of (1) potential applications, (2) knowledge of the market (structure) and the actors involved in these applications. This knowledge is required for all actors including customers to formulate strategies, articulate product requirements and find or target other actors. When actors lack such knowledge required for their role, this can affect the formation of several TIS building blocks.	(Kamp et al., 2004) (Kamp and Bermudez-Forn, 2016) (Lundvall, 1992) (Malerba, 2002) (Ortt et al., 2013)
3 Natural, human and financial resources	Resources can refer to natural, human and financial resources. Natural resources refer to raw materials that can be acquired by each organization separately or by associations of organizations. Human resources refer to individuals with the right knowledge and competences. Increasing human resources may involve education programs, courses and training on the job. Financial resources can come from various sources. Lack of natural, human or financial resources can affect the formation of TIS building blocks.	(Bergek et al., 2008) (Edquist, 2011) (Geels, 2004) (Kemp et al., 1998) (Malerba, 2002) (Vasseur et al., 2013)
4 Competition	Competition can refer to competition between products based on old and new technologies but may also refer to competition between different product versions with a new technology. Since different product versions often require different production systems and complementary products and services, competition arises between networks of companies. The combined complex patterns of competition may hamper the formation of TIS building blocks.	(Magnusson and Berggren, 2018) (Shapiro and Varian, 1999)
5 Macro- economic and strategic aspects	Macro-economic aspects refer to the overriding economic situation, such as a recession or economic growth. Strategic aspects refer to interests of countries which are often reflected in generic institutions and government policies. Macro-economic and strategic aspects can influence the formation of TIS building blocks.	(Bergek et al., 2008) (Edquist, 2011) (Kemp et al., 1998)
6 Socio-cultural aspects	Socio-cultural aspects refer to the norms and values in a particular culture or socio-technical system. These conditions might be less formalized than the laws and rules in the innovation-specific institutions. They include methods and habits, norms and values ("the way to do things") and may become visible in interest groups or relevant stakeholder groups. Socio-cultural aspects can influence the formation of different TIS building blocks.	(Bergek et al., 2008) (Geels, 2004) (Kemp et al., 1998)
7 Accidents and events	Accidents and events may emerge both outside a TIS (e.g., wars, political turmoil or natural disasters) or from within a TIS (e.g., accidents with products or in production, emergence of new technologies). Accidents and events can influence the formation of several TIS building blocks.	(Kemp et al., 1998) (Ortt et al., 2013)

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