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Identifying first signals of emerging dominance in a technological innovation system: A novel approach based on patents

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A B S T R A C T

Actors of an early stage technological innovation system (TIS) need to carefully attend to future developments given the high strategic uncertainty that often prevails in such systems. Such uncertainty is a reflection of the different technology categories that exist as well as the highly dynamic character of such systems in general. It is only gradually, as a result, that dominance of one technology category emerges against alternative categories and uncertainty is thereby reduced. Nonetheless, there has been limited attention so far to how researchers can operationalize some of the preliminary signals in order to anticipate which technology category is likely to emerge. In this paper, we therefore focus on how such early signals can be detected, i.e. by drawing upon patents and their underlying technology classification. Towards this end, we introduce two novel indicators based on the classification codes of patents: the Patent Trajectory (PT_t) indicator and the Category Concentration (CC_t) indicator. Joint application of both indicators enables us to operationalize the seminal concept of the technology cycle from Tushman and Rosenkopf (1992), which is specifically translated to the domain of TIS by distinguishing between the evolutionary phases of a TIS. To operationalize our novel methodological framework, we specifically employ the case of algae, ultimately concluding that this particular TIS tends to evolve in the direction of pharmaceutical applications. In a narrow sense, this framework can thus help to better understand the context of the TIS for algae. More significantly, however, the demonstrated ability of our approach to anticipate the evolution and formation of technological innovation systems signifies a worthwhile contribution for the larger domain of forecasting and strategic management.

1. Introduction

Technological innovation systems (TIS) have been used to make sense of the relevant actors (private firms, or firm sub-units, governmental and non-governmental agencies, universities, research facilities, venture capitalists, associations) as well as their interactions around a technology (Hekkert et al., 2007; Markard and Truffer, 2008). Understanding the evolution of a TIS and forecasting its potential formation has been the subject of a growing literature (Guo et al., 2012; Hekkert et al., 2007; Musiolik and Markard, 2011; Suurs et al., 2010). In this study we draw upon patents as a proxy for the level and direction of developments in a given TIS. In specific, this type of approach allows us to shed light on the types of technology categories that underlie and give shape to the formation of a TIS. In so doing, the use of patents in this way can help to offer prospective insight into a specific TIS, even as it continues to evolve.

There are many reasons why such insight is useful. Firstly, we argue that an early anticipation of the technology categories that emerge and characterize the TIS is crucial for all actors within the TIS, specifically so that they can orient and develop their strategies about how to best respond in order to benefit their interests. Some actors, such as firms, firm sub-units, and research facilities, might be constrained by their resource positions and the necessity of specializing within complex innovation ecosystems, the ability to anticipate promising technology categories can enable these actors to set research priorities and minimize the risk of sunk costs in case of inattentive R&D strategies (Helfat, 1994; Narayanan and Chen, 2012; Tavassoli, 2015). Other actors, including governmental and non-governmental agencies, can further benefit by being able to improve their policy approaches and enhance national innovation infrastructure (Guo et al., 2012), for instance, by establishing requisite incentives for entrepreneurs to make use of these new innovations. This counts especially for anticipating signals in an early stage TIS, in which socio-technical structures are still loose and the dominance of any one technology category has not yet emerged (Jacobsson, 2004; Suurs et al., 2010). In this regard, the emerging bioeconomy, which has been deemed to be pivotal for meeting the

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sustainable development goals outlined by the United Nations, stands out as a hub for many early stage TISs (Purkus et al., 2017; van der Laak et al., 2007). Accordingly, we select algae as a relevant case of a TIS within the bioeconomy. Algae is relevant given its status as an early stage TIS, along with the highly dynamic nature of its underlying technology and the attendant market uncertainties for the various product streams and value chains that are taking shape (Leu and Boussiba, 2014; Michalak and Chojnacka, 2015; Wijffels et al., 2013).

However, although the ability to anticipate early signals of technology dominance within a TIS is likely to be useful for actors, the extant literature lacks sufficient theoretical and empirical approaches for making this aim feasible. Indeed, extant studies in the domain of technology management demonstrate that the formation process of emerging dominance is highly trajectory to early impacts (Arthur, 1989). Instead of making ex-ante use of the early signals that exist, prevailing methods tend to be limited to assessing dominance within a technological system only in an ex-post fashion (Dewald and Achternbosch, 2016; Jacobsson, 2004; Vergne and Durand, 2011). Moreover, even the few approaches that seek to assess technology dominance ex-ante are unfortunately based either on large-scale data or rely on sources of information that are difficult to access and/or operationalize and, thus, are rarely suitable options for the practical uses of industrial actors (Bekkers et al., 2002; Curran et al., 2010; Peine, 2008; Stremersch et al., 2007). This study can therefore be seen to be motivated by one particular question: How and by what means can preliminary signals of category dominance be utilized to anticipate the development of an early stage TIS?

To answer this question, we apply the theoretical domain of technology evolution and make specific use of the concept of the technology cycle from Tushman and Rosenkopf (1992). Moreover, by translating this framework in the context of the TIS, we present a first operationalization that can be used to anticipate the emergence of technology categories. In specific, this is facilitated by drawing upon patent information and the introduction of two novel patent indicators related to the dynamic and static formation of technology categories within the TIS. Expected results of this study are twofold: First, we seek to develop and apply a method that is both practical and relevant for public and industrial stakeholders and, moreover, based on publicly available data (patent data) related to technology categories within a TIS. Among other things, this approach will allow actors to maintain their strategic flexibility and secure long-term success, even in a fundamentally changing ecosystem. Second, we aim to deliver empirical evidence related to the anticipation of technology categories and thereby discuss theoretical and practical implications for both the context of algae and more generally. These findings contribute to the research body of TIS and outline avenues for future research that can close existing theoretical gaps. Although this paper is set up from a TIS perspective, findings of our research are therefore likely to be relevant for a wider audience that seeks to forecast technological dynamics and innovation pathways: e.g., to the research stream of Huang et al. (2012), Guo et al. (2012), Zhang et al. (2016) and Cheng et al. (2017).

The paper is structured as follows: We first review the literature to outline research approaches that strive to anticipate dominance within a TIS, thereby motivating the development of two novel indicators. As such, the formation of technology categories represents the starting point of our research approach. More precisely, we endeavor to make sense of the formation of technology categories by operationalizing the technology cycle of Tushman and Rosenkopf (1992) in order to link these developments to specific characteristics and attributes of these evolutionary processes. In the next step, we utilize these insights to develop our methodological framework, which undertakes five research steps, and ultimately results in the introduction of two novel patent indicators. We then apply this framework to the case of algae before presenting a first validation of our approach by means of a second data set rooted in the established TIS of cement. In the ensuing discussion, we deduce methodological conclusions from the novel approach while also commenting on the strengths and weaknesses of the proposed methodological framework. Finally, we will derive some managerial implications of this novel approach and highlight specific directions for future research in the domain of TIS and technology forecasting.

2. Extant research on anticipating dominance for technological innovation systems

The conceptual foundation of this paper is twofold: the theoretical framework of the TIS; and the anticipation of early signals of category dominance. Thus, in this section, we first describe the concept of TIS and second, we review existing methods to anticipate emerging dominance.

2.1. Technological innovation systems

A technological innovation system (TIS) has been described as “set of networks of actors [...] that jointly interact in a specific technological field and contribute to the generation, diffusion and utilization of variants of a new technology and/or a new product” (Markard and Truffer, 2008, p. 611). Actors can thus be defined as components of the TIS, each having a specific function (Carlsson et al., 2002). The different functions include entrepreneurial activities and experimentation, knowledge development and diffusion, guidance of the search, market formation, resource mobilization, creation of legitimacy, and development of positive externalities (Bergek et al., 2008; Hekkert et al., 2007; Markard and Truffer, 2008). The formation from an early stage towards an established TIS is challenged by the broad increase in the amount of functions within a TIS which must be performed by its component actors (Bergek et al., 2008; Geels, 2004). It is also crucial to note, with regard to the complexity of such systems, that the components of the TIS themselves interact, thereby forming a number of dynamic relationships between them. For example, actors involved in the TIS may influence the development of standards and norms along with the specific technology categories that become dominant in the relevant application fields. This process can be further accompanied by the emergence of novel technological regimes (Kemp et al., 1998), a low differentiation among types of business models (Klepper, 2002), and path dependence with regard to the innovation patterns adopted by actors (Purkus et al., 2017). Concerning the knowledge base, it can also be challenging for inventors and researchers to think outside established categories within a TIS, for instance, to shift their perspective to consider alternative categories which might even be more efficient (Dewald and Achternbosch, 2016). Thus, the ability to anticipate the technology categories towards which a given TIS might evolve would help actors by enabling them to align their research strategies with one another, improve upon their competitive positions, and reduce the risk of sunk costs (Helfat, 1994).

2.2. Anticipating the emergence of dominance in a technological innovation system

In order to develop a methodological approach that identifies early signals towards which technology category the TIS emerges, we review how the emergence of such systems is envisioned in the literature. However, to the best of our knowledge, interest in how we might anticipate early signals of dominance within a TIS remains scarce. The topic of anticipating technology categories thus represents a novel research area. Indeed, although some research has focused on the respective challenges in the transition from an early stage to an established TIS (Dewald and Achternbosch, 2016; Laestadius, 2000; Suurs et al., 2010), a broad theoretical concept is still missing.

Nevertheless, the ability to anticipate dominance and other broad developments in a given sector is part and parcel of technology management research, specifically in the domains of technology development and dominant design (Aharonson and Schilling, 2016; Srinivasan et al., 2004; Suárez and Utterback, 1995; Utterback and Abernathy, 1975). In this regard, Utterback and Abernathy (1975) have analyzed firms' innovation changes (i.e. from product to process innovation) among five different industries. Meanwhile, Suárez and Utterback (1995), Srinivasan et al. (2004), and Theoharakis et al. (2007) have explored market-level data in order to detect the emergence of structures and features of innovation systems: e.g., Theoharakis et al. (2007) assess large sets of trade-media abstracts to measure adoption rates of competing technology standards. Furthermore, Terlaak and King (2007) have examined manufacturing data in order to validate bandwagon effects, while Soh (2010) has determined the extent to which the formation of alliances and strategic networks contributed to a dominant technology standard in the information and communication industries. Moreover, Lee and Lim (2001) have investigated market data of international trade statistics in various industries in order to demonstrate how dominance within technology product design can emerge. With regard to patents, Fai and von Tunzelmann (2001) have relied on such indicators to investigate dominance in firms' technological profiles in the chemical and electrical industries, while Aharonson and Schilling (2016) have used patents to determine the trajectory of firms' technological footprints with regard to both their spread technology terrain and its depth within the technology landscape.

However, the above approaches ignore the existence of sectoral relationships between different actors within a TIS, e.g. bandwagon effect or network externalities. As a result, the indicators that result from this research do not necessarily capture the dynamics of a TIS with sufficient validity (Bergek et al., 2008; Hekkert et al., 2007; Suurs et al., 2010). For this reason, it is necessary to introduce two novel patent indicators, notably, for the purposes of anticipating the dynamic and static formation of technology categories within the TIS. As a further shortcoming, most of the extant approaches are based on comprehensive data sets that are either not practical for industrial actors in their daily activities or difficult to access. Some theoretical approaches that have focused on the dynamics of a TIS are the classical theory of dominant design: e.g. Dosi (1982), Tushman and Rosenkopf (1992) and Nelson and Winter (2002). After reviewing how these conceptual frameworks can cover characteristics of a TIS carefully, we opted for the technology cycle in Tushman and Rosenkopf (1992) as the underlying framework for distinguishing between the different phases of a TIS. This decision is taken for two reasons. First, the concept makes a clear distinction among the evolving cycles into four different phases while also describing the in-depth characteristics of each phase. Owing to this, this framework makes it possible to accurately determine the status quo of a TIS at a given point of time (see Fig. 1). As a result, the point at which the function of knowledge development changes, which is the focus of this paper, can be alternatively linked to key phases of technology evolution (e.g. the ferment, dominant and discontinuity phases). Second, the fact that the framework of Tushman and Rosenkopf (1992) is both well cited in the TIS research domain and has given rise to a number of subsequent publications ensures our selection process (Hekkert et al., 2007; Huenteler et al., 2016; Walrave et al., 2017).

3. Framework development

While drawing upon the question towards which technology category the TIS emerges, we select the TIS of algae and introduce two novel patent indicators. These indicators are crucial for our capacity to operationalize the technology cycle of Tushman and Rosenkopf (1992) and thereby anticipate the emergence of technology categories within a TIS.

3.1. Theoretical reasoning of the patent approach

This approach is founded on the rationale that "the major shift in industry dynamics and strategic choice often occurs not when a product design or architecture becomes dominant […] but much earlier" (Argyres et al., 2015, p. 216) In order to gain a sense of the types of technology categories that are present, we therefore make use of patents as a proxy to anticipate the formation of an early stage TIS. Patents represent an accurate source for analyzing both cumulative technological developments (Patel and Pavitt, 1991) and changes in technology directions (Abbas et al., 2014). As such, patents are a useful tool for measuring the dynamic relationships among the components within a TIS. In specific, patents have been successfully used for measuring technology relatedness (Luan et al., 2013; Zhang et al., 2015), assessing technology distance (Aharonson and Schilling, 2016; Ardito et al., 2017), and mapping the emergence of new technologies (Goeldner et al., 2015; Tietze et al., 2009).

A further advantage of using patent information as a proxy for technology dominance is the fact that their standardized set-up enables one to readily make comparisons across categories, especially in terms of technology mining for identifying novel and competitive technologies (Porter and Cunningham, 2004). For example, the International Patent Classification (IPC) structures patents into eight different sections: i.e. from A to H, followed by a sub-structuring into classes, subclasses, groups and sub-groups, ultimately leading to > 70,000 different IPC codes. These IPC codes specifically indicate the applied technology category of the invention that is granted protection (Schmoch, 2008). Hence, patent analyses based on IPC codes, by providing a detailed technological background of the invention, offers the opportunity to understand technology trends and derive strategies for product development (Abbas et al., 2014).

3.2. Research setting: technological innovation system of algae

The TIS of algae is predicted to play an important role in the transition from a fossil to a bio-based economy, especially as algae represent a primary resource with various functionalities for bio-based production systems (Lorenz and Cysewski, 2000). Currently, technologies in this TIS have been developed for various application fields, though a dominant design for the extraction process as a whole does not yet exist (Griffiths et al., 2016; Leu and Boussiba, 2014; Mehta et al., 2018). Thus, by making it possible to anticipate potential technology application fields, this study supports actors of the TIS in their attempts to align their R&D strategies to continued developments in this domain.

3.3. Outlining the research steps

Development of our proposed methodological framework proceeds along five research steps in order to anticipate the formation of an early

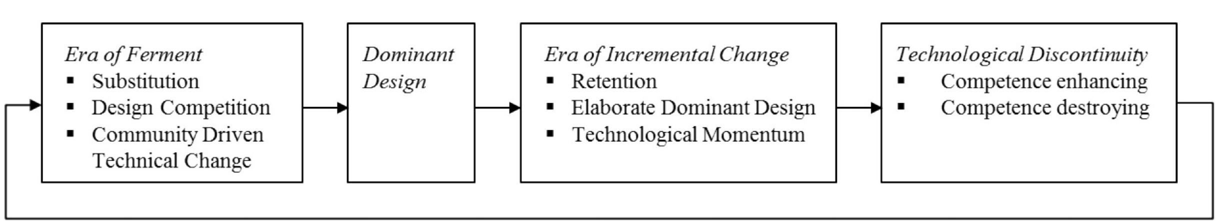


Fig. 1. A technology cycle.
Source: Tushman and Rosenkopf (1992, p. 317).

stage TIS. In the first step, keywords describing the TIS in question have to be defined. Different keyword-search strategies have been described in the literature (Arora et al., 2013; Xie and Miyazaki, 2013). However, defining the unit of analysis and determining the boundaries of the TIS still remains challenging (Bergek et al., 2008). It is therefore recommended to use existing research in order to understand the characteristics of the TIS and better set the focus on the core activities within the TIS. Nevertheless, in the second step, a general keyword string is applied to generate a more comprehensive patent sample. In the third step, out of the generated patent sample, the relevant IPC codes are translated into technology categories based on the WIPO IPC-Technology Concordance Table[1] (Schmoch, 2008). In the fourth step, the patent sample is then re-evaluated based on the applied technology categories with respect to the preliminary defined boundaries (see first research step). Evaluation of the applied technology categories specifically follows a semantic determination based on research of Moehrle and Gerken (2012) and Moehrle et al. (2018). This means that the most frequently used trigrams are calculated on the basis of the title of the patents, although, it must be noted, only for those patents that are solely assigned to the respective technology category. This helps to both understand the individual orientation of the applied technology category and to provide a basis for evaluating whether or not the applied technology category is within the focus of the TIS, or conversely if the technology category has to be excluded from the patent sample. However, if a patent is co-classified in technology categories that are simultaneously outside and inside the focus of the TIS, the patent is then counted, although only for categories that lie within the focus of the TIS. In the fifth step, we then introduce two novel patent indicators which allow us to forecast when the different phases of the technology cycle of Tushman and Rosenkopf (1992) are likely to occur (see Fig. 2). Crucially, the indicators have to be jointly applied, given that the Patent Trajectory (PT_t) indicator assesses dynamic development of an innovation system while the Category Concentration (CC_t) indicator calculates the static concentration rate of applied technology categories. More precisely, the indicators are defined as follows: Every patent ($P_{i,\,t,\,c}$) is assigned one identification number (i), has only one publication date (t), and could belong to multiple technological classification fields (c). Both indicators are moreover jointly considered in order to determine the technology category likely to emerge within a given TIS. In this regard, the Patent Trajectory (PT_t) indicator specifically calculates the number of applied WIPO technological classification fields (M_t) and the sum of published patents ($P_{i,\,c,\,t}$) per year:

$$PT_t = \frac{M_t}{\sum_{i=1}^{N} P_{i,t}}$$

$$\begin{aligned} i &= i_1, i_2, \ldots, i_N \\ t &= t_1, t_2, \ldots, t_q \\ c &= c_1, c_2, \ldots, c_M \end{aligned}$$

i = identification number; N is the number of patents
t = publication year; Q is the number of years
c = category; M is the number of applied WIPO technological classification fields

The trend line for the selected period is then derived by means of regression analysis at the level of calculated values of the *PT* indicator for each year. The trend of this regression offers a first indicator to understand the extent to which dominance has emerged within the TIS: i.e. a varying linear trend is indicative of Phase I (*Era of ferment*), a negative linear trend of Phase II (*Era of dominance*), and a positive linear trend of Phase III (*Era of discontinuity*). Moreover, we are also able to introduce the Category Concentration indicator ($CC_{c,\,t}$), which investigates the extent to which a certain applied technology category $\Sigma P_{i,\,c1,\,t}$ dominates the entire sample of $\Sigma P_{i,\,c,\,t}$in the respective year. The share of technology category 1, for example, can be calculated as follows:

$$CC_{c1,t} = \frac{\sum_{i=1}^{N} P_{i,c1,t}}{\sum_{i=1}^{N} \sum_{c=1}^{O} P_{i,c,t}}$$

The dataset of the technology categories is then classified based on the jointly consideration of the *PT* indicator and the *CC* indicator. The threshold levels for the Category Concentration indicator ($CC_{c,\,t}$) make reference to the definition that a technology category is dominant if it exceeds a share of adoption > 50% (Anderson and Tushman, 1990; Murmann and Frenken, 2006; Tegarden et al., 1999). Meanwhile, the Patent Trajectory (PT_t) indicator provides an initial indication for whether the concentration rate between the different applied technology categories increases or decreases over the selected period.

In order to identify dynamic developments occurring within a TIS and, moreover, to determine the technology category that is likely to emerge, the estimates of the jointly applied indicators are then classified in relation to the technology cycles of Tushman and Rosenkopf (1992). Thus far, this typology has not yet been operationalized in the literature, and specifically not for anticipating the development of technological innovation systems. In specific, the first phase of this cycle, i.e. the *Era of ferment*, is characterized by the existence of high technical variation given that multiple technologies have introduced at this point, though without being accompanied by structures within the TIS. Thus, regardless of whether the linear-regression trend of the *PT* indicator increases, decreases or stays constant, applied technology category within the *Era of ferment* can be expected to score below the threshold of 50% for the *CC* indicator. As soon as the technology categories begin to converge during the first phase, and with a resulting decline in the linear regression trend of PT_t indicator, we are likely to observe a single technology category beginning to dominate the others (i.e. *CC* indicator = 50%). At this point, we can conclude that the TIS has entered the phase of the *Era of dominance*. In this phase, the overall variety of technology categories is expected to further decline until one technology category ultimately dominates all the others, thus becoming characteristic of the TIS as a whole. Moreover, given that the regression trend of the *PT* indicator is likely to further decrease while the dominating category continues to expand its position against other categories, we can expect inertia to continually diminish as the introduction of new inventions and innovations occurs in an increasingly incremental fashion ($50\,\% < CC_{c,\,t} \leq 100$). Eventually, this phase gives way to the *Era of discontinuity*, in which the linear-regression trend of the PT_t indicator begins to increase while the one technology category continues to assert its dominance ($50\,\% < CC_{c,\,t} \leq 100\,\%$). Once this cycle has been run, a new technology cycle will sooner or later begin to emerge.

4. Illustrative example

In order to illustrate how this approach can help to identify first signals of technology dominance, we now apply the proposed five research steps to gain insight into the specific case of the TIS for algae.

4.1. Defining the technological innovation system for algae

In accordance with the first research step, we define the TIS of algae. In the literature, patents have been successfully used as a proxy for measuring the technological developments and applications of algae. For instance, Olivo et al. (2011) compared the quantity of patent applications of different patent offices for biophotolysis (i.e. the component of various bacterial and algal cultures), while Kessler and Sperling (2016) and Adenle et al. (2013) have both used patent data to

[1] In order to facilitate > 70.000 IPC codes, the World Intellectual Property Organization (WIPO) published a coding system that translates IPC codes into 35 different technology categories. This study is based on the version of 2013.

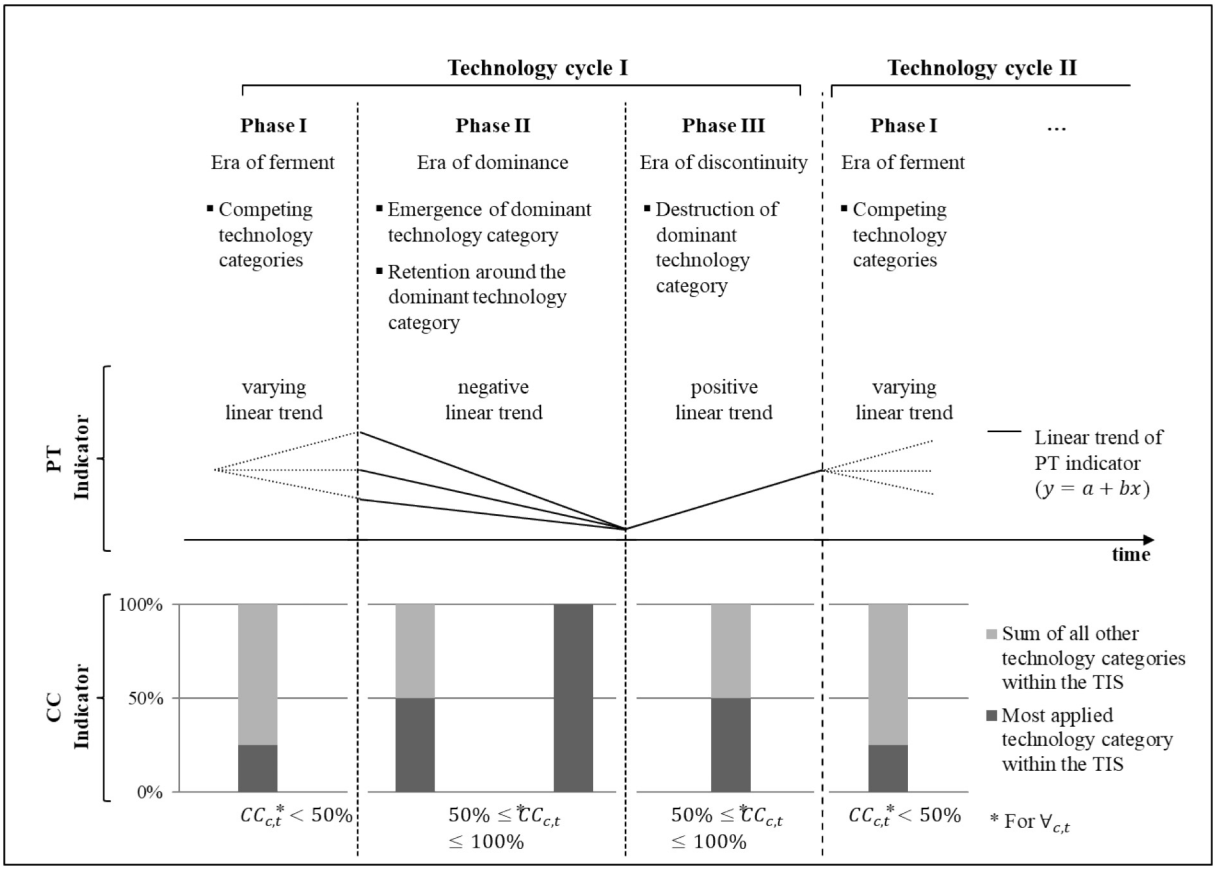


Fig. 2. Measuring the emerging dominance of a technology category within a technological innovation system based on two jointly considered indicators. Source: Own figure based on Tushman and Rosenkopf (1992).

measure the research and development of algae biofuel production. In general, these studies have added to the growing interest in measuring developments of biotechnological innovations using patents as a proxy (Golembiewski et al., 2015; Rothaermel and Thursby, 2007).

At first glance, looking at the studies of Harun et al. (2010), Brennan and Owende (2010), Wijffels et al. (2013), Leu and Boussiba (2014) and Michalak and Chojnacka (2015), the TIS of algae appears to have the characteristics of an early stage TIS: high knowledge development with first cases of different industry applications; many entrepreneurial activities; moderate access to resources; high expectations and visionary foresight for future technological trajectories; growing political and public interest; and dynamic developments in market formation. Therefore, we choose not to distinguish within the TIS between uses of micro- and macro-algae – although when the TIS is fully established, the desire to separate these two types of algae could be recommended.

Moreover, there are the more general difficulties with regard to how an innovation system is to be delineated (Markard and Truffer, 2008). In this study, we set system boundaries on national level because the development of the TIS of algae is also shaped by national policy programs (e.g. by regulation of the U.S. Environmental Protection Agency or stimulating or by Strategic Plans of the U.S. Department of Energy). Thus, we define the TIS of algae from the perspective of an actor producing algae in the US market. In the TIS of algae, products have to this point predominantly been commercialized in the categories of the fuel, food, pharmaceutical, nutraceutical, and personal care industries (Leu and Boussiba, 2014; Lorenz and Cysewski, 2000; Wijffels et al., 2013). Since the extraction process for any of those technology categories can be expected to gain scale advantages by ramping up learning curves and exceeding the investments accrued by other application fields, the ability to anticipate the formation of technology categories, especially at the early stages of these systems, is exceedingly advantageous for actors in the TIS. However, as we have adopted the perspective of an actor who produces algae, it must be noted that not all activities lie within the focus of the TIS. Accordingly, we exclude activities related to, e.g., machinery, measurement and vehicles, which only have accompanying roles related to the value-added stages of the TIS.

4.2. Keywords, data-sample generation, and translation into WIPO technology categories

In the next step, we generated a broad keyword search-string[2] based on technology names that also limited the search to title, claim, and abstract to create the sample data (Preschitschek et al., 2013; Song et al., 2017; Wang et al., 2015). As its specific focus, this study considered photosynthetic, aquatic organisms that are usually summarized under the term algae.[3] Accordingly, we made use of US patents to reflect identical market conditions across the entire TIS, and focus on granted patents to ensure data quality as well as to consider their higher impact on the formation of a TIS due to their proofed claims. We further limited the sample by publication date, specifically specifying the time period of 2008–2017 to determine the status quo of the TIS. We opted to use the publication date since it refers to the date when the patent first begins to affect the TIS. At this point, the applied IPC codes and respective publication years are then extracted from the data set.

[2] Conducted using the database Derwent Innovation of Derwent Innovation of Clarivate Analytics; Specific search string for this analysis was: CTB = (alga or algal or algae or microalga* or micro-alga* or macroalga* or macro-alga*).

[3] Cyanobacteria (blue algae), Glaucophyta (blue-green algae), Rhodophyceae (red algae), Chlorobionta (green algae) and other unicellular photosynthetic, eukaryotic organisms, comprising both micro- and macro algae; see Hoek et al. (1995).

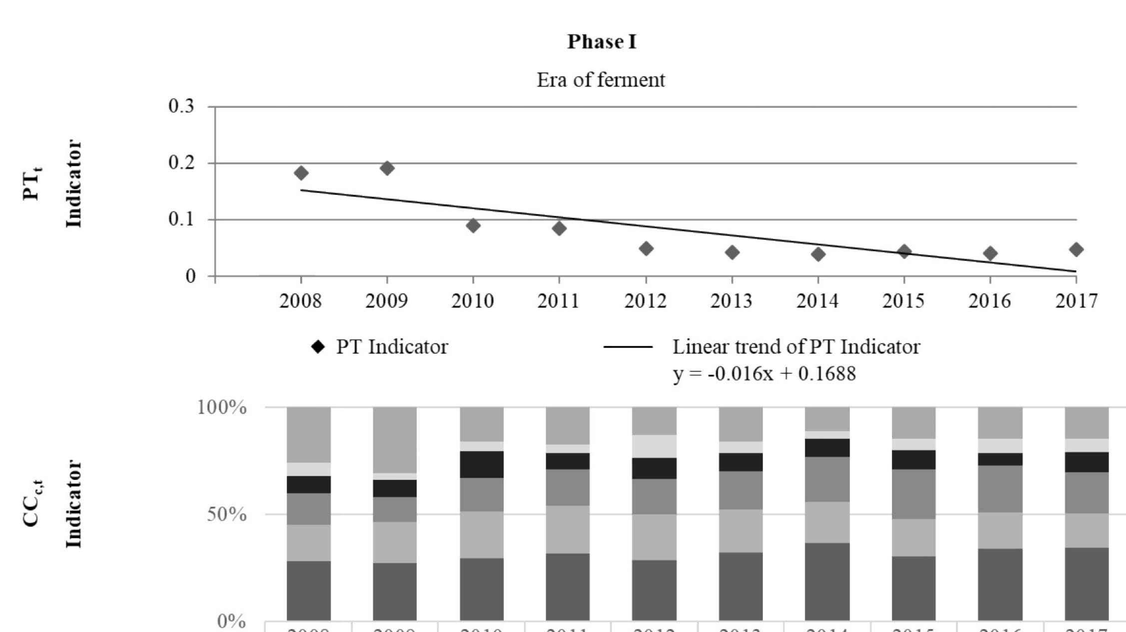
We find that a total of 2353 granted US patents were published between 2008 and 2017, as well as that these patents were assigned IPC codes signifying 33 distinct technology categories. In order to better understand technology orientation of the TIS as a whole and potential overlaps between the technology categories, we set ourselves the task of identifying those patents, 1163 in total, which are only assigned to one technology category. On this basis, we then calculated trigrams based on the title of these patents, and following the n-gram approach of Moehrle and Gerken (2012) and Moehrle et al. (2018). The most frequent trigrams were then used as a basis for further evaluation of whether a technology category lies inside or outside of the focus of the TIS. While again taking the perspective of an actor producing algae, we ultimately conclude that 13 technology categories form the principal focus of the TIS for algae: food chemistry; basic materials chemistry; organic fine chemistry; chemical engineering; macromolecular chemistry, polymers; biotechnology; environmental technology; medical technology; pharmaceuticals; semiconductors; textile and paper machines; transport; surface technology, coating. After excluding those patents that could only be assigned to a category outside the TIS, the final sample contained 2208 US patents which had been granted during the specified period (see Appendixes A and B).

4.3. Analyzing towards which technology category the technological innovation system of algae emerges

To measure the dynamic development of technology categories within the TIS of algae, we make use of the *PT indicator*, the value of which is calculated for each year in the study period (2008–2017). As indicated in Fig. 3, the ten-year linear-regression trend peaked in 2009, while the linear trend decreased overall from 2008 to 2017, namely from 0.18 to 0.04. Using the *CC indicator* for each respective category and year, we then further investigated the underlying technology categories. To clarify, the group "other" here summarizes all those technology categories that were not among the top five most applied technology categories in the algae domain. Also, our analysis reveals that not a single applied technology category had year a *CC indicator* value higher to or equal than 50% at any time during the study period.

The results of the joint application of the *PT indicator* and *CC indicator* highlight that the developments within the TIS of algae can be classified as being part of *the Era of ferment*: i.e. decreasing linear regression of the *PT indicator* and with no single technology category having a value for the *CC indicator* equal to or > 50%. Nevertheless, the continuously decreasing values of the *PT indicator* also indicate that the variety of technological alternatives is slowly consolidating, perhaps leading ultimately towards the dominance of one of the options. This potentiality is also expressed in the decreasing share of the residual group "Other" during the sample period, which fell from 25.5% in 2008 to 14.6% in 2017 – although it should be noted that the amount of patents in the TIS for algae is still increasing. One explanation for this finding is that R&D trajectory of more often applied categories can often act to limit the breakthrough of new categories (Dosi, 1982; Kirkels, 2014). Indeed, this type of trajectory can be seen for the category of "Biotechnology" (34.4% in 2017) which remains the strongest category within the TIS, followed by "Basic materials chemistry" (19.3% in 2017) and "Organic fine chemistry" (16.0% in 2017).

In the TIS for algae, the category "Biotechnology" is moreover linked to many other application fields, thus reflecting its relevance as a platform technology in this domain. However, the application of extended patent-data mining also reveals that the category "Biotechnology" strongly overlaps with that of pharmaceutical applications (Schmoch, 2008). In fact, together with the category of "Organic fine chemistry", which also strongly corresponds with



	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Others	25.8%	30.8%	16.2%	17.5%	13.1%	16.0%	11.2%	14.6%	14.9%	14.6%
Chemical engineering	6.5%	3.0%	4.1%	3.9%	10.6%	5.6%	3.4%	5.7%	6.5%	6.4%
Food chemistry	8.1%	8.3%	12.8%	7.7%	10.0%	8.1%	8.6%	9.0%	5.7%	9.4%
Basic materials chemistry	14.5%	11.3%	15.8%	16.8%	16.4%	18.2%	21.1%	23.1%	22.2%	19.3%
Organic fine chemistry	17.2%	19.5%	21.8%	22.5%	21.7%	20.2%	19.2%	17.2%	17.0%	16.0%
Biotechnology	28.0%	27.1%	29.3%	31.6%	28.3%	31.9%	36.5%	30.5%	33.7%	34.4%

Based on 2,208 (granted) US Patents; 4,967 applied IPC codes

Fig. 3. Development of technology categories in the algae TIS; period 2008–2017.

pharmaceuticals (Schmoch, 2008), these categories accounted for a share of 50.3% of all patents in 2017. These results stress the role of algae as a rich source of both pharmacologically active natural products and nutraceuticals. In view of the evolving structure and stability in technology regimes (for example through institutional isomorphism), actors within the TIS for algae should therefore carefully monitor the future dynamics within the most categories of "Biotechnology" and "Organic fine chemistry" most closely in order to prepare their R&D strategies for the potential situation of emerging dominance. We thus conclude that the TIS for algae is still at the *Era of ferment*, which means that developments within this TIS consist predominantly of high technical variation and novel characteristics and require e.g. lead users that have both the expertise and understanding of relevant attributes and an appreciation of the (latent) needs likely to characterize the demands of customers and users at future stages (Tushman and Rosenkopf, 1992; von Hippel, 1986).

4.4. Comparing results with current literature

Overall, we conclude that the TIS for algae is currently at *the Era of ferment*. Crucially, this finding echoes those of other studies. For example, Harun et al. (2010) conducted a review of current developments of algae and thereby concluded that a wide range of product portfolios can be expected. Meanwhile, other studies have tended to focus more on foundational research and less on issues related to potential large-scale processing or commercialization (Brennan and Owende, 2010; Leu and Boussiba, 2014). This provides another indication that the current developments in this domain belong to the *Era of ferment*. Eventually, our findings also show a burgeoning orientation towards the application field of pharmaceutics, as expressed by the prevalence of the technology categories of "Biotechnology" and "Organic fine chemistry". Although not much research has been carried out using patent analysis to assess the general potential of algae-related technologies, a variety of other studies have concluded that there is a high potential for deriving pharmaceutical components from such resources. For example, Lorenz and Cysewski (2000) demonstrated the commercial potential of Haematococcus, a highly valuable component of microalgae, as a specific pharmaceutical resource. Leu and Boussiba (2014) also referred to other promising components of microalgae, including carotenoids and omega-3 and omega-6 polyunsaturated fatty acids. In this line, Dmytryk et al. (2017, p. 295) have more recently concluded that algae contains "an abundant source of bioactive compounds which have a great potential to be used as pharmaceuticals", therefore identifying product development and market readiness as some of the most significant hurdles that currently exist.

4.5. Validating the proposed methodological framework using data of established TIS for cement

In order to further validate the proposed approach, we moreover applied the methodology to facilitate a more retrospective analysis of a TIS in which socio-technical structures have already been established: the TIS for cement. The TIS for cement (Portland cement) first emerged in the mid. 19th century and, owing to its early and exclusive use in the construction industry, a number of other relevant applications have been demonstrated, e.g. in the medical, dental and semi-conductor industries (Azzone, 1998; Chung, 2001; Xuan et al., 2012; Yilmaz and Degirmenci, 2009). Beside the presence of established structures, we also selected the TIS for cement because it has been widely used as a case in the technology management literature (Dewald and Achternbosch, 2016; Tushman and Rosenkopf, 1996; Yilmaz and Degirmenci, 2009). Moreover, the TIS of cement shares a host of resource-related and technological characteristics with the TIS for algae, as well as offers sufficient patent data for longer-term assessment of our proposed indicators.

Regarding the TIS for cement, we more narrowly define our focus as that of a cement-producing actor of the mid-20th century, given that, at this point, this TIS was already well-established and with cement predominantly applied for construction purposes, i.e. before it also became an important material for dental products from the 1970s[4] (Tushman and Rosenkopf, 1996; Wilson, 1978). Taking the perspective of a cement-producing actor, we therefore exclude activities including machinery, measurement and vehicles, similar to the case of algae. Based on a keyword search-string that we developed,[5] and which we limited to title, claim, and abstract, we identified 11,438 US patents that were granted between the publication years of 1920 and 1970 and which contained the required data (i.e. Patent No., Title, IPC codes and Publication Date). The period is set to start in 1920, given that it is only from this year that identified patents contain the required information. Following the process outlined in 4.2, we then identified those patents that could be assigned to only one technology category, before then concluding that 15 categories formed the core of the TIS for cement. In sum, this resulted in a final sample of 5386 patents that had been granted (see Appendixes C and D).

Before examining how well our indicators can account *ex post* for the transition from one phase to the next, it is necessary to first gain a general understanding of how the TIS for cement has developed throughout the selected time period. Accordingly, we explore the changing composition of technology categories by calculating values of the *CC indicator* for each respective year. Among other things, this analysis highlights that the technology category of "Civil engineering" was dominant during both the first half and at the end of the period.[6] Thus, we would expect there to have been two transitions from one phase to another during this period, notably, one occurring around 1944, and a second taking place around 1965. Hence, we select the period between the years of 1940–1949 and 1960–1969 to measure how well the application of both indicators is able to identify this transition post hoc.

In the first selected period, as indicated in Fig. 4, the joint application of the *PT indicator* and *CC indicator* signals the occurrence of a transition from dominating structures in Phase III (*Era of discontinuity*) towards a period of discontinuity and deconstruction, ultimately leading to the emergence of a new Phase I (*Era of ferment*). Exploring this in more depth, we observe for the first period (1940–1944) that the *PT indicator* only slightly increases from 0.09 to 0.11, while the technology category of "Civil engineering" remains dominant with shares of 50.4% in 1940, 57.9% in 1941 and 53.4% in 1944. Meanwhile, the *PT indicator* strongly increases in the second period (1945–1949) from 0.12 to 0.21, while the technology category of "Civil engineering" also notably falls below the key threshold of 50% adoption in the TIS for cement.

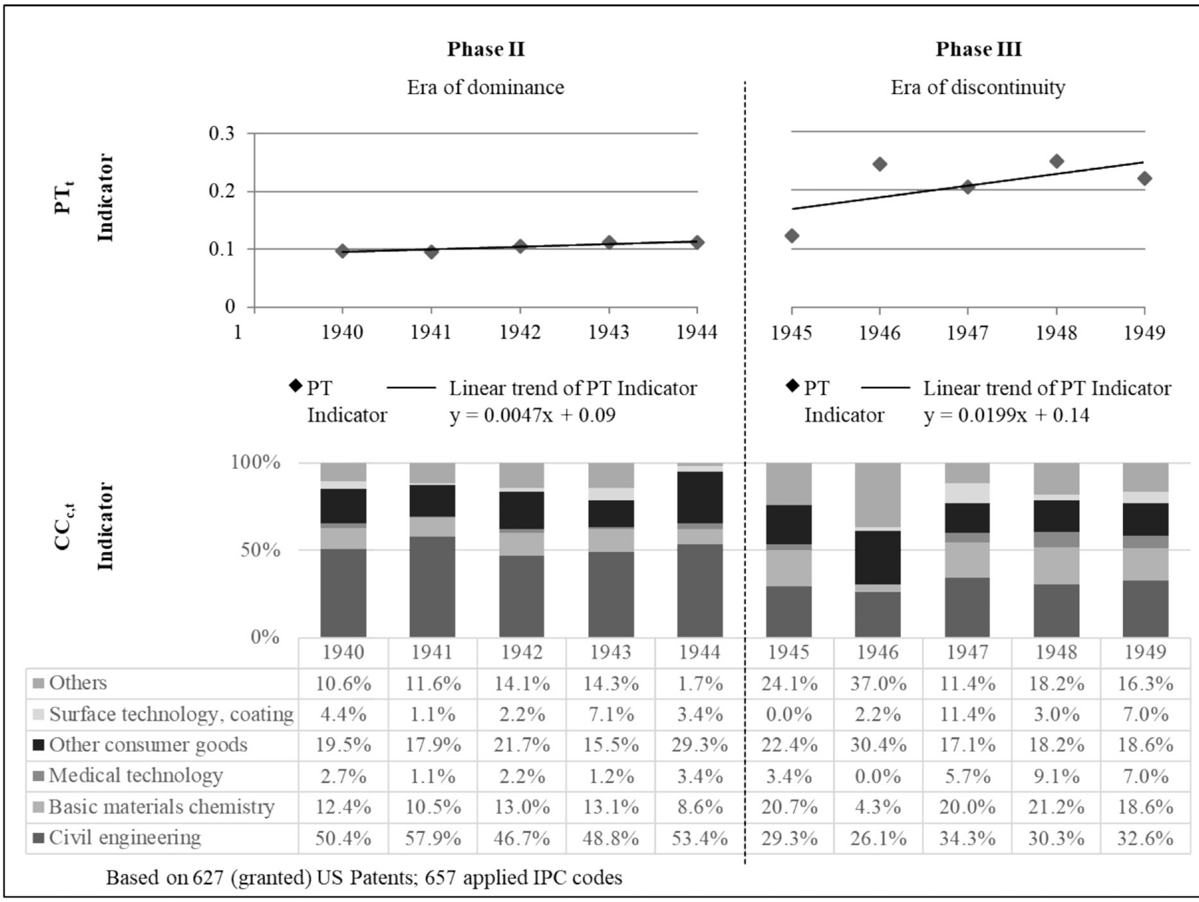
In the second selected period (1960–1969), both indicators again signal the transition from Phase I (*Era of ferment*) to Phase II (*Era of dominance*). While the *PT indicator* decreases from 0.19 to 0.14 from 1960 to 1964 and from 0.10 to 0.09 from 1965 to 1969, it was during this time that the category of "Civil engineering" became dominant, holding shares of 52.9%, 56.0%, 52.3% and 54.4% between 1965 and 1969 (Fig. 5).

We therefore conclude that our proposed framework is successfully applicable to explore the dynamics of an established TIS. This serves as an initial validation of our methodological framework, while also

[4] From the 1970s, material research, knowledge development or the mobilization of resources for medical cement technologies became much more explicit and advanced (Tushman and Rosenkopf, 1996; Wilson, 1978). Thus, from this time the application of medical cement technology could be seen as an independent TIS which is no longer covered by the previously used search terms and defined boundaries.

[5] Conducted using the database Derwent Innovation; Search string for this analysis was: CTB = (cementum or cementum or cäment or cement).

[6] Namely in the years 1920, 1921, 1922, 1923, 1924, 1925, 1927, 1928, 1932, 1933, 1938, 1939, 1940, 1941, 1944, 1965, 1966, 1967 and 1968.



	1940	1941	1942	1943	1944	1945	1946	1947	1948	1949
Others	10.6%	11.6%	14.1%	14.3%	1.7%	24.1%	37.0%	11.4%	18.2%	16.3%
Surface technology, coating	4.4%	1.1%	2.2%	7.1%	3.4%	0.0%	2.2%	11.4%	3.0%	7.0%
Other consumer goods	19.5%	17.9%	21.7%	15.5%	29.3%	22.4%	30.4%	17.1%	18.2%	18.6%
Medical technology	2.7%	1.1%	2.2%	1.2%	3.4%	3.4%	0.0%	5.7%	9.1%	7.0%
Basic materials chemistry	12.4%	10.5%	13.0%	13.1%	8.6%	20.7%	4.3%	20.0%	21.2%	18.6%
Civil engineering	50.4%	57.9%	46.7%	48.8%	53.4%	29.3%	26.1%	34.3%	30.3%	32.6%

Fig. 4. Development of technology categories in the cement TIS; period 1940–1949.

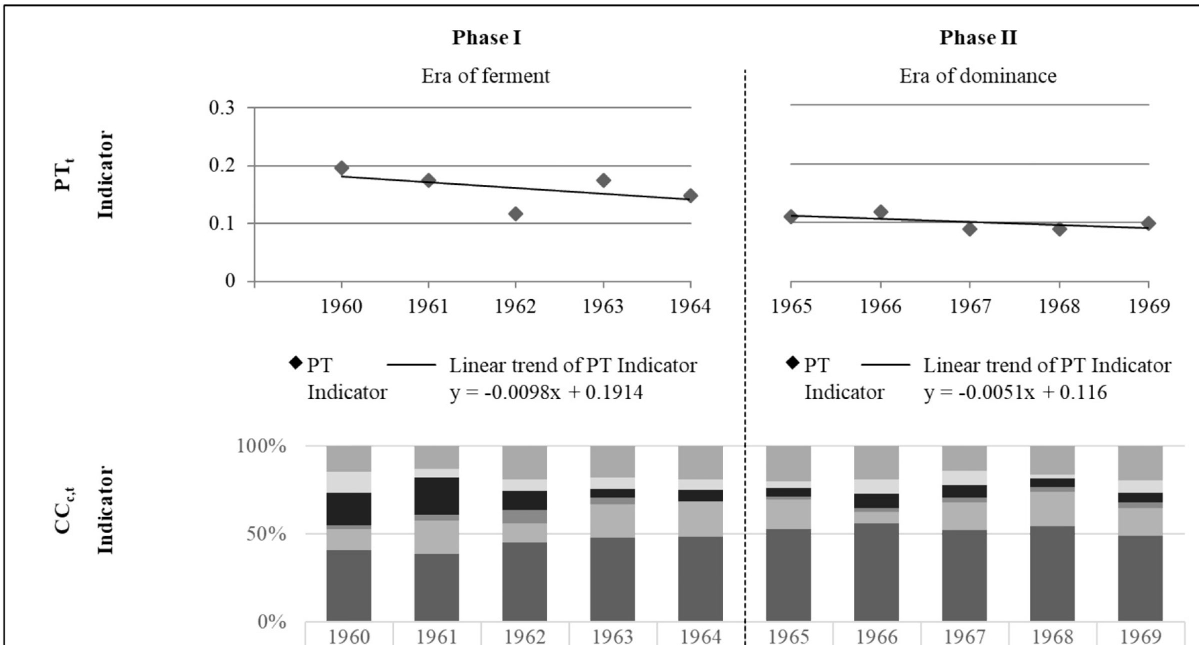
highlighting how a joint consideration by means of dynamic and static indicators can be advantageous for measuring the complex intricacies by which technological innovation systems evolve and ultimately become established.

5. Conclusion

By drawing upon patent information to explore the underlying technology categories of technological innovation systems, this study proposes a novel approach for anticipating the early signals of emerging dominance. In specific, we introduce two novel measures based on the classification codes of patents, namely the Patent Trajectory (PT_t) indicator and the Category Concentration (CC_t) indicator. The joint application of both indicators enables us to operationalize the concept of the technology cycle from Tushman and Rosenkopf (1992) and, on this basis, classify developments in relation to the evolutionary phases of technology categories within a TIS. Specifically applying this framework to the case of algae, we were able to provide an initial demonstration of how these novel patent indicators could be used to assess and characterize the development of evolving technology categories in an emerging innovation system.

Furthermore, our operationalization of the technology cycle of Tushman and Rosenkopf (1992) provides further insight into the dynamic relationships that exist between the components of these technologies. As a result, it becomes possible for us to examine developments across industry and market boundaries more closely while also considering the existence of institutional isomorphism: e.g. bandwagon effect and network externalities (Khazam and Mowery, 1994). By introducing the Patent Trajectory (PT_t) and the Category Concentration (CC_t) indicator and classifying different technology stages, we moreover establish a foundation for actors to improve their understanding and strategic position vis-à-vis the ongoing formation of the TIS, i.e. so that they can maintain strategic flexibility and secure long-term success. What is more, given that all of this is done by using publicly available data, we provide a practical tool that can support actors in their daily practices by, inter alia, allowing them to quantify and characterize historical and current developments of a given TIS. Through applying this tool, actors can therefore track their technology footprints within the TIS and thereby evaluate the extent to which their R&D planning is congruent and in line with those dynamics. Further practical implications also correspond to the high strategic importance of the capacity of these actors to identify at a sufficiently early stage the specific technology categories that underlie the emergence of the TIS. By continuously tracking those patent activities occurring within a specific TIS, actors are able to explore new technology opportunities that have potentially been overlooked. Moreover, actors can use this information to foster greater awareness of those applications in the selected technology category where the necessary resource accumulation is most likely to occur. Thus, our proposed approach is able to both support timing decisions of actors, e.g. with regard to when would be best to invest in a novel application and/or enter an emerging market, and supplies quantitative indicators for tackling difficult questions: e.g. to what degree can we classify a certain TIS as established? How many new applications have been patented in this TIS so far? How much does a certain technology category dominate the other categories within the TIS? By enabling us to answer questions such as these, our work makes significant contributions not only for the identification of research intense categories such as “Biotechnology”, “Basic materials chemistry” and “Organic fine chemistry” but also for heretofore-niche categories from which disruptive innovations typically emerge (Kemp et al., 1998; van der Laak et al., 2007).

More generally, the theoretical contribution of this paper is twofold:



	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969
Others	14.3%	12.9%	18.7%	17.7%	18.8%	20.2%	19.0%	13.9%	16.3%	19.3%
Surface technology, coating	12.2%	4.8%	6.6%	6.3%	6.3%	3.4%	7.8%	7.9%	2.0%	6.9%
Other consumer goods	18.4%	21.0%	11.0%	5.1%	6.3%	5.0%	8.6%	7.3%	4.8%	5.5%
Medical technology	2.0%	3.2%	7.7%	3.8%	0.0%	1.7%	1.7%	2.6%	2.7%	3.4%
Basic materials chemistry	12.2%	19.4%	11.0%	19.0%	20.3%	16.8%	6.9%	15.9%	19.7%	15.9%
Civil engineering	40.8%	38.7%	45.1%	48.1%	48.4%	52.9%	56.0%	52.3%	54.4%	49.0%

Based on 627 (granted) US Patents; 657 applied IPC codes

Fig. 5. Development of technology categories in the cement TIS; period 1960–1969.

First, we further elaborate the possibility of utilizing underlying technology categories as an initial signal of the degree to which a TIS can be said to be established. In this regard, the paper introduces additional empirical evidence into the discussions about dynamic formation within TIS of Hekkert et al. (2007), Bergek et al. (2008) and Markard and Truffer (2008). Second, by instituting a better understanding of how technology categories evolve over time, the paper extends the existing research on technology dynamics and innovation pathways. In specific, the presented methodology could offer worthwhile assistance and help to complement some of the different studies that seek to anticipate new technologies and emerging innovation pathways. For instance, the method could be used to assist technology-oriented workshops by encouraging and providing the basis for participants to shift their innovation perspectives beyond those technology categories with which they are most familiar (Huang et al., 2012). In a similar vein, we also envision this approach to support those methods striving to forecast developments in future technology roadmaps, since it facilitates the anticipation of future phases within the evolution of TIS (Lee et al., 2012; Petrick and Echols, 2004; Zhang et al., 2015). Finally, by helping to visualize the processes by which the formation of technology categories occurs, we contribute to a better understanding of the relevance of disruptive technologies within a TIS (Cheng et al., 2017; Dewald and Achternbosch, 2016).

Nevertheless, the proposed method also currently has shortcomings that demand the attention of future research. Notably, the careful definition of the boundaries of a TIS vis-a-vis the applied keyword search-string, the scope of technology categories, and selected time period turn out to be highly crucial, both for delineating the TIS and, moreover, for minimizing some of the main shortcomings.

Future research could help to address these limitations by, for instance, comparing and analyzing the extent to which dominant technology categories have ended up becoming commercially successful, not to mention the specific conditions in which this occurs. For instance, future work could focus on building upon the *PT indicator* and improving the statistics of the linear-regression trend e.g. through the application of more advanced time-series analysis. As seen in the TIS for cement, the proposed methodological framework has further relevance for the post hoc analysis of dynamics, especially with regard to identifying the transition points between different phases of technology cycles. This could therefore serve to improve the general understanding of TIS-related developments and, more specifically, to support any future studies in assessing technological trajectories, path dependence, and/or the emergence of dominant design. Moreover, future studies could link up with additional data sets, including market-share and merger and acquisition data and patent application data, in order to use this approach to anticipate other types of innovation-related developments. This would also help to improve the overall data quality while still enabling the approach to be applied to the daily practices of actors. In the case of organizations operating on a global scale, the approach could also be utilized to examine the boundaries of a TIS in a broader sense, e.g., by taking patent data from around the world.

These possibilities notwithstanding, this paper predominantly focused on the evolving knowledge and technology base in order to characterize the evolution of the TIS. As a result, those other functions such as entrepreneurial activities and experimentation, market formation, or resource mobilization have been more or less ignored. In itself, the potential application of our proposed methodological framework is broadly limited by the existence of sufficient patent data over a given time period (e.g. ten years), which often is not feasible for novel technologies in an early stage TIS. Ultimately, the use of patents as a proxy for TIS is subject to a few limitations. As in many other cases, operationalization of a typology of this kind must necessarily simplify the evaluation that can be expected. Most notably, the selected thresholds of the different phases can only be defined in a rather vague fashion, which could have the unfortunate side-effect of limiting our ability to characterize transitions between phases. Beside this more general limitation, there is the further issue that not all inventions are ultimately patented, or indeed inherently patentable. As such, we are certainly aware of the issue that patent data is unlikely to ever fully reflect the dynamic processes leading to the establishment of TIS. What is more, patenting strategies can often be incoherent across sectors given that they are contingent on, e.g., the respective innovation settings and managerial strategies that prevail here. For example, whereas some actors and firms tend to be highly patent-averse, preferring for instance to protect radical and incremental innovations via non-disclosure agreements, others could opt for a middle path where they opt to rarely protect innovations by means of patents. On this point, we note that Arundel and Kabla (1998) have demonstrated that firms' patent behavior also depends on the respective industry background. As a result, it might prove difficult to make definitive conclusions on the basis of patents without also considering the larger industrial settings in which such decisions are made.

In conclusion, this study has developed, presented, and offered an initial validation of a novel methodological approach for anticipating early signals of emerging category dominance in a TIS. However, although this proposed framework has successfully delivered preliminary empirical evidence for both the applicability of this tool for understanding the formation of a TIS and its potential relevance for actors operating within a TIS, future work is needed to not only further elaborate on the initial promise of this approach for operationalizing the concept of technology cycles but to moreover deliver empirical demonstrations of its applicability across a range of relevant industrial cases.

Acknowledgements

A first idea of this paper was presented at the R&D Management Conference 2015 in Pisa, Italy and we would like to thank the audience for helpful comments and a fruitful discussion.

Appendix A. Context of TIS algae

Table 1
Setting the context for the TIS of algae.
Source: Own table; Technology categories are based on (Schmoch, 2008); Semantic analysis uses title of patents that are solely assigned to the respective technology category; Identification of trigrams within frame of five words and using stop word list.

Tech. category inside TIS			Tech. category outside TIS		
Technology category	No. of patents	Results of semantic analysis	Technology category	No. of patents	Results of semantic analysis
Food chemistry	43	Dough flour improve; dough flour property; composition dough improve	Other special machines	34	Aquaculture life marine; animal aquatic composition; animal aquatic treatment
Basic materials chemistry	193	Algal biomass extraction; alcohol ester triglyceride; alcohol heterogeneous triglyceride	Handling	0	–
Organic fine chemistry	231	Derive fish oil; fish mixture oil; alleviate composition joint	Micro-structural and nano-technology	0	–
Chemical engineering	49	Extraction protein solvent; air apparatus carbon; air apparatus dioxide	Telecommunications	1	Apparatus communication device; apparatus communication fluid;
Macromolecular chemistry, polymers	10	Aqueous flame retardant; composition flame retardant; flame liquid retardant	Mechanical elements	1	Self-draining hose
Biotechnology	381	Acid fatty production; acid fatty polyunsaturate; carotenoid gene ketolase	Electrical machinery, apparatus, energy	9	Cell fuel heat; complex luminescent material; luminescent material source
Environmental technology	67	Apparatus treatment water; treatment water water; apparatus purification treatment; biological treatment wastewater;	Thermal processes and apparatus	3	Cleaning tank treatment; cleaning tank water; cleaning treatment water
Medical technology	13	Access hemodialysis patient; access hemodialysis preservation; access hemodialysis vascular; access patient preservation	Measurement	27	Analyte detection device; analyte detection nmr; analyte device nmr; detection device nmr
Pharmaceuticals	0	–	Analysis of biological materials	0	–
Semiconductors	37	Device light white; apparatus manufacturing semiconductor; device gallium light material polar	Control	0	–
Textile and paper machines	8	Comprise macroalga tissue; carbon macroalga nanotube; carbon nanotube produce	Computer technology	2	Device monitor water; device level monitor; level monitor water
Transport	1	Alternative composition fuel; alternative composition generation; alternative composition geoengineering	IT methods for management	0	–

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Table 1 (*continued*)

Tech. category inside TIS			Tech. category outside TIS		
Technology category	No. of patents	Results of semantic analysis	Technology category	No. of patents	Results of semantic analysis
Surface technology, coating	17	Biobase composition proppant; coat polyolefin technology; composition prepare proppant; dispersion resin sand	Basic communication processes	0	–
			Digital communication	0	–
			Civil engineering	7	Alga moss roof; moss roof strip; alga growth moss; alga growth roof
			Furniture, games	1	Adapt cleaning lap; adapt cleaning scrubber; adapt cleaning surface
			Other consumer goods	1	Alarm capability redundant; alarm capability safety; alarm capability switch; alarm
			Optics	8	Device laser semiconductor; anthraquinone base pigment red; crystal display liquid
			Audio-visual technology	2	Emit light phosphor; color display light; color display structure
			Machine tools	0	–
			Engines, pumps, turbines	9	Apparatus dispersion paddlewheel; apparatus generate paddlewheel
			Materials, metallurgy	8	Alloy amorphous produce; alloy amorphous product; amorphous base produce

Appendix B. Development of patents and technology categories within the TIS of algae

Year	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	Sum
Patents	66	63	133	154	244	313	335	303	320	277	**2208**
Technology category											
Basic materials chemistry	27	15	42	48	74	101	150	196	184	135	972
Biotechnology	52	36	78	90	128	177	260	259	279	241	1600
Chemical engineering	12	4	11	11	48	31	24	48	54	45	288
Environmental technology	19	17	15	9	21	21	20	32	27	32	213
Food chemistry	15	11	34	22	45	45	61	76	47	66	422
Macromolecular chemistry, polymers	7	2	5	10	3	21	18	46	47	31	190
Medical technology	4	2	7	6	11	5	13	10	21	9	88
Organic fine chemistry	32	26	58	64	98	112	137	146	141	112	926
Pharmaceuticals	2	4	2	1	4	7	5	3	1	2	31
Semiconductors	8	8	6	6	10	18	6	12	9	13	96
Surface technology, coating	5	7	7	12	6	9	12	11	8	3	80
Textile and paper machines	3		1	5	4	6	4	8	9	6	46
Transport		1		1		2	2	2	1	6	15
Sum	186	133	266	285	452	555	712	849	828	701	**4967**

Appendix C. Context of TIS cement

Table 2
Setting the context for the TIS of cement.
Source: Own table; Technology categories are based on Schmoch (2008); Semantic analysis uses title of patents that are solely assigned to the respective technology category; Identification of trigrams within frame of five words and using stop word list.

Tech. Category inside TIS			Tech. Category outside TIS		
Technology category	No. of patents	Results of semantic analysis	Technology category	No. of patents	Results of semantic analysis
Food chemistry	24	Cover edible feedstuff; cover edible livestock; cover feedstuff livestock; edible feedstuff livestock	Other special machines	1876	Block cement machine; apparatus concrete pipe; apparatus cement concrete; apparatus cement mold; block concrete mold
Basic materials chemistry	699	Cement composition comprise; cement cement composition; composition drill fluid	Textile and paper machines	797	Cement machine shoe; cement machine machine; cement cement machine
Other consumer goods	994	Manufacture shoe shoe; shoe shoe shoe; heel shoe shoe	Machine tools	416	Abrasive grind wheel; diamond hold polish; diamond polish polish;
Furniture, games	404	Furniture module produce; club golf shaft; floor hockey puck; latrine latrine pan	Materials, metallurgy	4476	Cement cement composition; cement composition concrete; cement composition composition
Medical technology	1957	Bone cement device; bone bone cement; apparatus bone cement	Handling	498	Bottle closure produce; apparatus bulk material; apparatus container material
Organic fine chemistry	291	Cement composition dental; cement dental dental; composition dental dental	Transport	441	Pneumatic tire tire; pneumatic pneumatic tire; motor roof vehicle
Pharmaceuticals	0		Micro-structural and nano-technology	0	–
Environmental technology	237	Barrier crash module; barrier retractable speed; assembly barrier crash	Macromolecular chemistry, polymers	550	Alkali metal production; cement composition rubber; cement polymer reduction
Surface technology, coating	359	Article cement coat; article cement composite; concrete reinforce structure	Engines, pumps, turbines	287	Metal molten pump; radioactive solidify waste; material radioactive waste
Biotechnology	10	Capture carbon dioxide; accelerate capture carbon; accelerate capture dioxide; accelerate carbon dioxide	Mechanical elements	481	Joint pipe pipe; concrete joint pipe; insulate pipe thermally
Civil engineering	5831	Apparatus casing cement; building construction wall; cement composition comprise	Electrical machinery, apparatus, energy	1311	Electric lamp lamp; base electric lamp; cathode ray tube
Optics	399	Form projection screen; device image optical; projection projection screen	Thermal processes and apparatus	697	Cement kiln rotary; apparatus cement kiln; cool kiln rotary
Telecommunications	36	Absorber radio wave; absorber absorber wave; absorber composition radio;	Measurement	707	Metal molten sample; device molten sample; device metal molten

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Table 2 (*continued*)

Tech. Category inside TIS			Tech. Category outside TIS		
Technology category	No. of patents	Results of semantic analysis	Technology category	No. of patents	Results of semantic analysis
Audio-visual technology	214	Board circuit print; apparatus assembly loudspeaker; attachment board circuit;	Analysis of biological materials	0	–
Semiconductors	99	Device display panel; device package semiconductor; display manufacturing panel	Control	46	Apparatus control flow; apparatus control record; device emergency firefighter
			Computer technology	37	Analytic learn machine; apparatus tag wireless; apparatus control electronic
			IT methods for management	12	Closeloop management production; closeloop produce production; determine price service
			Basic communication processes	35	Crystal holder piezoelectric; crystal device piezoelectric; apparatus crystal piezoelectric
			Digital communication	2	Apparatus channel machine; apparatus channel exchange; apparatus channel facsimile
			Chemical engineering	577	Bone cement mixer; bone cement delivery; bone cement device

Appendix D. Development of patents and technology categories within the TIS of cement

Year	**1920**	**1921**	**1922**	**1923**	**1924**	**1925**	**1926**	**1927**	**1928**	**1929**	**1930**	**1931**	**1932**	**1933**	**1934**	**1935**	**1936**	**Sum**
Patents	202	227	189	166	188	244	258	224	223	216	83	81	102	114	88	109	103	2817
Technology categories																		
Technology categories	3	4	3	5	4	7	12	10	10	10	2	5	6	3	3	7	4	98
Basic materials chemistry	15	21	16	12	5	13	15	11	8	13	10	5	8	13	8	15	9	197
Biotechnology							1											1
Civil engineering	111	118	110	92	98	129	129	121	119	105	42	37	52	67	38	57	47	1472
Environmental technology	4	3	2	5	3	6	6	4	5	5	1	5		1			1	51
Food chemistry		3			1		1		1	1				2	1			10
Furniture, games	16	13	19	11	18	29	23	20	18	24	3	6	4	5	3	6	1	219
Medical technology	11	18	12	2	13	11	13	11	6	5	4		2	2	2	4	3	119
Optics	11	7	6	7	9	9	7	9	11	9	4	1		4	1		4	99
Organic fine chemistry			3	2	2	6	4	3	2	2	1	1	1	3	1		1	32
Other consumer goods	29	41	25	30	39	39	48	36	43	48	15	18	27	18	28	21	31	536
Pharmaceuticals																		0
Semiconductors																		0
Surface technology, coating	6	2	5	2	1	5	5	5	3		5	4	3	2	5	5	6	64
Telecommunications		1					1							1				3
Sum	206	231	201	168	193	254	265	230	226	222	87	82	103	121	90	115	107	2901
Year	**1937**	**1938**	**1939**	**1940**	**1941**	**1942**	**1943**	**1944**	**1945**	**1946**	**1947**	**1948**	**1949**	**1950**	**1951**	**1952**	**1953**	**Sum**
Patents	100	95	99	104	94	86	80	54	57	45	34	32	41	48	70	75	51	1165
Technology categories																		
Audio-visual technology	5		1	2	2	2	1		5	2	2			4	6	3	2	37
Basic materials chemistry	13	1	11	14	10	12	11	5	12	2	7	7	8	8	10	14	7	152
Biotechnology				1														1
Civil engineering	38	59	56	57	55	43	41	31	17	12	12	10	14	21	27	32	27	552
Environmental technology	3		1	1	1	3	1	1		1			1	1		1		15
Food chemistry		1												1	1			3
Furniture, games	7	5	3	4	5	3	5		4	4		1	1	2	3	3	3	53
Medical technology	4	2	2	3	1	2	1	2	2		2	3	3	4		3	2	36
Optics	1	3	1	4	3	5	5		5	5	2	4	4	3	2		2	49
Organic fine chemistry	1	2	1							1							1	6
Other consumer goods	30	22	22	22	17	20	13	17	13	14	6	6	8	7	19	19	5	260
Pharmaceuticals																		0
Semiconductors										1					1	1	1	4
Surface technology, coating	4	4	2	5	1	2	6	2		1	4	1	3	1	7	4	4	51
Telecommunications		1								3		1	1	1				7
Sum	106	100	100	113	95	92	84	58	58	46	35	33	43	53	76	80	54	1226
Year	**1954**	**1955**	**1956**	**1957**	**1958**	**1959**	**1960**	**1961**	**1962**	**1963**	**1964**	**1965**	**1966**	**1967**	**1968**	**1969**	**1970**	**Sum**
Patents	52	34	62	50	73	76	46	57	85	69	61	110	101	125	123	122	158	1404
Technology categories																		
Audio-visual technology	1	1	1		3	2	2	2	1	3	4	4	2	4	3	2	12	47
Basic materials chemistry	11	1	7	15	17	16	6	12	10	15	13	20	8	24	29	23	20	247
Biotechnology																		0
Civil engineering	18	13	34	20	31	35	20	24	41	38	31	63	65	79	80	71	79	742
Environmental technology	1			1	1					2		2			3	3	2	15

Food chemistry	1				1					1			5	2				10
Furniture, games	6	2	2		1	4	1	1	2	2	2	4	3	3	6	4	11	54
Medical technology	2	2		2	1	2	1	2	7	3		2	2	4	4	5	9	48
Optics	3	3	5	2	5	5	2	3	11	3	2	8	6	5	4	7	16	90
Organic fine chemistry	2			1	1	1		1	1	2	1	2	2		2	9	4	29
Other consumer goods	8	6	9	12	8	10	9	13	10	4	4	6	10	11	7	8	12	147
Pharmaceuticals																		0
Semiconductors		1	3		1	1		1	2	1	3	3	3	5	6	2	7	39
Surface technology, coating	4	6	9		8	7	6	3	6	5	4	4	9	12	3	10	11	107
Telecommunications	1	1	2	1	2		2					1	1	2		1	3	17
Sum	58	36	72	54	80	83	49	62	91	79	64	119	116	151	147	145	186	1592

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