Why space matters in technological innovation systems – Mapping global knowledge dynamics of membrane bioreactor technology

Christian Binz[a], Bernhard Truffer[b] and Lars Coenen[c]

[a] Corresponding author. Eawag, Swiss Federal Institute of Aquatic Science and Technology, Überlandstrasse 133, 8600 Dübendorf, Switzerland. christian.binz@eawag.ch. Tel: +41 (0)58 765 5674, Fax: +41 (0)58 765 5028

[b] Eawag, Swiss Federal Institute of Aquatic Science and Technology, Überlandstrasse 133, 8600 Dübendorf, Switzerland. benrhard.truffer@eawag.ch

[c] Circle, Lund University, Sweden. lars.coenen@circle.lu.se

Keywords: Technological innovation system, relational space, system functions, knowledge creation, social network analysis, membrane bioreactor

Abstract

Studies on technological innovation systems (TIS) often set spatial boundaries at the national level and treat supranational levels as a geographically undifferentiated and freely accessible global technological opportunity set. This article criticizes this conceptualization and proposes instead to analyze relevant actors, networks and processes in TIS from a relational perspective on space. It develops an analytical framework which allows investigating innovation processes (or 'functions') of a TIS at and across different spatial scales. Based on social network analysis of a co-publication dataset from membrane bioreactor technology, we illustrate how the spatial characteristics of collaborations in knowledge creation vary greatly over relatively short periods of time. This finding suggests that TIS studies should be more reflexive on system boundary setting both regarding the identification and analysis of core processes as well as in the formulation of policy advice.

Binz, C., Truffer, B., & Coenen, L. (2014). Why space matters in technological innovation systems-mapping global knowledge dynamics of membrane bioreactor technology. Research Policy, 43(1), 138-155. https://doi.org/10.1016/j.respol.2013.07.002

1. Introduction

Technological innovation systems (TIS) have become a popular and resourceful approach for the analysis of innovation processes and early industry emergence, especially in the context of recently developing clean-tech sectors (Markard et al., 2012). However, this literature's narrow geographical focus on industrialized countries and the overriding emphasis on processes at the national scale are increasingly criticized (Berkhout et al., 2009; Coenen et al., 2012). Continuing globalization and the fast rise of new industries in emerging economies add considerable complexity to the spatial extent of innovation processes (Berkhout et al., 2009; Bunnell and Coe, 2001). It thus becomes increasingly important for innovation scholars and policy makers to understand how innovative activity is organized globally and how innovation processes work at and between increasingly interrelated spatial scales.

The technological innovation system (TIS) concept allows in principle for such an international analysis. Conceptualizing innovation systems without setting *a priori* territorial boundaries can be seen as a distinctive feature of the TIS concept. In contrast to other innovation system approaches that have pre-defined territorial delineations, e.g. at the national (Lundvall, 1992) or regional (Cooke et al., 1997) scale, TIS proponents argue that by taking technology as a starting point, the approach cuts across spatial boundaries (Hekkert et al., 2007). Counter to this original vantage point, most of contemporary TIS literature delineates empirical studies ex-ante on the basis of territorial (often national) boundaries (Coenen et al., 2012; Markard et al., 2012). The broader (global) context of the system under study is often conceptualized as representing a ubiquitous 'global technological opportunity set' (Carlsson, 1997a), to which all actors have indiscriminate access.

Mindful of the uneven geographical distribution of innovative activity (Asheim and Gertler, 2005), Coenen et al. (2012) propose a more careful treatment of space in TIS studies which is pronouncedly relational and multi-scalar, avoiding a priori scalar boundaries and hierarchies. Also other TIS proponents have started acknowledging the need to better understand relationships between technological and other types of innovation systems (regional, national) to avoid a reified, decontextualized treatment of technological innovation systems and to improve policy advice based on the TIS approach (Jacobsson and Bergek, 2011).

Therefore, in applying a relational conceptualization of space, the objective of this paper is to develop an analytical framework for TIS that is explicitly spatial but at the same time avoids a fixation on specific territorial units or singular scales. This suggests to start from a network perspective and 'follow the network wherever it leads' throughout its development over time (Coenen et al., 2012). This means using the relational properties of the actors to identify relevant places and spatial levels of a TIS, *a posteriori*. In developing this analytical framework, the paper elaborates on how to specify whether, why and how space matters in studies of technological innovation systems, what errors might be incorporated in nationally delimited case studies and how policy advice could accordingly be improved.

The specific approach presented in this paper aims at explicating the spatial reach of core processes driving TIS dynamics, the so called TIS functions (Hekkert et al. 2007). By tracking the activities of core actors over time, processes like knowledge creation, entrepreneurial experimentation or market formation can be related to specific spatial setups. A relational view emphasizes that actors contribute to these processes by drawing on resources that they can access through specific networks. These networks may be confined to specific regions (e.g. as in the case of industry clusters) but they can as well span over several continents. An explicit analysis of the geography of these functions thus scrutinizes the differential access of TIS actors to resources and institutional contexts that are unevenly distributed across space. The notion of a global opportunity set is therefore replaced by a concept of differential access to unevenly distributed resources in the spaces of a 'global TIS'. While the conceptual argument is explicated for all TIS functions, we are restricting the empirical illustration to one core function that often plays a dominant role in early formation processes (Bergek et al., 2008a): knowledge creation. We will measure the spatial structure of actors and their collaborations by analyzing co-authored ISI publications in the field of membrane bioreactor (MBR) technology.

In the next section, the problems of limiting TIS studies to a national level will be discussed and the potential benefits of a relational geographic perspective for assessing the spatial reach of core functions will be elaborated in more detail. Section 3 introduces social network analysis as a tool for spatial analysis of TIS functions and develops and operationalizes a set of respective indicators. Section 4 discusses the selected co-publication dataset and applies the framework to knowledge creation in the TIS of MBR technology. The results suggest that knowledge creation in this field evolved from a nurturing phase dominated by globally spanning networks to a Europe-based expansion phase and finally to a multi-scalar, Europe- and Asia centred consolidation phase. We conclude by discussing the implications of the observed strong spatial-temporal dynamics in innovation activities for future TIS studies and policy making.

2. Conceptualizing space in TIS

The TIS concept emerged in the early nineties from a quickly expanding innovation system literature, which is rooted in evolutionary economics and industrial dynamics (Freeman, 1987; Lundvall, 1992; Nelson, 1993). TIS are defined as a "network of agents interacting in a specific economic/industrial area under a particular institutional infrastructure or set of infrastructures and involved in the generation, diffusion, and utilization of technology" (Carlsson and Stankiewicz, 1991, p.111). Innovation is conceptualized as an interactive, recursive process, embedded in a set of co-evolving actors, networks and institutions. TIS literature thus pronouncedly rejects the idea of linear innovation paths and emphasizes instead the importance of systemic interplay of complementary actors, interactive and recursive learning processes and the institutional embeddedness of innovation (Bergek et al., 2008a; Carlsson and Stankiewicz, 1991). One does typically divide between TIS structure and processes (or 'functions'). Structure is defined as the actors, networks and institutions that conjointly support the generation, diffusion and utilization of a new technology (Bergek et al., 2008a). A structural analysis is complemented with a dynamic view on innovation system build-up, by focusing on a set of functions, as defined in two programmatic papers by Bergek et al. (2008a) and Hekkert et al. (2007). A TIS most successfully creates and diffuses new technologies if its actors sustain six key system-building processes, namely knowledge creation, entrepreneurial experimentation, market formation, influence on the direction of the search, resource mobilization and creation of legitimacy[1].

2.1 The need for a notion of space in TIS

The conceptualization of space in TIS studies is rather simplistic and ignores that system build-up is an inherently spatial process which might transcend territorial boundaries and

[1] We synthesized the two lists of functions slightly: Creation of external economies, which is only mentioned by Bergek et al. (2008) was not considered here, whereas 'knowledge development' (Bergek et al., 2008; Hekkert et al., 2007) and 'knowledge diffusion through networks' (Hekkert et al., 2007) are summarized in the shorter term 'knowledge creation'.

spatial scales. So far, TIS studies have essentially employed national borders as scalar envelopes (Cooke, 2005) that contain all the relevant processes of an innovation system. Especially the interaction of various TIS elements with the ‘global technological opportunity set’ (Carlsson, 1997a) has not been further specified. When outlining the original framework, Carlsson (1997b, p.776) assumed that “the technological opportunities facing any economic agent are virtually unlimited; the pool of global possibilities has practically no boundaries”. This view is increasingly criticized (Coenen et al., 2012). In many sectors, the global opportunity set is conditioned by differential absorptive capacities at the level of individual organizations. Actors differ in their ability to tap into external knowledge sources and to make use of it for innovative activities. This explains why, despite the potential existence of a ubiquitous global opportunity set, innovation activities are not uniformly or randomly distributed across the global landscape. Moreover, tacit dimensions of knowledge may be sticky, which means it does not travel easily beyond the context in which it was generated (Gertler, 2003). This results in dual knowledge flows for innovation activities that consist not only of localized learning embedded in local nodes (Maskell and Malmberg, 1999) but also global knowledge networks in the form of international epistemic communities (Amin and Roberts, 2008), corporate networks of transnational companies (Chaminade and Vang, 2008) or temporary proximity and face-to-face interaction at international trade fairs and conferences (Bathelt and Schuldt, 2008). Scrutinizing these interconnected relational dynamics has been ignored so far by TIS research, but become one of the hallmarks in the so-called relational turn in economic geography (Bathelt and Gluckler, 2003; Boggs and Rantisi, 2003).

2.2 Applying a relational perspective on TIS space

In a relational perspective, spaces and places are shaped not only by processes and interactions happening within a specific territory but also by the impact of wider sets of structures and processes (Bathelt and Gluckler, 2003; Yeung, 2005), that are fluent and constantly reorganizing at all scales (Amin, 2002). Actors thus have significant relationships (through which they seek to access resources to achieve their individual goals) at different spatial levels that simultaneously influence their behaviour (Amin, 2002; Bunnell and Coe, 2001; Coe and Bunnell, 2003; Coenen et al., 2012). Relational economic geography has therefore put a premium on networks as a conceptual and methodological underpinning to analyze (uneven) spatial development (Glückler, 2007; Ter Wal and Boschma, 2009).

Networks span space by establishing transversal and topological interlinkages among geographically dispersed locations or organizational units (Brenner et al., 2011). This does however not mean that a networked perspective by default presupposes distanced, global relations. Network spaces may as well be concentrated in a particular locality. Economic geographers have shown that often a combination of dense local ties and extended extra-regional connections creates successful long-term innovativeness of actors, places or innovation systems (Bathelt et al., 2004). We would thus expect that such local ties and extra-regional connections are equally relevant for the core innovation processes in a TIS. How this combination plays out empirically is however contingent on a number of factors such as the type of industry and its knowledge base (Asheim and Coenen, 2006) or the institutional conditions of a region (Tödtling and Trippl, 2005). A relational perspective on space thus suggests that relying only on interaction at one scale (e.g. the regional scale in regional innovation systems or the national scale in technological innovation systems) curtails the significance of relevant interaction at other scales or treats it as a merely exogenous factor. This reveals a key challenge for TIS research. While indeed the development of a technology or technological fields does not stop short of territorial borders, its spatial set-up is neither randomly spread across the geographical landscape, but contingent on the specific technology in focus and the resources and relationships of actors involved in driving the relevant innovation processes.

Analyzing networks therefore potentially allows scrutinizing the spatial extent and structure of core TIS processes. Networks have held a core position in the TIS approach since the earliest writings. The actual use of the term has, however, been restricted to a mostly qualitative and metaphorical level (Coenen and Díaz López, 2010; Kastelle and Steen, 2010). This is not very surprising as getting a grasp of the plentiful and very diverse types of networks that define a TIS is a delicate task: they can be formal, informal, short-run, long-lasting, trans-disciplinary, exclusive, open or strategic and spanning between diverse actor types (Musiolik and Markard, 2011). Nevertheless, they are of key importance for explaining how innovation and a supportive institutional context are created by TIS actors. Formal networks as a recent example have been shown to create system resources that are crucial for maturation and diffusion of new technologies (Musiolik et al., 2012). The spatiality of these actor networks which enact key system build-up processes (and ultimately structural change) has however not yet been further specified.

Thus, also when speaking about networks, TIS research so far mostly restricted its analytical focus to ties within national territories. It would therefore be adequate to explicitly label these studies as 'national TIS' snapshots of a wider 'global TIS'. Shifting to a relational perspective on space thus means explicitly analyzing TIS structure and processes from a global, relational perspective. Whether or not sufficiently coherent systemic interaction may be identified in specific countries, regions or continents can then be treated as an empirical question.

2.3 A networked perspective on TIS functions

This implies a fundamentally new inroad to the way TIS analysis is approached. Instead of delimiting system boundaries ex ante we propose to start with a technological boundary and to then empirically reconstruct whether sufficiently coherent sub-systems overlap with specific regional or national boundaries. Existing schemes of analysis (Bergek et al., 2008a; Hekkert et al., 2007) would accordingly have to be adapted. A relational spatial perspective demands an explicit consideration of spatially structured networks for driving core processes of TIS development. It thus becomes crucial to discuss where spatially extensive actor networks become important elements of TIS functions and where, as a consequence, a myopic focus on nationally bound networks is likely to miss out on important causal factors. [2]

Knowledge creation, for instance, is usually defined without reference to the actors or networks involved in the process, but with a focus on the way it is generated; e.g. Hekkert et al. (2007) distinguish between knowledge produced through "learning by searching" or "learning by doing". In our view, a distinction between codified and tacit knowledge could be a fruitful extension here: Codified (or 'explicit') knowledge can be easily transferred between creator and recipient; codified knowledge bases of technologies are thus – at least partly – public goods e.g. created in the science system and "originating from various geographical areas all over the world" (Bergek et al., 2008a, p.414). Tacit knowledge is in contrast hardly accessible in conscious thought, only producible in practice and strongly context-dependent (Gertler, 2003). It therefore evolves in much more complex settings: its creation and dissemination is in many cases still restricted to interaction in densely co-located actor networks (Gertler, 2003; Maskell and Malmberg, 1999), yet also increasingly mobilized and

[2] Note that at this point it will not be possible to expound an exhaustive 'theory' on the relationship between different TIS structures and functions.

effectively shared in international networks and communities (Bathelt and Schuldt, 2008; Crevoisier and Jeannerat, 2009; Wenger, 1998). As tacit and codified knowledge co-evolve, one can assume to find considerably complex geographic network structures underlying knowledge creation: Subnational clusters of dense interaction, combined with increasing distant connections between actors in international networks and communities. A respective analytical framework for this function will be proposed in this paper.

Entrepreneurial experimentation depends on new companies entering a field, and especially the networks forming between them and supportive partners in an experimentation process, typically in protected market niches (Bergek et al., 2008a, p. 416). This process is inherently spatial as there are proximity advantages for new firm start-ups: “The social ties of the potential entrepreneurs are likely to be localized, and induce entrepreneurs to start their firm in close proximity to their homes and to their current employers” (Stam, 2010, p. 142). At first sight, one could thus expect entrepreneurial activities to build up mainly in localized settings. Yet, also entrepreneurial networks can be shaped by more international interrelations. Transnational entrepreneurship literature shows how e.g. returnee entrepreneurs induce entrepreneurial experimentation as “new argonauts” (Saxenian, 2007) in places that were initially unconnected to a TIS emerging in other places and thereby span relevant networks between at first sight unrelated national subsystems (for a more extensive overview of this argument see Drori et al., 2009). This function could accordingly be analyzed by reconstructing the social networks of entrepreneurs and their dynamics over time, e.g. based on primary survey data, industry association’s member lists, data on actors in R&D projects or patent data.

Market formation usually develops in different stages with distinctive features of the relevant user-producer networks (Bergek et al., 2008a). Especially in very early nursing markets, collocation between users and producers may form important ‘learning spaces’ (Kemp et al., 1998), which facilitate repeated and trustful feedback loops between companies (or entrepreneurs) and their customers (Lundvall, 1992). Early markets for wind power and photovoltaics as an example were strongly shaped by such interactive learning at local to regional levels (Dewald and Truffer, 2012; Garud and Karnoe, 2003). Yet, especially in later bridging and mass market phases, producers and users do not necessarily have to be co-located to form and supply markets: Actors in regions without markets could also sell their products in other subsystems of the same TIS, e.g. by compensating missing spatial proximity to foreign market places with other forms of (organizational, institutional, cultural or cognitive) proximity (Lagendijk and Lorentzen, 2007), or in extended user-producer relations in global production networks or multinational companies (Coe et al., 2004). Chinese PV manufacturers as a case in point developed into a market leading position by strongly exploiting spatially distant foreign markets in Europe and the US (de la Tour et al., 2011). Empirically, networks of market formation could be mapped based on surveys on relevant user-producer interactions, market reports, or - in later development phases - trade statistics.

'Influence on the direction of search' describes the selection process dealing with variety emerging from knowledge creation (Hekkert et al., 2007). It works through a combination of regulations or long term policy goals set by governments and the creation of vision and collective expectations on a new technology among different TIS actors (Bergek et al., 2008a; Hekkert et al., 2007). In this context it is often assumed (but seldom verified) that national institutions constitute the most relevant context for effective policy intervention. However, supranational political institutions and treaties like the EU, UN, WTO or the clean development mechanism of the Kyoto protocol can have increasingly strong influence on innovation processes, especially in clean-tech sectors (Binz et al., 2012; Gosens et al., submitted). A similar argument holds for the second main dimension of that function, the shaping of expectations. Bergek et al. (2008a) explicitly argue that expectations might be influenced by growth occurring in TISs in other countries or by changes in the socio-technical landscape, which lies outside the influence sphere even of specific national agents. E.g. direction of the search in the German wind power TIS was reportedly strongly influenced by developments in California and Denmark (Bergek and Jacobsson, 2003). Also the spatiality of this function is therefore far from restricted to a specific spatial scale. Similar arguments hold for another closely related function, creation of legitimacy. This complex process of expectation shaping and institutional change is created through e.g. lobbying in political networks, the global climate change debate or experiences from 'sister' TIS (Bergek et al., 2008b). The performance of both functions is thus closely related to the emergence of supportive advocacy coalitions, interest groups, networks and intermediaries which jointly opt for coordinated technological and institutional change (Bergek et al., 2008a), much in the sense of the work of Musiolik et al. (2012). Also here, whereas some relevant actor networks might be restricted in their spatial reach, others might consciously aim at creating guidance and legitimacy at a more international scale - as e.g. in the case of membrane technology policies in the Netherlands and Japan (van Lente and Rip, 1998). Empirical analysis of these functions should thus focus on the perception of key actors on the potential of new technologies and the formation of advocacy coalitions. Perception of key actors about the legitimacy of a technology can be scrutinized with discourse analysis methods (in the context of TIS studies see for instance (in the context of TIS studies see for instance Konrad et al., 2012) or some newer forms of discourse network analysis, as done in political sciences (see e.g. Fisher et al., 2012). Relevant data sources can be newspaper articles or protocols of parliamentary discussions. Formation of advocacy coalitions and intermediaries could in turn be analyzed based on affiliation data from the core industry associations or interest networks in a field or again by conducting surveys.

Resource mobilization, finally, involves the deployment of financial and human capital (Hekkert et al., 2007). Mobilization of financial capital essentially depends on the investment decisions of private or public investors. Whereas some of these investments are likely coming from local sources, venture capital might as likely be mobilized through the global financial system (Avdeitchikova, 2012). Similarly, human capital could be mobilized in local specialized labor markets, national education institutes or increasingly also through attracting foreign talent in the form of entrepreneurs, specialized professionals or academicians (Saxenian, 2007). Actor networks underlying financial resource mobilization could thus be reconstructed through data on the investment shares of financial institutes or other investors in key companies of a field. Scrutinizing the mobilization of human capital could in turn be followed by e.g. mapping the ego-networks of key actors in a field or through graduation records of specialized engineers.

In summary, specifying how actor networks at different spatial scales influence functional dynamics is an important analytical problem that remains to be addressed in TIS research. The short discussion above reveals that further work is needed in particular to better theorize and empirically analyze the networked spatialities of TIS functions. Rather than trying to assign functions to their appropriate spatial level, we suggest to examine in more detail how processes in networks at different spatial levels interact and thereby shape key processes and ultimately innovative outcomes of both specific national subsystems and the global TIS as a whole. Unpacking these high spatial complexities in TIS was avoided for a long time due to problems of data availability - in particular if the focus is extended beyond the borders of small European countries. Obviously, new methodologies and indicators are needed for tackling innovation processes in a more global perspective. The following section will therefore propose a first step in this direction by developing a set of indicators based on social network analysis that allow for a spatial analysis of the actor networks underlying TIS functions. To reduce complexity and enable an in-depth study of spatial dynamics, the analysis will be limited to one function, knowledge creation, whereas the framework's potential applicability to the other key processes will be discussed in the concluding sections.

3 Measuring international network topologies of TIS functions

Based on the discussion above, we can distinguish between three ideal-type network patterns characterizing the spatial setup of innovative interaction in a specific function or – if the assessment of different functions are combined – a TIS as a whole. First, as assumed in existing TIS research - relevant networks might form exclusively in localized setups, at regional to national scales. In such a setup, innovation would be created based on processes emerging in largely unrelated subsystems, e.g. in different countries. On the other extreme, networks might be exclusively global, spanning between actors in distant places, as e.g. in an innovation network of multinational companies or the networks of open source programming. In this case, relevant TIS space would hardly be assignable to any fixed place or country, but rather be completely embedded in internationalized networks. Third and in between these extreme cases, relevant actor networks might be multi-scalar, incorporating a set of both spatially proximate and distant ties. This setup essentially represents small-world networks, which efficiently connect tight clusters of local interaction with occasional nonlocal links to other clusters (Watts and Strogatz, 1998). Small-world networks are assumed to increase creative output as they combine spatially dense and trustful collaborative innovation processes with ties to more distant, complementary ideas (for a critical discussion see Fleming et al., 2007). Consequently, if actor networks underlying TIS processes show small world properties, then this has strong implications on a respective TIS study, as it implies that scrutinizing interrelations between different territorial subsystems gets crucial to understanding the structural and functional properties of its innovation processes.

For analyzing what network setup characterizes a TIS or given function at a specific point in time, a new methodological approach is needed. Here social network analysis (SNA) enters the stage as a tool that provides heuristic routines for scrutinizing actor network evolution in global space (Wasserman and Faust, 1994). A respective analytical framework will be operationalized based on four types of indicators: First of all, general properties of network structure can be characterized with conventional SNA indicators like mean distance, network diameter or centralization index.[3] Secondly, a "nationalization index" is developed, which gives a direct measure for how much of the cooperation in a given function is actually confined to national borders. Thirdly, areas of dense collaboration in the overall network are analyzed as 'coherent subsystems'. Such subsystems are here defined as groups of diverse actors (companies, academia, government, intermediaries) which show particularly tight interaction. As TIS research assumes such interaction to be crucial for the innovation process, coherent subsystems can point to core areas of innovative activity in a given function. Obviously, such subsystems may be strongly localized, but they may as well develop in regional agglomeration, form between actors at a national or even international level. Finally, a measure for the overlap between these subsystems is introduced. Coherent subsystems might in some cases form in isolation from each other, whereas in other cases they might strongly overlap, thereby integrating subsystems at different spatial scales to densely integrated 'global' TIS (see Figure 1).

3.1 Measuring the relative relevance of national networks

The 'nationalization index' is defined as the average ratio of links among actors inside one country versus the links with actors outside a country. Its definition is based on the E-I index by Krackhardt and Stern (1988), but combined with the spatial attributes 'national' and 'international'. This index gives a direct measure for the average importance of nationally delimited interaction in the actor networks underlying a function. The following formulae capture this relationship:

1) $$N_c = \frac{\sum L_i - \sum L_e}{\sum L_i + \sum L_e}$$

N_c := 'nationalization index' of all actors in a specific country in the TIS, L_i:= internal link, L_e:= external link of actors in a specific country c

2) $$N_{gTIS} = \frac{\sum N_c}{c}$$

[3] As these are standard measures in SNA methodology, they will not be introduced here, but directly in the results section. Detailed descriptions can be found in Appendix A.

N_{gTIS} := nationalization index of the TIS as a whole, c:= number of countries

Equation 1) assesses the nationalization of activity in a specific country in the TIS, whereas equation 2) calculates the average of all nationalization indexes, thus providing a cumulated measure for the importance of nationally bound cooperation in the whole TIS. If most actors are cooperating in national or subnational contexts, these ratios will show values above 0 and tend towards 1. If internal and external links are equally important, the value will be close to zero. Consequently, if international interaction is dominant, it will take on negative values and tend towards -1.[4]

3.2 Identifying coherent subsystems

Coherent subsystems will be assessed by identifying and characterizing network components and cohesive subgroups. Components depict isolated fractions of a network, whereas cohesive subgroups are defined as a subset of a network that displays stronger interaction within a group of actors than with actors outside the group. Subgroup identification will here be based on n-clan analysis. N-clans are defined as subgraphs in which the largest (geodesic[5]) distance between any two nodes is not greater than n and the diameter does not exceed the set n-value (Wasserman and Faust, 1994, p.258-261). As such, n-clans identify cohesive subgroups based on reachability. This helps to understand processes that work through an intermediary, like e.g. the diffusion of knowledge among different actors in a TIS. In addition, it allows specifying some of the properties of the cohesive subgroups in focus. In the following analysis, an n-value of 2 was chosen, meaning that every actor in each 2-clan is divided from all other actors by no more than one intermediary. In addition, n-clans allow for the definition of a minimum value of participants, which was set at 9 actors.[6]

---

[4] Note that this index is partly dependent on the size of countries. Large countries will always have more national cooperation, simply because there are more potential cooperation partners inside their boundaries. For regression studies this point should be controlled for, in this contribution it suffices to keep this caveat in mind.

[5] The shortest possible path between two connected actors in a network.

[6] This value was chosen based on the properties of our co-publication data. One publication in the dataset contains 8 authors, four of them 6 actors, 96% less than 4 authors. The threshold level was therefore set at nine actors to avoid single publications from forming one distinct n-clan and therefore biasing the used n-clan measure. If more multi-author publications appear in a dataset, n-clan measures should be normalized with the number of publications per n-clan.

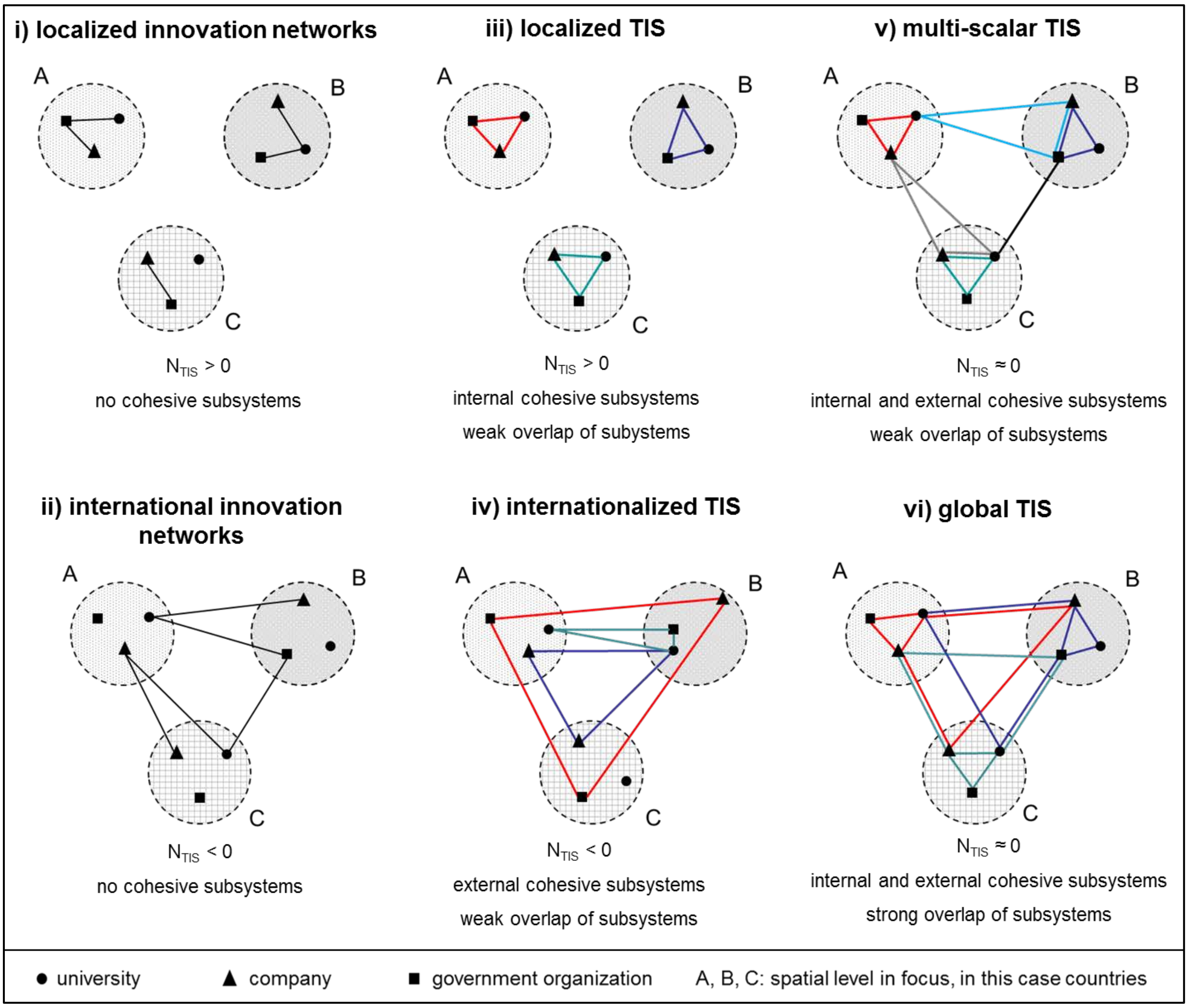
3.3 Analyzing the overlap between coherent subsystems

Finally, the overlap between coherent subsystems has to be assessed. This will be done here based on exploring 2-clan-overlap matrixes. After identifying all 2-clans in our network, they can be arranged in a 2-clan overlap matrix which measures overlap between any pair of clans through the number of shared actors. In some cases, clans might consist of different actors, whereas in other cases they might almost completely overlap. Analyzing this pattern can reveal if coherent subsystems of a TIS are isolated from each other or if they are integrated in an interconnected set of subsystems. Here 2-clan overlap will also be visualized and assessed from a geographic perspective, in order to identify spatial scales at which cohesive subsystems are forming and overlapping.

3.4 Analytical framework

Summarizing, the spatial setup of actor networks underlying a given function can thus be assessed based on the degree of nationalization, the geographic reach of its 2-Clans and the strength of 2-clan overlap. Based on this selective spatial characterization, the rough typology of spatial TIS setups developed above can be further differentiated (Figure 1).

Figure 1: Typology of spatial TIS setups[7]



Firstly and secondly, innovation in a given function might be based on networks without 2-clans, but high levels of either national (Figure 1 i) or international interaction (Figure 1 ii). In both cases cooperation ties are not (yet) integrated into coherent subsystems, thus hinting at interaction failures in a respective TIS (Jacobsson and Bergek, 2011). Thirdly, networks might include 2-clans that largely overlap with national boundaries but show weak interconnectivity ('localized TIS' in Figure 1 iii). In this case, subsystems of a TIS would develop largely independent from each other in different parts of the world. Fourthly, networks might include 2-clans that do not overlap with national boundaries but at the same time also not overlap with each other ('internationalized TIS' in Figure 1 iv). Such a case

[7] This framework strongly profited from inputs of one of the anonymous reviewers.

would describe a TIS driven by different international networks (e.g. by multinational companies) that develop independently from each other. Fourthly, there might be networks with cohesive subgroups that are mainly confined within national boundaries, but also show substantial connections among each other ('multi-scalar TIS', Figure 1 v). This case exemplifies a small-world network with plentiful shortcuts between areas of dense local interaction. Finally, networks might be structured as in Figure 1 vi), with 2-clans transcending national boundaries and at the same time strongly overlapping each other. In such a case, most activities in a TIS would get integrated in a complex network of overlapping coherent subsystems, forming what can be labeled a 'global TIS'.

3.5 Analyzing knowledge creation in the MBR TIS

For illustrating the benefits of this framework, it will be applied to the illustrative case of knowledge creation in membrane bioreactor technology. MBR technology represents a case in point for a recently emerging environmental technology which strongly depends on systemic innovation (Truffer et al., 2012). MBR plants are based on conventional biological wastewater treatment, combined with a micro-porous membrane. They produce a directly reusable, reliably clean effluent and thereby promise to significantly improve the efficiency of industrial, municipal and particularly on-site wastewater treatment systems (Fane and Fane, 2005). The basic process was invented in 1966 in a lab of Dorr-Oliver Inc. in the USA (Wang et al., 2008), but innovation in this field remained rather dormant in the following 20 years. Activities re-gained momentum only after a decisive innovation by a Japanese professor in 1989 and especially in the past ten years (Judd and Judd, 2006; Lesjean and Huisjes, 2008). The MBR TIS is thus in a late formative phase. Commercial applications are booming recently (Lesjean and Huisjes, 2008; Zheng et al., 2010), but the technology is still subject to particular uncertainties, not yet fully standardized and developed by a multifaceted set of small start-ups, large transnational companies and various research institutes and universities worldwide (Binz et al., 2012).

3.6 Data sampling

Knowledge creation on MBR technology relies on integrating a mix of synthetic and analytical knowledge bases from areas as diverse as process engineering, biology and advanced materials sciences. It is strongly engineering-driven and tightly intertwined with actors from companies, utilities and government agencies and that foster pilot plant applications. In the MBR field, such pilot plant experimentation is crucial for interactive learning and the development and diffusion of the technology.

The results of such experimentation are widely published in international academic journals or presented at specialized conferences. Relatively abundant data about innovative cooperation is thus included in the MBR publication record, which was chosen as a source of network data. Publication data could not be complemented with patent data. A respective search in the global database of the European patent office retrieved 575 patents, among which more than 87% originated from small Chinese companies and were of questionable quality, whereas most major commercial players did not file one single patent[8]. Contextual knowledge of the sector confirms that most important MBR companies prefer non-disclosure of their production processes over patenting as a strategy to protect their intellectual property. This notwithstanding, the co-publication dataset includes a balanced set of actor types (only 53% of actors originate from universities, the rest includes companies, research institutes, government agencies and associations, see Table 1). We thus maintain that in the specific case of MBR technology – and despite well documented limitations of publication data (Katz and Martin, 1997) - a sufficiently indicative part of the knowledge creation network is covered with this dataset.

Data collection was based on a query in Thomson Reuters web of knowledge.[9] A dataset of 1,068 publications covering a timeframe from 1992-2009 was obtained by searching for TS=('membrane bioreactor' AND water) and filtering for research areas that contribute to knowledge generation in MBR technology.[10] Publications after 2009 were excluded, as the records did not yet appear to be complete at the time of data sampling. After manually

[8] Search string: "membrane bioreactor" AND "water" in title or abstract. Search performed on October 2, 2012 on the website of the European Patent Office, http://worldwide.espacenet.com/advancedSearch?locale=en_EP

[9] Thomson Reuters Web of Knowledge, http://apps.isiknowledge.com/

[10] Search string: TS=("membrane bioreactor" AND water) AND SU=(water resources OR engineering, chemical OR environmental sciences OR engineering, environmental OR biotechnology & applied microbiology OR polymer science OR chemistry, multidisciplinary OR biochemistry & molecular biology OR engineering, civil OR energy & fuels OR agricultural engineering OR food science & technology OR microbiology OR chemistry, analytical OR chemistry, applied OR materials science, textiles OR multidisciplinary sciences OR ecology OR engineering, aerospace OR engineering, biomedical OR engineering, electrical & electronic OR engineering, multidisciplinary OR environmental studies), Databases=SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, Timespan=1960-01-01 - 2010-01-01, Lemmatization=On

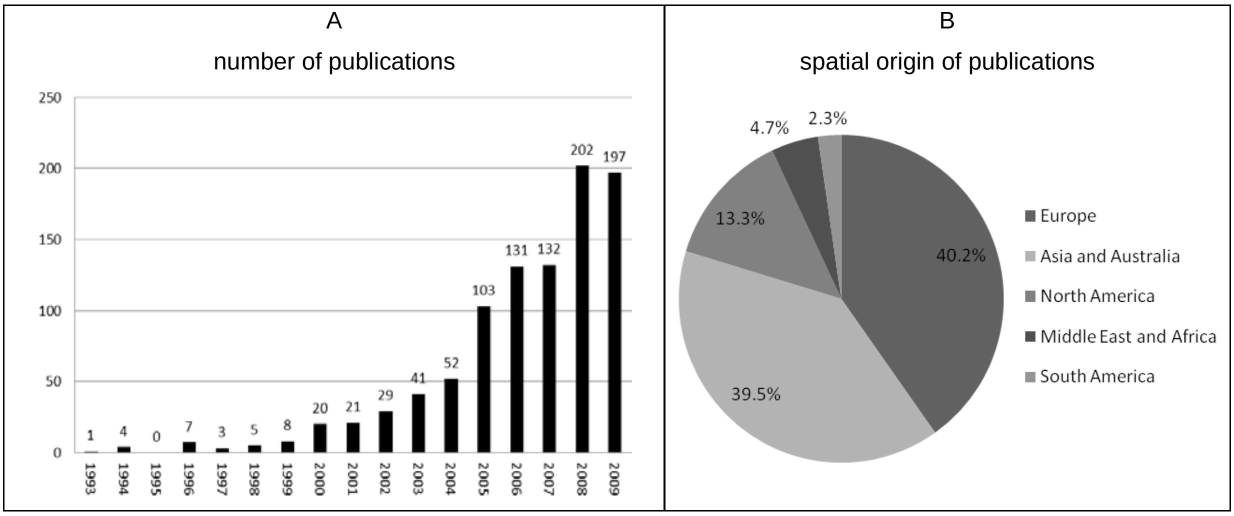
eliminating thematically completely unrelated entries in the database, 911 publications covering a time frame from 1993-2009 were left for a co-authorship analysis. Even though co-publications are the source of relational data, actors in this study are defined not at the level of single authors, but at the level of organizations such as companies, universities, research institutes or government agencies.[11] Network nodes thus represent organizations and ties between them represent their cooperation in the co-publication process. Nodes that are linked to themselves indicate cooperation between different departments of the same organization (e.g. different faculties of the same university). The dataset was evaluated and visualized using Net Miner 3 software.

4 The spatial evolution of knowledge creation in the MBR TIS

4.1 General characteristics of the dataset

MBR technology is in a booming period: Publications grew exponentially from 1999 to 2009 (see Figure 2A), in parallel with rapid market growth and increased commercial dissemination of MBR systems (Lesjean and Huisjes, 2008; Wang et al., 2008).

Figure 2: Publications on MBR technology, 1993-2009



Source: Own design, based on data from web of knowledge

[11] Interpretation of the 2-mode data is simplified by operationalizing links between organizations as co-publications and analyzing them as a one-mode network (organizations interacting in a network with other organizations). We maintain that this simplification is legitimate as co-authorship in MBR technology often involves pilot-scale experimentation and prototyping which includes extended cooperation among significant parts of the participating organizations.

Table 1 further reveals that the publication record of MBR technology contains a mixed set of academic, commercial and public actors and abundant data on cooperation between them. Actors from 46 countries are involved in the network. Seen from this aggregate perspective, knowledge creation is thus forming around three key blocks of innovative activity in Europe, Asia and – to a lesser extent – North America (Figure 2B).

Table 1: Actors and form of cooperation in publications on MBR technology

Actor type	Number	%
University	273	53.2
Company	109	21.2
Research Institute	84	16.4
Government Agency	39	7.6
Research Institute of Company	5	1.0
Association	2	0.4
Government Research Institute	1	0.2
Total	**513**	**100**

Actors per publication			
1	44.8%	3	15.4%
2	35.8%	≥4	4%

Form of cooperation	
international cooperation	22.1%
national cooperation	24.1%
internal cooperation	9.0%
single authored publication	44.8%

To discuss temporal dynamics, the evolution of the MBR TIS will be divided into distinct development phases, based on the dynamics observable in the evolution of the co-publication network.[12] As publications are relatively sparse in the first ten years of development, the aggregated network data between 1993 and 2001 is taken as a starting point for a more detailed analysis between 2001 and 2009. Appendix D and network measures in Table 2 show how co-variation of key network measures allows distinguishing three stylized development phases. Between 2001 and 2003, relatively short paths span between most actors in a dense network. After 2003, the network expands quickly; new actors enter the field and mean distance between actors grows longer. This trend reverses only after 2007, when average

[12] Note that the focus of this contribution is introducing our analytical frame based on an illustrative example. We had to refrain from a thorough control for many of the problems typically arising when comparing networks over time and across different contexts. E.g. most network measures are very sensitive to network size as in growing networks the number of existing ties increases linearly when the number of maximum possible ties increases in quadratic terms. Future studies applying this framework and comparing properties of networks of various sizes, across contexts or over time should address these caveats, by e.g. comparing properties of each observed network against values expected in equal-size (i.e. same density, same number of nodes or similar degree distribution) random networks.

connecting paths get shorter again. In parallel, the network oscillates from a centralized to a more equally connected and back to a more centralized setup (see Appendix D).

Table 2: Three phases of network evolution (non-cumulative except for 'number of actors')

	Number of actors	Number of Links	Mean Distance	Network diameter	Centralization index	Components > 9 actors
93-03	104	201	2.597	7	19.174	2
03-07	291	553	5.540	15	4.456	6
07-09	513	945	4.963	13	6.953	1

Explanations of the indicators used in this table are summarized in Appendix A, a threshold value of 9 actors was chosen for the component analysis to avoid publications with many co-authors from being interpreted as a distinct component.

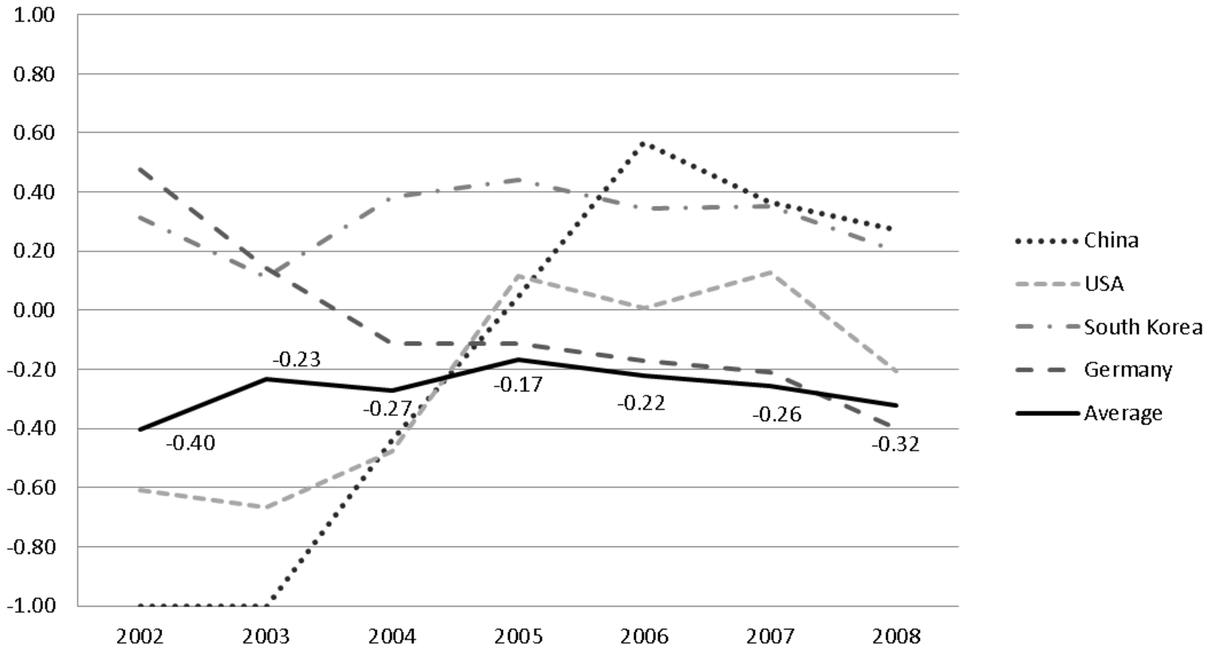
These three phases can be characterized as follows: First a nurturing phase between 1993 and 2003 in which activity is growing and first cooperative ties form around a few central actors in a dense and centralized network. Subsequently a rapid expansion phase (2003-2007) in which knowledge creation grows exponentially and many new actors enter an increasingly broad and decentralized network. Third and finally a consolidation phase (2007-2009) in which growth slows down and knowledge creation gets intensified among existing actors.

A comparison with secondary sources shows that the first 20 years of TIS development are not covered by this dataset. Publication records only start after a decisive invention at the end of the 80ies (Judd and Judd, 2006). Our dataset thus misses the very early invention phase between 1960 and 1990, but covers the later nurturing phase between 1990 and early 2000 when activities start growing and first commercial MBR plants emerge (Lesjean and Huisjes, 2008; Wang et al., 2008). The subsequent phase matches an expansion phase in the TIS when commercial applications start booming and many new actors enter the field in different parts of the world (Judd and Judd, 2006). The last phase finally corresponds with a consolidation in the MBR industry where dominant designs emerge and some companies leave the field or are bought by large transnational companies (Binz et al., 2012; De Wilde et al., 2008). This very general characterization of our data can now be complemented with the spatial analytical framework and indicators outlined in section 3.

Nationalization index

Figure 3 shows that knowledge creation on MBR technology is most internationalized at the beginning of the nurturing phase. In the consecutive expansion phase the trend is reversing and cooperation at a national level gets slightly more important, whereas the consolidation phase is characterized by another dip towards more internationalized values. This pattern interestingly suggests that knowledge creation in the MBR TIS started in a rather globalized network structure and turned into more differentiated multi-scalar spatial setups only in the later expansion and consolidation phases.

Figure 3: Nationalization index of knowledge creation in the whole TIS and 4 national subsystems



Source: Own design, based on data from ISI web of knowledge. Values depict shifting (3 years) averages.

The dominant form of interaction in specific countries shows strong temporal variation, too. E.g. Chinese actors' nationalization index values are exclusively international in the first two years and then increasingly switch to nationalized index values until 2006. This shift happens at a time when many new Chinese actors enter the TIS and MBR technology gets increasingly integrated into strategic national R&D programs (Wang et al., 2008; Zheng et al., 2010). This pattern thus reveals a catching-up process in which Chinese actors first tapped into global knowledge sources before domestic technological capabilities and policy incentives were built up. South Korean actors, in contrast exemplify a geographically stable cooperation strategy which was in all periods mainly confined to a national level.

Coherent subsystems identification and overlap analysis

The results of the 2-Clan analysis in 3 further substantiate the precedent insights. In the nurturing phase, all three identified 2-Clans are of global outreach. The expansion phase is dominated by six 2-Clans at a ‘continental’ level (mainly in the EU). Coherent subsystems get spatially more differentiated only in the consolidation phase when continental 2-clans are the dominant level of interaction, but global and national 2-clans emerge, too.

Table 3: Spatial reach of 2-clans

Type of 2-clan	Nurturing 1993-2003	Expansion 2003-2007	Consolidation 2007-2009
National 2-clan	0	0	9
Continental 2-clan	0	6	45
Global 2-clan	3	0	3

Source: own design. National 2-clans: 2-clans with more than ½ of the actors from one specific country; Continental: 2-clans with more than ½ of the actors from different countries of the same continent; Global: 2-clans containing actors from at least three different continents, without a dominant region

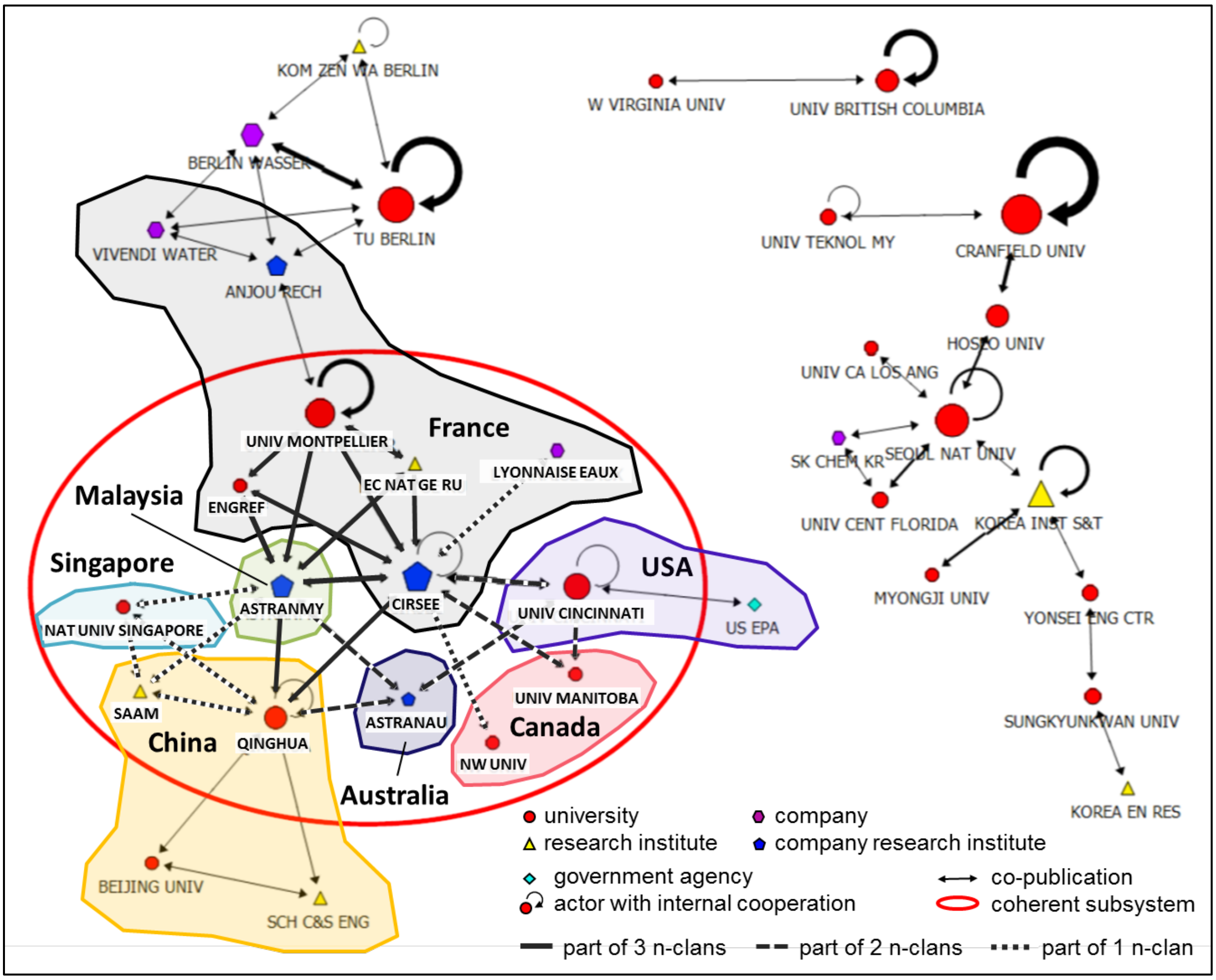
As the analysis of 2-clans and especially of 2-clan overlap needs careful interpretation, the next section will discuss these results in more detail and with contextual information.

4.2 1993-2003: Global, company-based knowledge creation

Figure 4 illustrates that in the nurturing phase, knowledge creation is split into two main components and three strongly overlapping 2-clans, containing actors from eight countries. The core coherent subsystem is centered on CIRSEE (Centre International de Recherche Sur l'Eau et l'Environnement), a French company owned research institute, and its subsidiaries in Malaysia (ASTRAN Malaysia) and Australia (ASTRAN Sydney). Another subsystem is forming around an isolated network component comprising Cranfield University, the National University of Seoul and other institutes in South Korea, the USA and Malaysia. However, cooperation in this component is less tight than in the main component around CIRSEE and no 2-clans can be identified in this part of the network.

Network measures in Table 2, the nationalization index and coherent subsystem analysis thus assert that international interaction is most relevant in the nurturing phase (also see network visualization in Appendix B). These results thus suggest that knowledge in the MBR TIS originated from a globalized coherent subsystem initiated by French water companies. As public funding for research and development on MBR technology was very limited at this early point of development (Lesjean and Huisjes, 2008), first innovative activities were pushed by private actors that mobilized financial resources and their extended international innovation network to developed the first commercial applications of the technology.

Figure 4: Coherent subsystem in MBR knowledge creation, 1993-2003



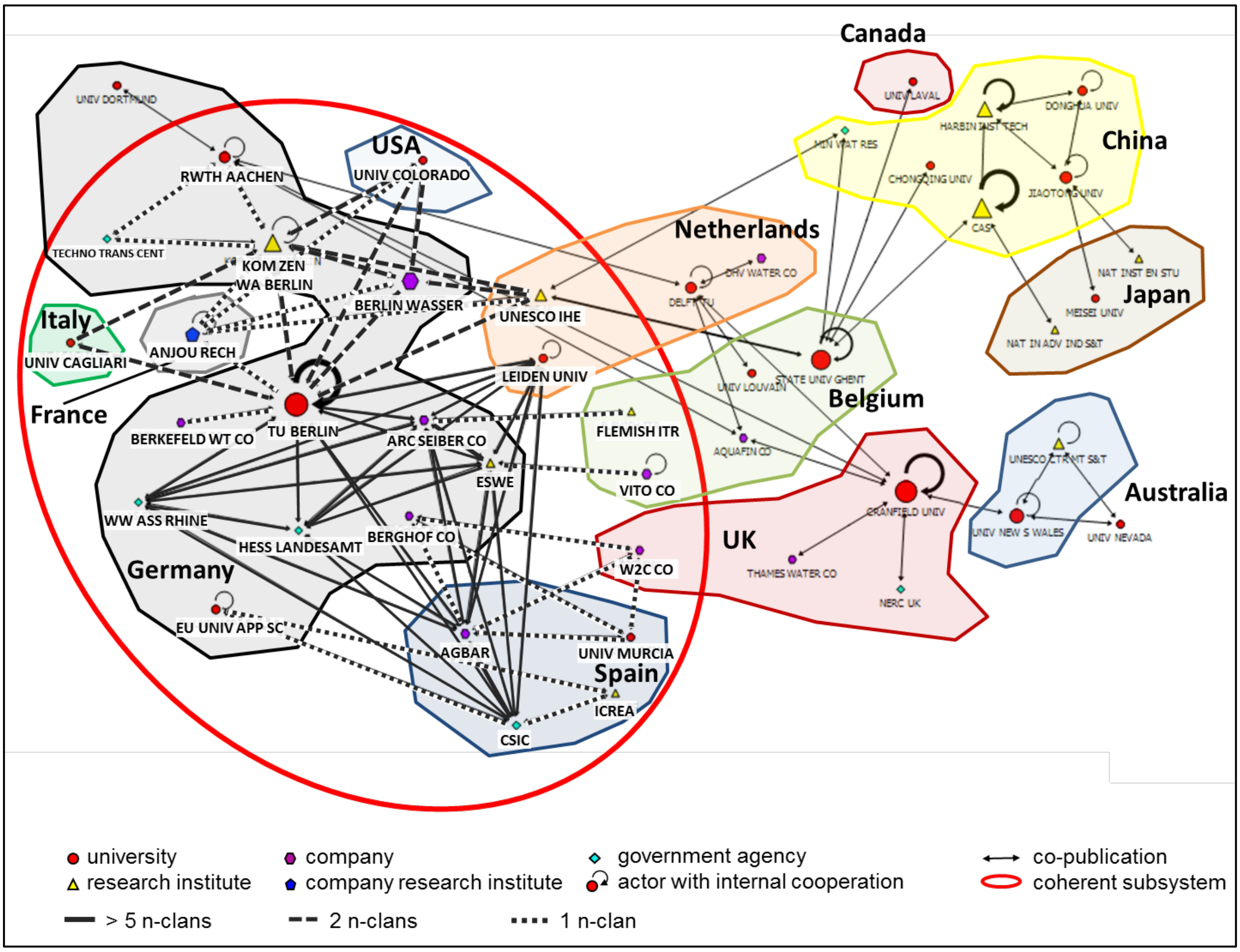
Source: Data from web of knowledge, visualized with NetMiner 3 software. Node size depends on sum of publications.

4.3 2003-2007: Multi-scalar, Europe-centered knowledge creation

The subsequent expansion phase was so far characterized as a multi-scalar setup with six 2-clans at a continental level and a sharp increase of involved actors. Also in this second period, most identified 2-clans are strongly overlapping. Figure 5 identifies a core coherent subsystem spanning between actors in 6 overlapping 2-clans in the European Union, connected mainly by German actors. Dense cooperation in the networks of French water companies is still relevant in that subsystem,[13] but the network around CIRSEE has lost its central position.

[13] Anjou Recherche and Berlin Competence Centre for Water are closely related to Veolia, a large French water corporation

Figure 5: Core coherent subsystem in MBR knowledge creation, 2003-2007



Source: Data from ISI web of knowledge, visualized with NetMiner 3 software. Node size depends on the number of publications.

Dense interaction now gets dominant especially inside the European Union, whereas the USA and Canada become the most disconnected region with a high number of single authored papers and correspondingly isolated actors (Appendix C). The actor base in Asia in contrast is expanding quickly and relevant cooperation forms especially among and between South Korean, Chinese and Japanese actors. In addition, many small components now appear, mainly connecting European and/or Asian actors. Knowledge creation as a whole is thus fragmenting into a main coherent subsystem and several isolated components in different regions of the world.

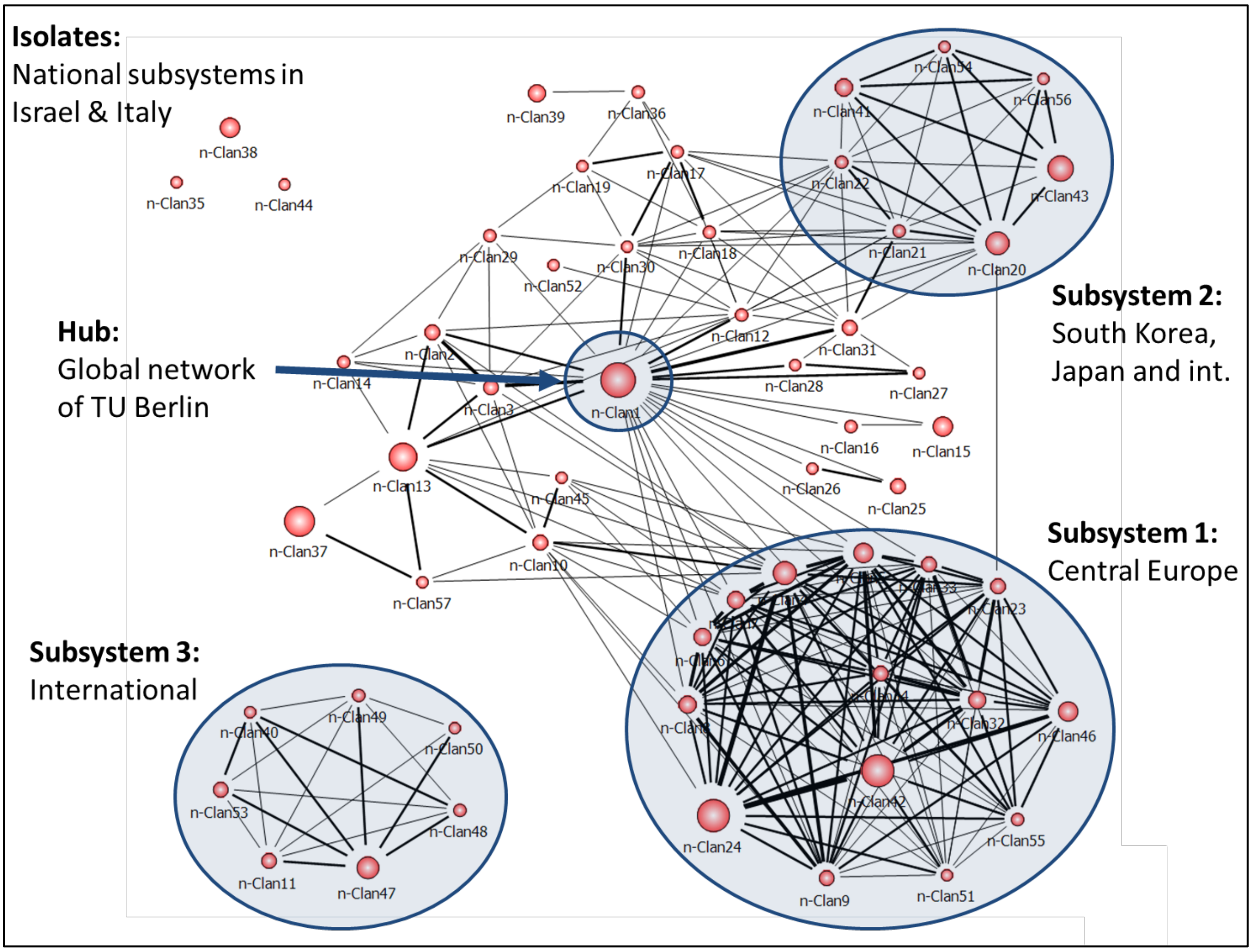
Comparing the results of the nurturing and the expansion phase reveals that the overall spatial setup and the composition of the most central actors in knowledge creation have switched considerably over a short period of time. Actors from Germany as an example occupied a rather peripheral position in the network until 2003 but quickly moved to a central position between 2003 and 2007. The core coherent subsystem furthermore changed qualitatively from a global, company-dominated mode to a more trans-disciplinary mode, now connecting seven universities, five companies, five research institutes, three government organizations and one company research institute mainly inside Europe.

This major spatial shift very likely reflects activities induced by MBR research programs of the European Union (Lesjean and Huisjes, 2008). Because European actors were increasingly lagging behind in the MBR field, a new relevant level of interaction was constructed in four large research initiatives of the 6th European framework program. These comprehensive projects were not only aimed at creating scientific knowledge, but also inducing entrepreneurial experimentation, guidance on the search and connecting different actors in a series of international conferences. The relative decline of the activities of transnational companies in knowledge creation might accordingly be explainable with the fact that they increasingly focused on internal optimization of their MBR technology and left more basic R&D activities to smaller actors in an increasingly vibrant surrounding technological innovation system in that second phase.

4.4 2007-2009: Multi-scalar knowledge creation between Europe and Asia

In the last phase of development, cooperation intensifies in an increasingly consolidating environment. Most actors are now included in a giant network component, connecting 340 nodes. Section 4.1 described this phase as a multi-scalar to globalized setup with 57 2-clans. The high number of frequently overlapping 2-clans (see Figure 6) now allows differentiating different coherent subsystems. First of all, a coherent subsystem with strongly overlapping 2-clans exists in central Europe, dominated by actors from German speaking countries. Secondly, a new subsystem now evolves in Asia, dominated by South Korean and Japanese actors in connection to international partners. Thirdly, a relevant subsystem is forming in an international network between European, Asian and North American actors, largely disconnected from the other coherent subsystems. Finally, also the national scale now contains a significant number of isolated subsystems, e.g. in Israel and Italy.

Figure 6: 2-Clan overlap in MBR technology knowledge creation, 2007-2009

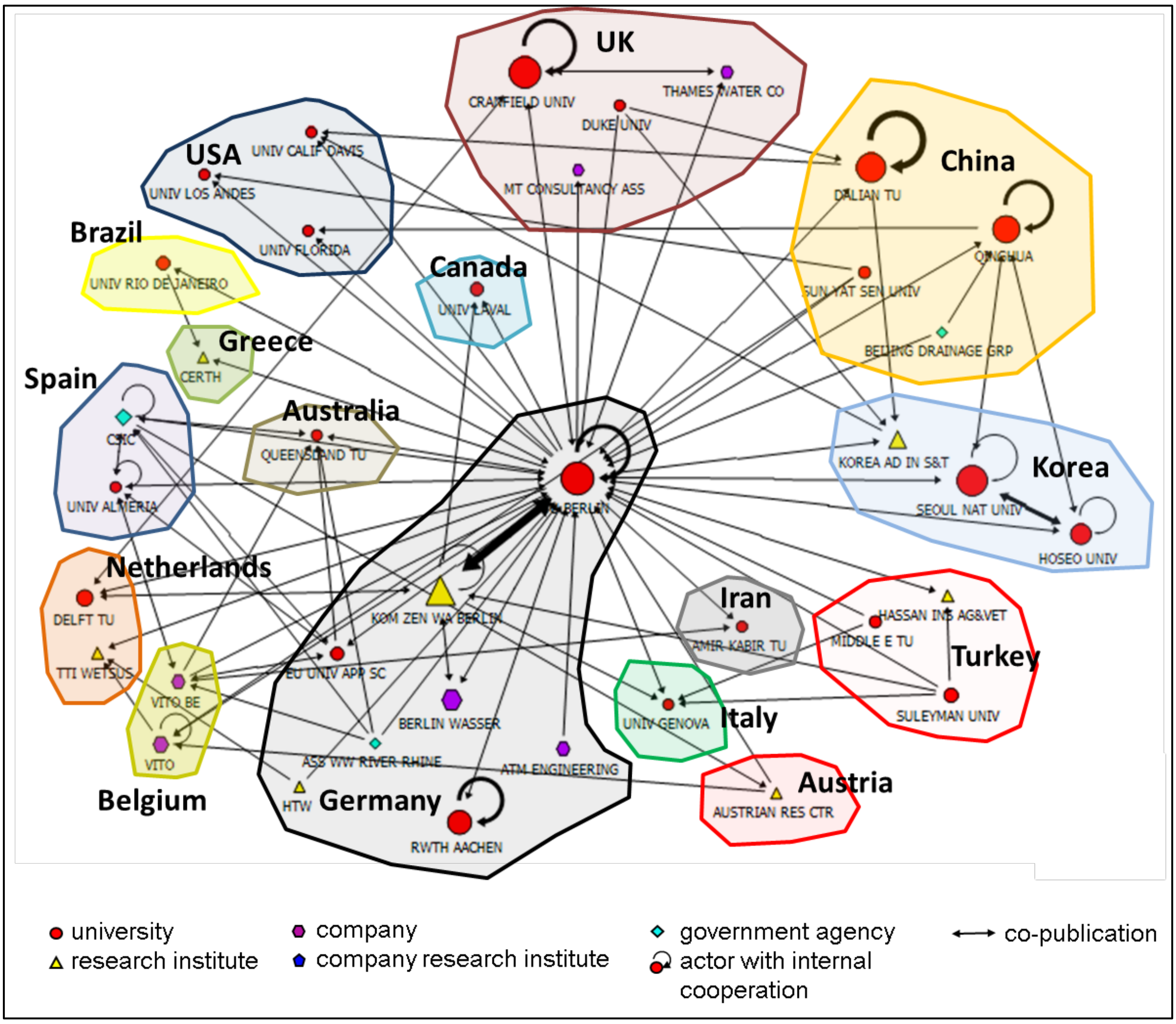


Source: data from ISI web of knowledge, visualized with NetMiner 3 software. Node size depends on number of actors in 2-clans, line thickness on number of overlapping actors, threshold value of links: 6.

Overall, the network takes on increasing small world properties with most 2-clans showing considerable overlap. Especially the subsystems in Europe and Asia are strongly coupled to each other through a major 2-clan containing 38 actors centred on TU Berlin (Figure 7).

This ‘hub’ perfectly exemplifies the importance of multi-scalar interaction in knowledge creation of MBR technology in that phase: On the one hand, innovation in this hub exhibits a global dimension, connecting actors from 16 countries and 5 continents. On the other hand, cooperation inside the European Union is the core level of activity (more than half of the actors are located in EU member states). Finally, cooperation among 8 actors at a national level in Germany (and dominantly in Berlin) is present in the structure, too. Innovative activity of German actors like the TU Berlin can accordingly not be solely attributed to the specific context constituted at a national scale. It rather has to be interpreted as the outcome of multiple relations established concomitantly at different scales and at the intersection between two coherent subsystems of a wider global TIS.

Figure 7: Central hub in MBR technology knowledge creation, 2007-2009



Source: data from ISI web of knowledge, visualized with NetMiner 3 software. The most central actor in the core of the 2-clan is the Technical University Berlin.

Summarizing, in the consolidation phase, the spatial setup of knowledge creation again differs considerably from the precedent phase and gets increasingly complex: International, continental and national scales now all contain relevant coherent subsystems, with the core of activity still in Europe, but increasingly shifting towards Asia and getting more integrated at a global level. This last switch likely reflects the increasing maturation of the TIS and the formation of an increasingly well-structured research and development community around MBR technology, which turns the underlying knowledge networks more and more into a globalized small world setup. Still, spatial imbalances in the global distribution of activity are much accentuated: Concentrated innovation efforts of Asian actors, especially in South Korea, Japan and China (Zheng et al., 2010), increasingly establish a relevant scale of interaction also in this part of the world. North American actors, in contrast, are still underrepresented in the most relevant subsystems of knowledge creation. This finding corresponds with empirical studies claiming that North American actors are partly decoupled from mainstream research activities and following a distinct technology development path focussing on side-stream MBR systems (Wang et al., 2008).

4.5 Discussion

Two main findings stand out from the observed strong spatial dynamics in knowledge creation of MBR technology. First, our results indicate that TIS function's underlying actor networks can shift considerably in space and that innovation processes in national (sub-)systems might be more strongly interconnected and influenced by a 'global TIS' level than could be assumed from existing studies. We thus support arguments from economic geographers and innovation system scholars that innovation (system) research should explore multi-scalar processes and especially the global scale in much more detail (Bunnell and Coe, 2001; Carlsson, 2006).

Secondly, the presented case study illustrates how assessing the spatial setup of functions can improve the understanding of innovation processes in a TIS. Knowledge created in networks spanning transnational companies and their research partners (as in the nursing phase of MBR technology) is clearly of a different quality than knowledge created in small world networks connecting different trans-disciplinary subsystems in a multi-scalar setup (as in the consolidation phase of MBR technology). Also the dominant level of the core coherent subsystems may shift in space. Policy interventions to sustain system buildup in specific countries should thus be responsive to (and try to anticipate) the shifts in the spatial configuration of core subsystems of a TIS.

A further direct added value of this framework is that it allows identifying spatial errors that might be incorporated in nationally delimited TIS studies (see Binz and Truffer, 2012). Firstly, in a TIS with functions dominated by localized interaction (setup i and iii in Figure 1), 'isolation errors' might occur: A study in a single country would only inform about innovation in one specific subsystem of the overall TIS. Decisive technological advances might however develop independently in another subsystem without the TIS analyst taking note. In the case of MBR technology, focusing on the USA, whose actors were in most phases of TIS evolution relatively decoupled from a dynamic international knowledge network, would likely have produced such isolation errors. Secondly, in multi-scalar or globalized setups (Figure 1 v and vi), errors of ‘omitted context’ might be conducted; a national case study would likely overestimate the importance of processes working at national to subnational scales. Developments stemming from outside could falsely be attributed to developments inside the focal subsystem and thereby again lead to inefficient policy advice. Internationalized TIS setups, finally (Figure 1 iv), could induce ‘system misinterpretation errors’. Here, innovation predominantly stems from activities embedded in international networks. National delimitations would accordingly lead to a complete misinterpretation of the most relevant level of innovative activity. In the case of MBR technology, doing nationally delimited TIS studies in the nurturing phase would arguably have produced this type of errors: As the central knowledge creating subsystem was dominated by globally operating companies at that time, nationally delimited studies would arguably not have identified the core actors and spatial level of this technology’s development.

Some limitations of the presented results also have to be mentioned here: First, we could only scrutinize one function in more detail and, secondly, left institutional contexts underexplored. To address the first issue, one could analyze the other functions of the MBR TIS with the same framework (following the suggestions of section 2.3) and try to identify overlaps between coherent subsystems in different functions. Places and scales where subsystems of different functions overlap could then be interpreted as the innovative core of a TIS at a given point in time and theories could be developed on how and why this core moves in space. In contrast, if only few overlaps between coherent subsystems in different functions of the same TIS exist, then the TIS in focus would have to be understood as a conglomerate of spatially dispersed functional dynamics, a finding that would strongly contradict existing TIS studies. Finally, as system functions are inherently interrelated, identifying the core actors and coherent subsystems of one function could be used for predicting the probability of activities in other functions emerging in the same place. Knowledge spillover theory of entrepreneurship as an example suggests that entrepreneurial activities emerge in close spatial proximity to the core knowledge creating subsystem of a TIS (Audretsch and Lehmann, 2005).

Considering the missing focus on institutional contexts, empirically identifying innovative cores of a TIS could also allow reconstructing to some degree which institutional settings in which places have been crucial for system development at specific points in time. In the case of MBR technology, institutional contexts of the EU were identified as being of key importance to foster knowledge creation also in other parts of the global TIS. However, the fundamental question on whether actor networks shape institutional contexts or vice versa could not be addressed here and clearly needs focused elaboration in future work.

Finally, our approach also leaves ample room for methodological improvements and the exploitation of new data sources. The observed high importance of international linkage in all development phases of knowledge creation in MBR technology might be partially attributable to the bias of publications from ISI web of knowledge towards research in international projects and published in international journals (Nelson, 2009). For a more balanced view, other case studies would have to integrate additional data types like patents or licenses, publications from non-ISI journals or other relational data from industry associations or conferences. SNA methodology also offers plentiful additional heuristic routines that might be fruitfully exploited for assessing network evolution over time and identifying cohesive subsystems.

5 Conclusions

This paper aimed at discussing the implications of the spatially implicit system boundary setting in current TIS studies and at illustrating how a spatialized TIS framework could contribute to empirically identifying meaningful system boundaries and analyzing linkages and relationships between its (territorial) subsystems. As shown in the literature review, adding relational space to TIS and functional TIS analysis is a promising way forward for improving conceptual rigor, empirical application and the policy advice derived from this conceptual approach. Mapping the global (yet uneven) TIS helps clarifying how national sub-TIS are related to each other and how specific spaces in the TIS might generate comparative advantage. The empirical case study indicates that knowledge creation in MBR technology happened in a global company-based, a science-driven Europe-centred, as well as in a multi-scalar Europe- and Asia based spatial setup. As national subsystems are embedded differently in each of these setups, nationally delimited studies would have to be adapted accordingly.

TIS space is thus fluent and innovation processes can change quickly both in spatial reach and nature.

Apart from showing where and when specific innovations develop and diffuse, a more explicit spatial perspective also sheds light on how innovation processes might interrelate between seemingly unrelated places. The MBR example shows that networks transcending national borders might be more relevant for innovation processes in TIS than has been acknowledged in previous studies. The ‘global technological opportunity set’ should accordingly not be understood as a ubiquitous resource for TIS actors. It rather has to be characterized as an uneven and dynamically evolving network structure to which actors with different relational positions and capabilities have differential access at different points in time. We thus argue in line with Carlsson (2006) that this scale needs more attention in future conceptual, empirical and especially methodological work.

The presented results also imply a central lesson for policy making: Innovation or industrial policy, for instance in the form of subsidies for specific technologies, have to consider the global spatial setup of a technological field (see Truffer, 2012). National support of specific technologies may otherwise lead to unintended effects like supporting industry growth in other countries (as exemplified by the impact of feed-in tariffs for photovoltaics in Germany, which strongly supported the growth of Chinese at the expense of German companies). Also in the specific case of knowledge creation, policy interventions are often predominantly targeting processes at a national level even though knowledge production increasingly takes place in complex international networks. Supporting couplings between national actors and their international TIS environment has accordingly been underrated as a policy option.

Future TIS research could be inspired by this contribution in two ways: Firstly, our framework could be used for spatially sensitive studies of other TIS functions, which could in turn improve the generalizability and explanatory power of the approach. Secondly, respective studies could feed into a spatialized TIS lifecycle theory. Understanding which spatial scales are relevant in what fields of technology and at what phase of system development could generate important input for improving TIS-based theory development and policy advice. Finally, our study just covers one illustrative case in water recycling technology. Similar studies in other technological fields are needed to further validate and improve the proposed framework.

Acknowledgements

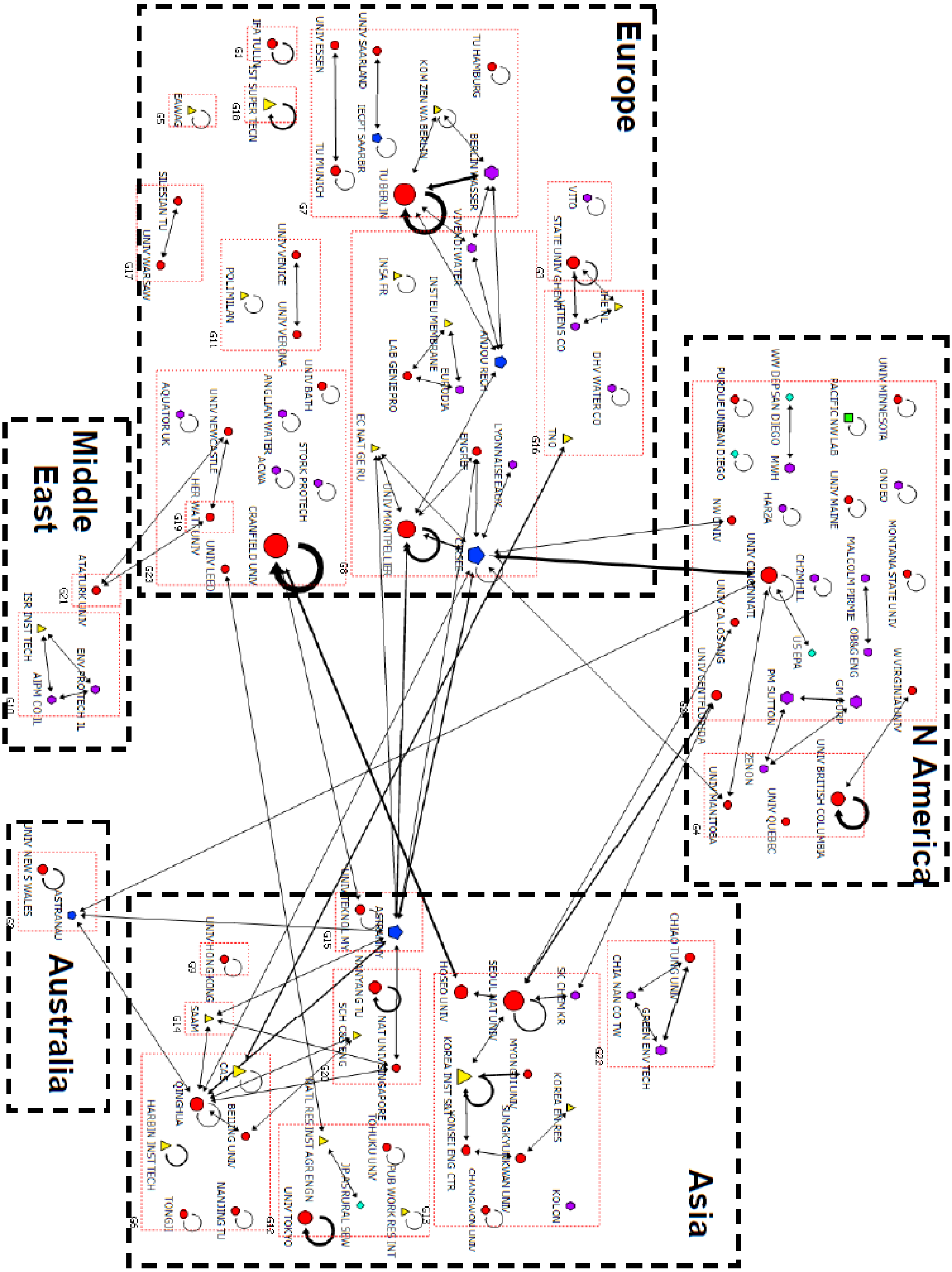
The authors would like to thank the Sino-Swiss Science and Technology Cooperation (SSSTC) for the funding of this project. Part of the work was conducted while one of the authors (B. Truffer) was a fellow in the sustainability Science Program at Harvard University. This paper profited from constructive input at the AAG annual meeting 2010, a DIME workshop 2010, the GLOBELICS conference 2010 and a TIS summer school in 2011. We would especially like to thank Karin Ingold, Frans Berkhout, Staffan Jacobsson, Philip Leifeld and Koen Frenken for very helpful inputs on earlier drafts. Finally, we would like to thank two anonymous reviewers for their extraordinarily constructive inputs to this paper.

Appendix

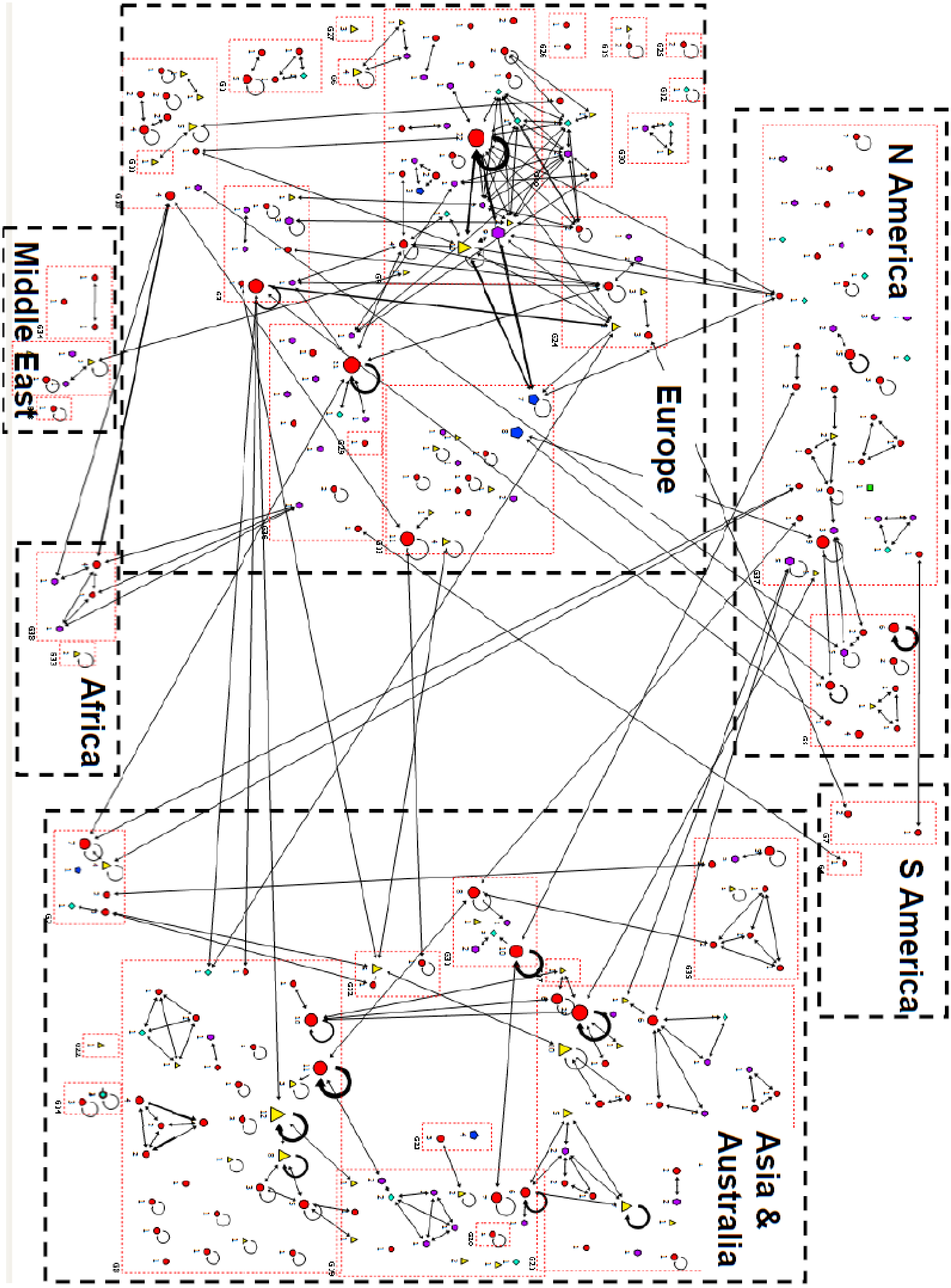
Appendix A: SNA indicators for network characterization

Indicator	**Definition**
Mean distance	Mean distance measures the average geodesic distance (shortest paths) between any pair of nodes in a network
Network diameter	Diameter describes the largest geodesic distance between any pair of nodes in a network. This indicator thus measures how many intermediaries a piece of information has to pass in order to travel on the shortest possible path between the two most distant actors in the network.
Centralization index	Index of variability of individual centrality scores. The most centralized network is a star network, where one actor has direct access to every other actor, the least centralized a circle network, where every actor has only access to two neighbors and thus all actors possess identical centrality

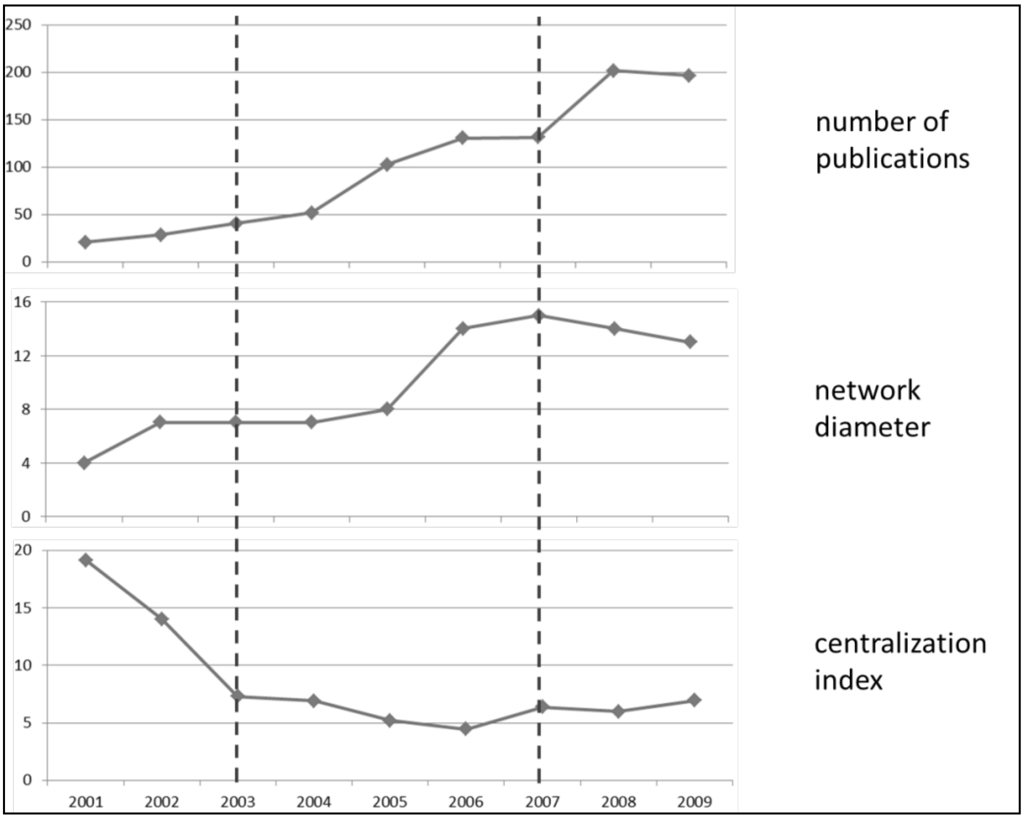
Appendix A: Knowledge creation of MBR technology 1993-2003



Appendix C: Knowledge creation of MBR technology 2003-2007



Appendix D: Identifying three phases of network evolution



Note that the data point in 2001 comprises the cumulated network data from 1993-2001

References

Amin, A., 2002. Spatialities of globalisation. Environment and Planning A 34, 385-399.

Amin, A., Roberts, J., 2008. Knowing in action: Beyond communities of practice. Research Policy 37 (2), 353-369.

Asheim, B., Coenen, L., 2006. Contextualising Regional Innovation Systems in a Globalising Learning Economy: On Knowledge Bases and Institutional Frameworks. Journal of Technology Transfer 31, 163-173.

Asheim, B.T., Gertler, M.S., 2005. The Geography of Innovation: Regional Innovation Systems. In: Fagerberg, J., Mowery, D., Nelson, R. (Eds.), The Oxford Handbook of Innovation. Oxford University Press, Oxford, pp. 291-317.

Audretsch, D.B., Lehmann, E.E., 2005. Does the Knowledge Spillover Theory of Entrepreneurship hold for regions? Research Policy 34 (8), 1191-1202.

Avdeitchikova, S., 2012. The geographic organization of ‚venture capital‘ and ‚business angles‘. In: Landström, H., Mason, C. (Eds.), Handbook of Research on Venture Capital: Volume 2. Edward Elgar, Cheltenham, UK, pp. 175-208.

Bathelt, H., Malmberg, A., Maskell, P., 2004. Clusters and knowledge: local buzz, global pipelines and the process of knowledge creation. Progress in Human Geography 28 (1), 31-56.

Bathelt, H., Schuldt, N., 2008. Between luminaires and meat grinders: International trade fairs as temporary clusters. Regional Studies 42 (6), 853-868.

Bathelt, H., Gluckler, J., 2003. Toward a relational economic geography. Journal of Economic Geography 3 (2), 117-144.

Bergek, A., Jacobsson, S., Carlsson, B., Lindmark, S., Rickne, A., 2008a. Analyzing the functional dynamics of technological innovation systems: A scheme of analysis. Research Policy 37 (3), 407-429.

Bergek, A., Jacobsson, S., Sandén, B.A., 2008b. 'Legitimation' and 'development of positive externalities': Two key processes in the formation phase of technological innovation systems. Technology Analysis and Strategic Management 20 (5), 575-592.

Bergek, A., Jacobsson, S., 2003. The Emergence of a Growth Industry: A Comparative Analysis of the German, Dutch and Swedish Wind Turbine Industries. In: Metcalfe, J.S., Cantner, U. (Eds.), Change, Transformation and Development. Physica-Verlag (Springer), Heidelberg, pp. 197-228.

Berkhout, F., Angel, D., Wieczorek, A., 2009. Sustainability transitions in developing Asia: Are alternative development pathways likely? Technological Forecasting & Social Change 76 (2), 215-217.

Binz, C., Truffer, B., 2012. Technological innovation systems in multiscalar space. Analyzing an emerging water recycling industry with social network analysis. Geographica Helvetica 66 (4), 254-260.

Binz, C., Truffer, B., Li, L., Shi, Y., Lu, Y., 2012. Prospective analysis of leapfrogging trajectories – An analytical framework and a case study in the Chinese wastewater sector. Technological Forecasting and Social Change 79 (1), 155-171.

Boggs, J.S., Rantisi, N.M., 2003. The relational turn in economic geography. Journal of Economic Geography 3, 109-116.

Brenner, T., Cantner, U., Fornahl, D., Fromhold-Eisebith, M., Werker, C., 2011. Regional innovation systems, clusters, and knowledge networking. Papers in Regional Science 90 (2), 243-249.

Bunnell, T.G., Coe, N.M., 2001. Spaces and scales of innovation. Progress in Human Geography 25 (4), 569-589.

Carlsson, B., 1997a. Technological systems and industrial dynamics. Springer, Boston.

Carlsson, B., 1997b. On and off the beaten path: the evolution of four technological systems in Sweden. International Journal of Industrial Organization 15 (6), 775-799.

Carlsson, B., 2006. Internationalization of innovation systems: A survey of the literature. Research Policy 35 (1), 56-67.

Carlsson, B., Stankiewicz, R., 1991. On the nature, function and composition of technological systems. Journal of Evolutionary Economics 1 (2), 93-118.

Chaminade, C., Vang, J., 2008. Globalisation of knowledge production and regional innovation policy: Supporting specialized hubs in the Bangalore software industry. Research Policy 37 (10), 1684-1696.

Coe, N.M., Hess, M., Yeung, H.W., Dicken, P., Henderson, J., 2004. Globalizing regional development: a global production networks perspective. Transactions of the Institute of British Geographers 29 (4), 468-484.

Coe, N.M., Bunnell, T.G., 2003. 'Spatializing' knowledge communities: towards a conceptualization of transnational innovation networks. Global Networks 3 (4), 437-456.

Coenen, L., Benneworth, P., Truffer, B., 2012. Toward a spatial perspective on sustainability transitions. Research Policy 41 (6), 968-979.

Coenen, L., Díaz López, F.J., 2010. Comparing systems approaches to innovation and technological change for sustainable and competitive economies: an explorative study into conceptual commonalities, differences and complementarities. Journal of Cleaner Production 18 (12), 1149-1160.

Cooke, P., 2005. Regionally asymmetric knowledge capabilities and open innovation: Exploring ‘Globalisation 2’—A new model of industry organisation. Research Policy, 34 (8), 1128-1149.

Cooke, P., Gomez Uranga, M., Etxebarria, G., 1997. Regional innovation systems: Institutional and organisational dimensions. Research Policy 26 (4-5), 475-491.

Crevoisier, O., Jeannerat, H., 2009. Territorial knowledge dynamics: From the proximity paradigm to multi-location milieus. European Planning Studies 17 (8), 1223-1241.

de la Tour, A., Glachant, M., Ménière, Y., 2011. Innovation and international technology transfer: The case of the Chinese photovoltaic industry. Energy Policy 39 (2), 761-770.

De Wilde, W., Richard, M., Lesjean, B., Tazi-Pain, A., 2008. Towards standardisation of the MBR technology? Desalination 231 (1-3), 156-165.

Dewald, U., Truffer, B., 2012. The Local Sources of Market Formation: explaining regional growth differentials in German photovoltaic markets. European Planning Studies (3), 397-420.

Drori, I., Honig, B., Wright, M., 2009. Transnational entrepreneurship: An emergent field of study. Entrepreneurship: Theory and Practice 33 (5), 1001-1022.

Fane, A.G., Fane, S.A., 2005. The role of membrane technology in sustainable decentralized wastewater systems. Water Science and Technology 51 (10), 317-325.

Fisher, D.R., Leifeld, P., Iwaki, Y., 2012. Mapping the ideological networks of American climate politics. Climatic Change, 1-23.

Fleming, L., King, C., Juda, A.I., 2007. Small worlds and regional innovation. Organization Science 18 (6), 938-954.

Freeman, C., 1987. Technology and economic performance: lessons from Japan. Pinter, London.

Garud, R., Karnoe, P., 2003. Bricolage versus breakthrough: distributed and embedded agency in technology entrepreneurship. Research Policy 32 (2), 277-300.

Gertler, M.S., 2003. Tacit knowledge and the economic geography of context, or The undefinable tacitness of being (there). Journal of Economic Geography 3 (1), 75-99.

Glückler, J., 2007. Economic geography and the evolution of networks. Journal of Economic Geography 7 (5), 619-634.

Gosens, J., Lu, Y., Coenen, L., submitted. Clean-tech Innovation in Emerging Economies: Transnational Dimensions in Technological Innovation System Formation. Technological Forecasting & Social Change.

Hekkert, M., Suurs, R., Negro, S., Kuhlmann, S., Smits, R., 2007. Functions of innovation systems: A new approach for analysing technological change. Technological Forecasting and Social Change 74 (4), 413-432.

Jacobsson, S., Bergek, A., 2011. Innovation system analyses and sustainability transitions: Contributions and suggestions for research. Environmental Innovation and Societal Transitions 1 (1), 41-57.

Judd, S., Judd, C., 2006. The MBR book. Elsevier, Oxford.

Kastelle, T., Steen, J., 2010. Using network analysis to understand innovation. Innovation: Management, Policy and Practice 12, 2-4.

Katz, J.S., Martin, B.R., 1997. What is research collaboration? Research Policy 26 (1), 1-18.

Kemp, R., Schot, J., Hoogma, R., 1998. Regime Shifts to Sustainability Through Processes of Niche Formation: The Approach of Strategic Niche Management. Technology Analysis & Strategic Management 10 (2), 175-195.

Konrad, K., Markard, J., Ruef, A., Truffer, B., 2012. Strategic response to hype and disappointment: the case of stationary fuel cells. Technological Forecasting & Social Change 79, 1084-1098.

Krackhardt, D., Stern, R.N., 1988. Informal Networks and Organizational Crises: An experimental simulation. Social Psychology Quarterly 51 (2), 123-140.

Lagendijk, A., Lorentzen, A., 2007. Proximity, knowledge and innovation in peripheral regions. On the intersection between geographical and organizational proximity. European Planning Studies 15 (4), 457-466.

Lesjean, B., Huisjes, E.H., 2008. Survey of the European MBR market: trends and perspectives. Desalination 231 (1-3), 71-81.

Lundvall, B., 1992. National Systems of Innovation - toward a Theory of Innovation and Interactive Learning. Pinter, London.

Markard, J., Raven, R., Truffer, B., 2012. Sustainability transitions: An emerging field of research and its prospects. Research Policy 41 (6), 955-967.

Markard, J., Truffer, B., 2008. Technological innovation systems and the multi-level perspective: Towards an integrated framework. Research Policy 37, 596-615.

Maskell, P., Malmberg, A., 1999. The competitiveness of firms and regions. 'Ubiquitification' and the importance of localized learning. European Urban and Regional Studies 6 (1), 9-25.

Musiolik, J., Markard, J., 2011. Creating and shaping innovation systems: Formal networks in the innovation system for stationary fuel cells in Germany. Energy Policy 39, 1909-1922.

Musiolik, J., Markard, J., Hekkert, M., 2012. Networks and network resources in technological innovation systems: Towards a conceptual framework for system building. Technological Forecasting and Social Change 79 (6), 1032-1048.

Nelson, A.J., 2009. Measuring knowledge spillovers: What patents, licenses and publications reveal about innovation diffusion. Research Policy 38 (6), 994-1005.

Nelson, R., 1993. National Innovation Systems: A Comparative Analysis. Oxford University Press, New York.

Saxenian, A., 2007. The new argonauts: Regional advantage in a Global Economy. Harvard University Press, Boston, MA.

Stam, E., 2010. Entrepreneurship, evolution and geography. In: Boschma, R., Martin, R. (Eds.), The handbook of evolutionary economic geography. Edward Elgar, Cheltenham, UK, pp. 139-161.

Ter Wal, A.L.J., Boschma, R.A., 2009. Applying social network analysis in economic geography: Framing some key analytic issues. Annals of Regional Science 43 (3), 739-756.

Tödtling, F., Trippl, M., 2005. One size fits all? Towards a differentiated regional innovation policy approach. Research Policy 34 (8), 1203-1219.

Truffer, B., 2012. The need for a global perspective on sustainability transitions. Environmental Development 3, 182-183.

Truffer, B., Binz, C., Gebauer, H., Störmer, E., 2012. Market success of on-site treatment: a systemic innovation problem. In: Larsen, T., Udert, K., Lienert, J. (Eds.), Wastewater Treatment: Source Separation and Decentralisation. IWA Publishing, London, pp. 209-223.

van Lente, H., Rip, A., 1998. The Rise of Membrane Technology: From Rhetorics to Social Reality. Social Studies of Science 28 (2), 221-254.

Wang, Z., Wu, Z., Mai, S., Yang, C., Wang, X., An, Y., Zhou, Z., 2008. Research and applications of membrane bioreactors in China: Progress and prospect. Separation and Purification Technology 62 (2), 249-263.

Wasserman, S., Faust, K., 1994. Social Network Analysis: Methods and Applications. Cambridge University Press, Cambridge, UK.

Watts, D.J., Strogatz, S.H., 1998. Collective dynamics of 'small-world' networks. Nature 393 (6684), 440-442.

Wenger, E., 1998. Communities of practice - Learning, meaning, and identity. Cambridge University Press, Cambridge, UK.

Yeung, H.W., 2005. Rethinking relational economic geography. Transactions of the Institute of British Geographers 30 (1), 37-51.

Zheng, X., Zhou, Y., Chen, S., Zheng, H., Zhou, C., 2010. Survey of MBR market: Trends and perspectives in China. Desalination 250, 609-612.