The Triple Helix in the context of global change: dynamics and challenges

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Understanding how economies change through the interactions with science and governance as different spheres of activity requires both new conceptual tools and methodologies. In this paper the evolution of the metaphor of a Triple Helix (TH) of university-industry-government relations is elaborated into an evolutionary model, and positioned within the context of global economic changes. We highlight how triple-helix relations are both continuing and mutating or changing, and the conditions under which a Triple Helix might be seen to be unraveling in the face of pressures on each of the three helices – university, industry, and government. The reciprocal dynamics of innovation both in the Triple Helix thesis and in the global economy are empirically explored: we find that "footloose-ness" of high-tech manufacturing and knowledge-intensive services counteract upon "embedded-ness" prevailing in medium-tech manufacturing. The geographical level at which synergy in TH-relations can be expected and sustained varies among nations and regions.

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Introduction

The Triple Helix thesis emerged in the mid-1990s, a time when universities and industry were exhorted by policy makers to work together more closely for the benefit of society resulting from the commercialisation of new knowledge (see, for example, Branscomb, 1993; Fujise, 1998). The thesis became articulated as a confluence between Henry Etzkowitz' long-term interest in the study of university-industry relations and Loet Leydesdorff's interest in an evolutionary model in which there is a reflexive overlay of communications between different and independent spheres of activity. The first paper, Etzkowitz & Leydesdorff (1995), "The Triple Helix---University-Industry-Government Relations: A Laboratory for Knowledge-Based Economic Development" came about after Etzkowitz' (1994) participation in a workshop in Amsterdam and an ensuing volume, entitled *Evolutionary Economics and Chaos Theory: New Directions in Technology Studies* (Leydesdorff & Van den Besselaar 1994).

The metaphor of a Triple Helix emerged thereafter in discussions about organizing a follow-up conference under this title in Amsterdam in January 1996.[1] Since then, Etzkowitz & Leydesdorff (2000) further elaborated the Triple Helix of University-Industry-Government Relations into a model for studying both knowledge-based and developing economies. Over time, this model has evolved, been re-interpreted, and critiqued (e.g., Shinn, 2002, Carayannis & Campbell, 2009; Cooke & Leydesdorff, 2006; Lawton Smith & Ho, 2006). In this paper, the objective is to position the dynamics and evolution of university-industry-government relations (TH) within the context of challenges facing the global economy—unemployment, low or no growth, spiraling healthcare needs, rapidly emerging digital business models, unsustainable changes to the environment, and both coordinated and uncoordinated regulatory systems.

In this context, the analysis is concerned with where the model's basic elements continue in practice and as a policy agenda. We further consider the conditions under which the original elements of the model have become distorted through political and competitive pressures. Have the pressures on the individual components forced them apart? Underpinning all of these is the key question: How can the Triple Helix approach contribute to the understanding of what exists in terms of institutional relations and what is known in terms of mechanisms in order to provide the specification of 'an

[1] Precursors of using this metaphor can be found in Lowe (1982) and Sabato (1975). Lewontin (2000) uses the same metaphor in a biological context.

enterprising state' in which universities, businesses, and governments can co-innovate to solve global economic challenges?

Following from this, the crucial issues are those of: under which conditions can the three functions—wealth generation, organized knowledge production, and normative control—operate synergistically, to what extent or at which level, and at what price? In order to answer the questions by exploring these issues, we first turn to the model to examine its evolution and consider how it might continue to mutate and/or to unravel as the three spheres are under increasing pressures from global changes. We consider the three functional dynamics—wealth generation, governance, and novelty production—as further heuristics in the application of a Triple Helix model in theory and in practice.

The model, its different versions, and its evolution

The Triple Helix model of university-industry-government relations is depicted in Figure 1 as alternating between bilateral and trilateral coordination spheres of activity. The relationships between them remain in transition because each of the partners develops also its own (differentiating) mission. Thus, a trade-off can be generated between integration and differentiation as possible synergies can be explored and potentially shaped. The form these relationships take, their drivers and outcomes are a reflection of context-dependent forces and agendas.

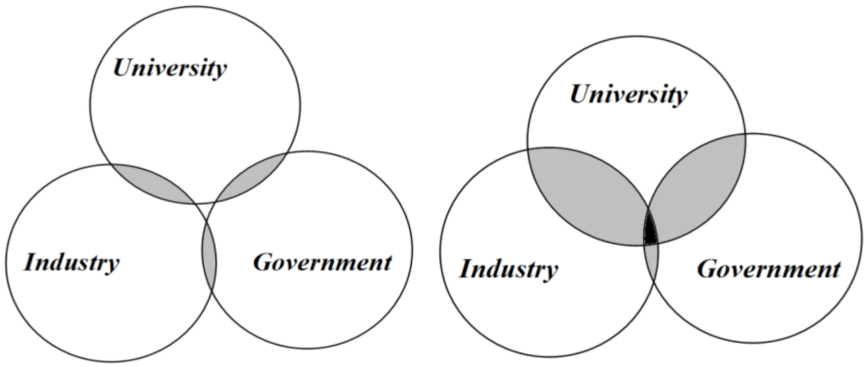

Figure 1: A Triple Helix configuration with negative and positive overlap among the three subsystems.

The Triple Helix (TH) model can be considered as an empirical heuristics which uses as *explanantes* not only economic forces (e.g., Schumpeter, 1939; Nelson & Winter, 1982), and legislation and regulation by regional or national governments (e.g., Freeman, 1987; Freeman & Perez, 1988), but also the endogenised dynamics of transformations by science-based inventions and innovations (Noble, 1977; Whitley, 1984). The TH model does not exclude focusing on two of the three dynamics—for example, in studies of university-industry relations (Clarke, 1998; Etzkowitz, 2002) or as in the "variety of capitalism" tradition (Hall & Soskice, 2001)—but the third dynamics of organized knowledge production should at least be declared as another source of variation (e.g., Carayannis, Alexander, & Ioannidis, 2000).

TH models can be elaborated in various directions (Meyer *et al*., 2014). Firstly, the networks of university-industry-government relations can be considered as neo-institutional arrangements which can be made the subject of social network analysis (e.g., Owen-Smith *et al*., 2002; Powell *et al*., 2005). This model can also be used for policy advice about network development, for example in the case of transfer of knowledge ("brokerage") or the incubation of new industry. The new and potentially salient roles of universities in knowledge-based configurations have been explored in terms of different sectors, countries, and regions (Godin & Gingras, 2000; Shinn, 2002). Over the past decade or so, this neo-institutional model has also been developed into a discourse about "entrepreneurial universities" (Clark, 1998; Etzkowitz, 2002, 2008; Mirowski & Sent, 2007). Regions ("regional triple helix spaces," Etkowitz 2002) are then considered as endowed with universities that can be optimized for the third mission as an incentive additional to higher education and internationally oriented research (e.g., Venditti *et al*., 2013).

Secondly, the networks of *relations* span an architecture in which each relation occupies a *position*. One can thus obtain a systems perspective on knowledge-based innovations in a hypothesized function space; this theoretical construct—the knowledge-based economy—can also be informed by systematic observations and data analysis (e.g., Leydesdorff & Fritsch, 2006; Strand & Leydesdorff, 2013). The distinction between relations and positions—as a consequence of patterns of relations—has important methodological consequences (Burt, 1984): positions are structural and defined with reference to flows and selection environments, whereas relations are instantaneous, hierarchical, and local. An action-oriented TH-model will tend to focus on relations, whereas a systems-oriented one focuses on the structural conditions of innovation.

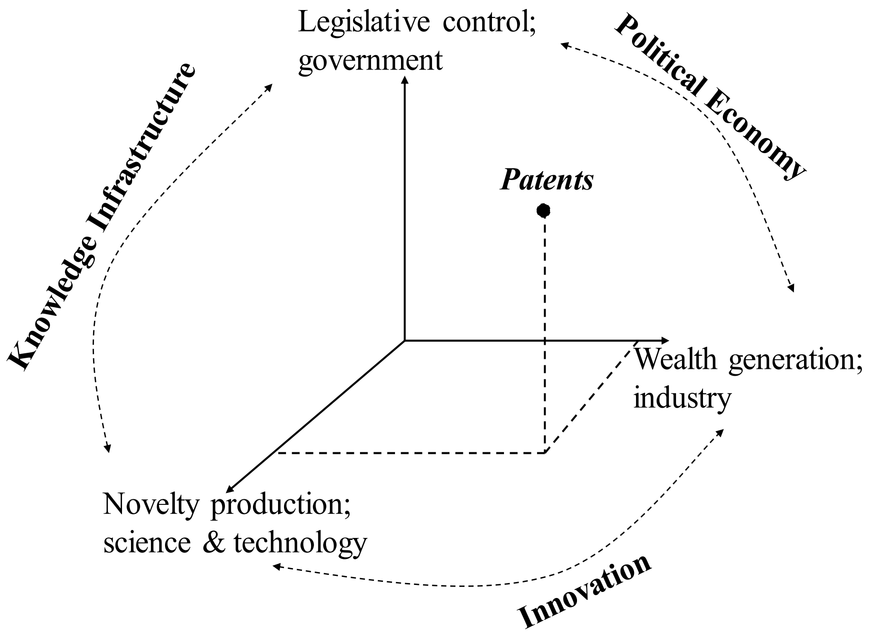

Figure 2: Patents as events in the three-dimensional space of Triple Helix interactions. (Source: Leydesdorff, 2010, at p. 370.)

For example, patents can be considered as positioned in terms of the three social coordination mechanisms of (1) wealth generation on the market by industry, (2) legislative control by government, and (3) novelty production in academia (Figure 2). Not only patents, but also university-industry relations can be considered as events in this space. Whereas patents can be used as output indicators for science and technology, they function as inputs into the economy. Their main function, however, is to provide legal protection for intellectual property. Transfer offices—a second example—can be generated in response to national policies, and be evaluated in terms of what they mean for industry or science.

In other words, relations and events in a knowledge-based economy can be positioned in this three-dimensional space of industry, government, and academia (e.g., Petruzzelli, 2011). Since patents can also circulate among the partners, three-way interaction effects can also be expected. The knowledge-based economy contributes to the political economy by endogenizing the social organization of knowledge as R&D into a three (or more) dimensional system's dynamics (e.g., Dangelico *et al*., 2010). Unlike a two-dimensional dynamic such as between economic exchanges and political regulation, a three-dimensional dynamic cannot be expected to return to equilibrium (Ivanova & Leydesdorff, 2013; Nelson & Winter, 1982).

The three functions in Figure 2 can also be considered as interaction terms among relational exchange processes (e.g., in an economy), political positions in a bordered unit of analysis (e.g., a nation), and the reflexive and transformative dynamics of knowledge. When these interaction terms exhibit second-order interactions, a knowledge-based economy can increasingly be expected to operate (Figure3; cf. Foray, 2004; Leydesdorff, 2006).

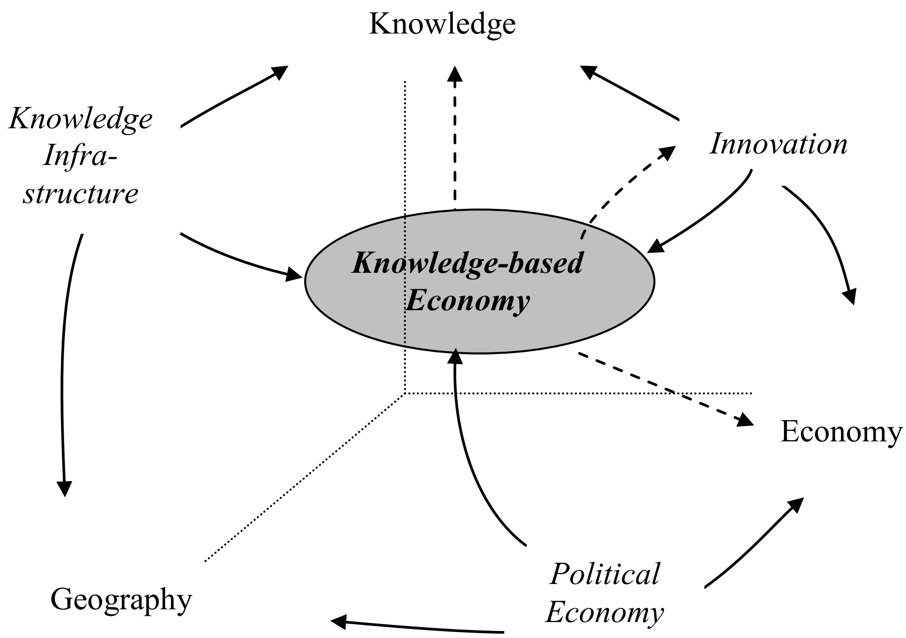

Figure 3: The first-order interactions generate a knowledge-based economy as a next-order system. (Source: Leydesdorff, 2010, at p. 379.)

Whereas innovation agencies may be in favor of university-industry-government relations for institutional reasons (Mirowski & Sent, 2007; cf. Etzkowitz, 2008), the crucial research issues remain related to systemic questions such as: under which conditions can the three functions operate synergistically, to what extent or at which level, and at what price? Is a country or region able to retain "wealth from knowledge" and/or "knowledge from wealth" (as in the case of oil revenues). Such a synergy can be expected to perform a life-cycle (Carayannis, 1999). In the initial stage of emergence, "creative destruction" of the relevant parts of the old arrangements is a driving force. New entrants (scientists, entrepreneurs) can be expected to attach themselves preferentially to the originators—the innovation organizers—of the new developments. How should networks be constructed in terms of participating institutions, and in which order? Can one locally construct a path-dependency and therewith a competitive advantage? (Cooke & Leydesdorff, 2006.)

In addition to “creative destruction” as typical for Schumpeter Mark I, Soete & Ter Weel (1999) proposed considering “creative agglomeration” as typical of the competition among knowledge-intensive corporations (Nonaka & Takeuchi, 1995). This changes the dynamics of development in the later stages of development, and is sometimes called “Schumpeter Mark II” (Freeman & Soete, 1997; Gay, 2010). In a bibliometric study of the diffusion of the new technology of RNA interference (Fire *et al*., 1998; Sung & Hopkins, 2006), for example, Leydesdorff & Rafols (2011) found a change of preferential attachments from the inventors in the initial stage to emerging “centers of excellence” at a later stage. In the patent market, however, a quasi-monopolist leads the market located in Colorado, whereas the research centres of excellence were concentrated in major cities such as London, Boston, and Seoul (Leydesdorff & Bornmann, 2012). Drug development requires a time horizon different from that required by the application of a technique in adjacent industries, such as the production of reagents for laboratories (Lundin, 2011).

In other words, the new technologies can move along trajectories in all three relevant directions and with potentially different dynamics. The globalization of the research front requires an uncoupling from the originators and a transition from “Mode-1”—a system with strong institutional (e.g., disciplinary) boundaries—to “Mode-2” research—in which trans-border transformations prevail—can make a technique mutable (Gibbons *et al*., 1994; Latour, 1987). From this perspective, “Mode-1” and “Mode-2” provide an analogy to Schumpeter’s Mark I—the entrepreneur leads the innovation—and Mark II—oligopolies are leading—but within the domain of organized knowledge production and control.

Universities are poorly equipped for patenting and carrying the innovation (Leydesdorff & Meyer, 2010). Some of the original patents may profitably be held by academia. In the case of RNA interference, for example, two original US-patents were co-patented by MIT and the Max Planck Society in Germany (MIT Technology Licensing Office, 2006), but a company was founded as a spin-off to further develop the technology. As noted, the competition thereafter shifted along a commercial trajectory.

In summary, whereas one can expect synergies to be constructed, the emerging system "self-organizes" the interactions in terms of relevant selection environments, while leaving behind institutional footprints in the network space. Three selection environments are of paramount importance in terms of flows through the networks: the economic, political, and socio-cognitive potentials for change. Both local integrations and global pressures for differentiation can continuously be expected—which have implications for the partial unraveling and reconstruction of university-industry-government relations.

Geography and the Triple Helix indicator

These complexities are further shaped by geography—place and space. Different from discussions about national (Lundvall, 1988; Nelson, 1993) or regional systems of innovation (Cooke, 1992, Braczyk *et al*., 1998), the Triple Helix model enables us to consider empirically whether specific synergies among the three composing media have emerged at national and/or regional levels. With respect to the latter, in various countries the Triple Helix concept has been used as an operational strategy for regional development and to further the knowledge-based economy; for example, in Sweden (Jacob, 2006) or for comparing Malaysia with Algeria (Saad *et al*., 2008). In Brazil, the Triple Helix became a "movement" for generating incubators designed to promote enterprise-formation in the university context (Almeida, 2005). In other cases, however, sectors and/or technologies (e.g., biotechnology) may be more relevant systems of reference for innovations than geographical units of analysis (Carlsson, 2006). The relation between the localized region and global developments is also a key concept underpinning the current "Smart specialization" agenda of European Union's (2011) Regional Policy. Leydesdorff & Deakin (2011) analyzed this relation as "meta-stable".

From the perspective of geography, the TH thesis can be considered in relation to Storper's (1997) definition of a territorial economy as *stocks of relational assets* among technologies, organizations, and territories. The patterns of relations determine the dynamics of the system:

> Territorial economies are not only created, in a globalizing world economy, by proximity in input-output relations, but more so by proximity in the untraded or relational dimensions of organizations and technologies. Their principal assets—because scarce and slow to create and imitate—are no longer material, but relational. (Storper, 1997: 28)

In this context, Storper (1997, at p. 49) illustrated this "holy trinity" of technologies, organizations, and territories using Figure 4 in which he combined the two configurations distinguished in Figure 1 above, as follows:

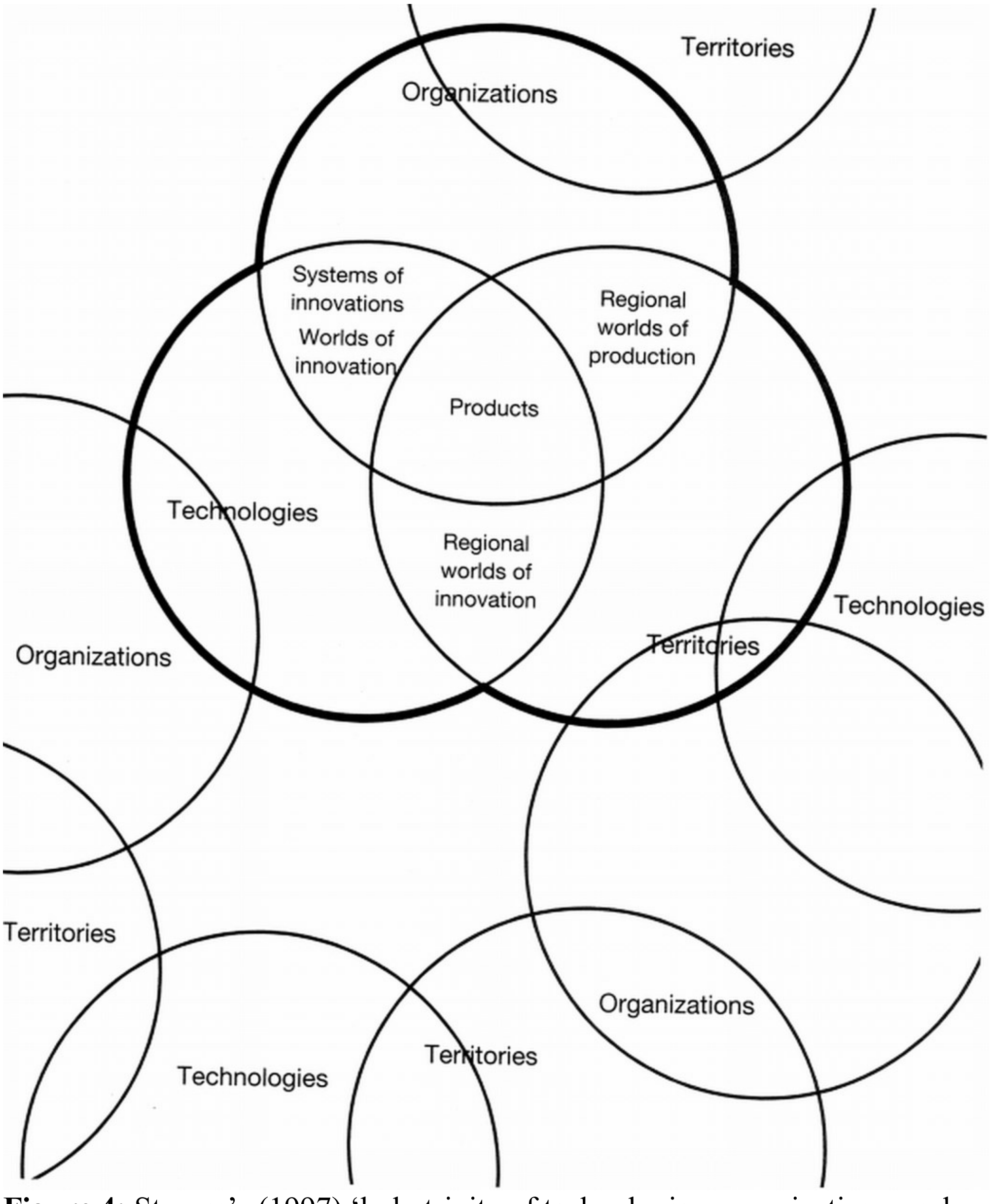

Figure 4: Storper's (1997) 'holy trinity of technologies, organizations, and territories' provides an overlap in the resulting 'products'. Source: Storper (1997, p. 49).

As in Figure 1, the circles—representing sets—can overlap, but also be bilaterally connected. For example, if technology is not directly involved, one obtains a "regional world of production" or in terms of Figure 3 above, a regional economy. How can this model be further developed into a model that allows also for positions in terms of patterns of aggregated relations and non-relations? How can hybridization versus division of labor be indicated and at different systems levels?

Building on McGill (1954), Ulanowicz (1986:143) proposed a more abstract conceptualization: the mutual information in *three* (or more) dimensions provides a *signed* entropy statistics that is able to indicate emerging systemness in relations as reduction of uncertainty in ecological systems (Yeung, 1998:59f.; cf. Ulanowicz, 2009). Whereas two distributions can "mutually shape" each other in a co-evolution along a trajectory, the correlation between two variables can also be spurious upon a latent third one in the case of three sources of variance. Elaborating on Krippendorff's (2009a and b) critique of this measure, Leydesdorff & Ivanova (2014) showed that one then measures "mutual redundancy" rather than Shannon-type information.

This signed information measure can indicate (e.g., in bits) the possible reduction of uncertainty that prevails at a systems level, as negative entropy that results from the interactions in relations. Negative entropy indicates reduction of uncertainty as in a niche. Such a niche within a communication system can also be considered as a result of "auto-catalysis" (Ulanowicz, 2009; Ivanova & Leydesdorff, 2014): the dynamics among the three circles may be virtuously closed if government is able to catalyze mutual relations between universities and industries, for example, within a national system. An auto-catalytic (next-order) system of innovations, however, can be expected to select resources flexibly in order to sustain its growth.

Using the keywords "university," "industry," and "government" in the respective national languages (Korean and Dutch) at the major search engine of the time (AltaVista), Park *et al*. (2005) developed this "Triple Helix indicator" first at the global level. The Triple Helix overlay operated within the Netherlands and South Korea first at a similar level (Figure 5, left pane). In 2001, however, a discontinuity in the South-Korean curves signaled the collapse of the dot-com bubble in South Korea at the time. Thus, the indicator flagged a substantial difference in the underlying dynamics that is also illustrated in the right-hand panel of Figure 5.

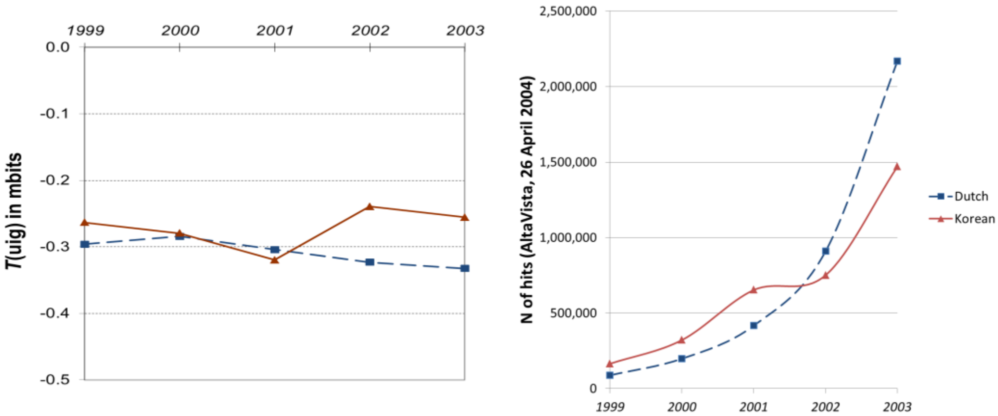

Figure 5: The dotcom crisis of 2000-2001 and its backlash on the Korean "knowledge-based economy" compared with the Dutch one. (Source: Park *et al*., 2005, pp. 11f.)

This indicator was then applied to a number of national systems of innovation in a series of (ongoing) studies, but using firms (instead of documents) as units of analysis and three orthogonal variables: the NACE codes as proxies for the technologies,[2] address information as a proxy for governance, and organizational size as a proxy for the economic dimension (e.g., SMEs). Two studies of the Netherlands (Leydesdorff *et al*., 2006) and Germany (Leydesdorff & Fritsch, 2006), respectively, led us to drawing the following conclusions:

1. In the Netherlands, a national system of innovations was indicated as adding synergy to regional systems (such as the regions of Amsterdam, Rotterdam, and Eindhoven) at the NUTS-3 level; in Germany, however, synergy was indicated at the level of federal States (*Länder*);
2. At the level of German federal States, the east-west divide between the former GDR and GFR prevailed in Germany (using 2004 data), but this divide no longer dominated the next-lower level of "Regierungsbezirke" (NUTS 4);
3. In both economies, medium-tech firms contributed more to the synergy than high-tech; we explained this in terms of "embeddedness" (Cohen & Levinthal, 1989);
4. Knowledge-intensive services tend to uncouple from regional economies: proximity to an airport or train station may be more important for such a

[2] NACE stands for Nomenclature générale des Activités économiques dans les Communautés Européennes. The NACE code can be translated into the International Standard Industrial Classificiation (ISIC).

> firm than its specific location. Different from "embeddedness," one can use the concept of "footloose-ness" (Vernon, 1979) for explaining the uncoupling effect of high-tech manufacturing and knowledge-intensive servicing.

Using the same methodology but with Hungarian and Norwegian data, the results became more complicated although the effects of embeddedness and footloseness held also for these sets. In Hungary, Lengyel & Leydesdorff (2011) did not find national surplus value. The 2005-data indicated three regional innovation systems: (1) a metropolitan innovation system around Budapest; (2) an innovation system in the western provinces integrated into the neighboring EU countries, notably Austria; and (3) synergy in the remnants of an innovation system that was state-led in the eastern parts of the country. This interpretation could be supported by a new reading of existing statistics.

In Norway, Strand & Leydesdorff (2013) found that the knowledge-based economy (operationalized in terms of these measurements) is driven by FDI in the maritime and marine industries at the west-coast more than by the Oslo and Trondheim regions where the large universities are established. However, Norway generates also surplus synergy at the national level (Fagerberg *et al*., 2009).

In summary, in these two nations we found an effect of globalization: when Hungary entered the competition after the fall of the Berlin wall (1989) and the demise of the Soviet Union (1991), it was too late to establish a "national system of innovations" because the transition was coupled to the ambition of accessing the EU. Norway went through the gradual transition to a knowledge-based economy because of its offshore (oil) industry. Given these unexpected conclusions, we wanted to test our methods on the Swedish innovation system because for this system one can expect on the basis of the literature (e.g., Fagerberg *et al*., 2009; Hallencreutz & Lundequist, 2003) a rather precise national system of innovations with the knowledge-based synergy concentrated in the regions of Stockholm, Gothenburg, and Malmö/Lund.

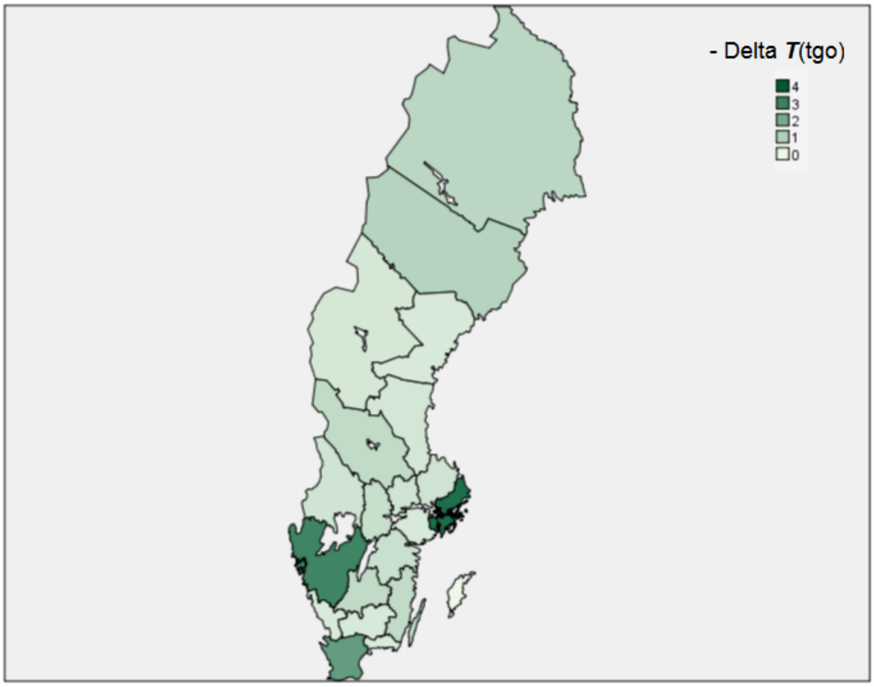

Figure 6: Contributions to the reduction of uncertainty at the level of 21 Swedish counties; *T*(gto) provides the mutual information in the three dimensions of (t)echnology; (g)overnment, and (o)rganization. Source: Leydesdorff & Strand (2013).

Figure 6 provides the map of regional innovation systems in Sweden measured by the Triple Helix indicator. Aggregation at the regional level (NUTS3) of the data organized at the municipal level (NUTS5) showed that 48.5% of the regional synergy is provided by the three metropolitan regions of Stockholm, Gothenburg, and Malmö/Lund. Indeed, Sweden can be considered as a centralized and hierarchically organized system (cf. Leydesdorff & Zhou, 2014).

These results accord with other statistics, but this Triple Helix indicator measures synergy more specifically and quantitatively. Furthermore, one does not have to pre-define whether an innovation system is considered regional or national, but can specify the percentage of synergy at each level. As noted, decompositions along the other axes—for example, in terms of low-, medium- or high-tech or in terms of SMEs versus other organizational sizes—are equally possible.

Globalisation

Globalisation has brought about a transformation in the configuration of the Triple Helix model in varying degrees depending on the openness of countries, which amounts to a possible mutation. In the case of Japan, for example, Leydesdorff & Sun (2009) used scholarly publication data with industrial, academic, and governmental addresses (cf. Abramo *et al*., 2009), and found that since the opening of China and the demise of the Soviet Union in 1991—both major changes in international competition—the national science system of Japan has increasingly become a retention mechanism for international relations. Thus, a further differentiation between the national and the global level was needed in this explanation. However, Kwon *et al*. (2012) did not find this differentiation between the national and international level as useful for explaining trends in Korean data.

Unravelling can also be seen in practice. In the noted study of Hungary, for example, the national system of innovations fell into three regional systems of innovation following the transition during the 1990s and the accession to the EU in 2004. Under the pressure of globalization, the roles of the academic, industrial, and governmental contributions are also not given. The central role of universities in many TH studies is based on the assumption that this system is more adaptive locally than the others because of the continuous flux of students (Shinn, 2002). In the study of Norway, however, Strand & Leydesdorff (2013) found foreign direct investment via the offshore (marine and maritime) industries in the Western part of the country to be a greater source of synergy in the knowledge-based developments of regions than the university environments of the national centers of academia in Trondheim and Oslo.

Two conclusions were drawn from these nation-based studies: (*i*) medium-tech industry is more important for synergy than high-tech, and (*ii*) the service sector tends to uncouple from geographical location because a knowledge-intensive service is versatile and not geographically constrained. These conclusions accord with the emphasis in the literature on embeddedness (Cohen & Levinthal, 1989) versus the footlooseness of high-tech industries (Vernon, 1979). Certain Italian industrial districts, for example, while very innovative, are under the continuous threat of deindustrialization because incumbent multinational corporations may buy and relocate new product lines (Beccatini, 2003; dei Ottati, 2003). In institutional analyses that focus on local and regional development using the Triple-Helix model, the structural effects of globalisation are sometimes not given the significance that is needed in understanding new configurations.

Conclusions and future directions

What is the contribution of these models in terms of providing heuristics to empirical research and policy practices? How do we understand the Triple Helix model in the context of global change? We considered new theoretical advances matched by new empirical evidence. First, the neo-institutional model of arrangements among different stakeholders can be investigated in case study analysis. Case studies can be enriched by addressing the relevance of the *three* relevant selection environments on an equal footing *ex ante*, with insights into possible mutations or unravellings. Research can then inform about specifics, such as path-dependencies (e.g., Etzkowitz *et al*., 2000; Viale & Campodall'Orto, 2002). Thus, the Triple Helix perspective does not disclaim the legitimacy of studying, for example, bi-lateral academic-industry relations or government-university policies. However, one can expect more interesting results by studying the interactions among the three sub-dynamics in the context of global change.

Secondly, the model can be informed by the increasing understanding of complex dynamics and simulation studies from evolutionary economics (e.g., Ahrweiler *et al*., 2011; Ivanova & Leydesdorff, 2013 and 2014; Malerba *et al.*, 1999; Pyka & Scharnhorst, 2009; Windrum, 1999). Thirdly, the Triple Helix model adds to the meta-biological models of evolutionary economics the sociological notion of meaning being exchanged among the institutional agents (Luhmann, 1995). Finally, on the normative side of developing options for innovation policies, the Triple Helix model provides an incentive to search for *mismatches* (mutations, unravellings) between the institutional dimensions in the arrangements and the social functions performed by these arrangements (Freeman & Perez, 1988).

The frictions between the two layers (knowledge-based expectations and institutional interests), and among the three domains (economy, science, and policy) provide a wealth of opportunities for puzzle solving and innovation. We plead for a shift of focus from "best practices" to systematic learning about the dynamics from also failures. The evolutionary regimes are expected to remain in transition as they are shaped along historical trajectories. A knowledge-based regime continuously upsets the political economy and the market equilibria as different sub-dynamics. Conflicts of interest can be deconstructed and reconstructed, first analytically and then perhaps also in practice in the search for informed solutions to problems of economic productivity, wealth retention, and knowledge growth.

The rich semantics of partially conflicting models reinforces a focus on solving puzzles among different selection environments reflexively. The lock-ins and bifurcations are systemic, that is, largely beyond control; further developments are based on the variation and the self-organizing dynamics of interactions among the three environments. The three sub-dynamics can also be considered as different sources of variance which disturb and select from one another.

Resonances among selections can shape trajectories in co-evolutions, and the latter may recursively—by including a third selection environment—drive the system into new regimes. This neo-evolutionary framework assumes that the processes of both integration and differentiation in university-industry-government relations remain under reconstruction. How reconstruction is observed as processes of continuance, mutation, and unraveling in theory and practice sets a research agenda with both industrial and policy relevance at international, national and regional scales.

References

Abramo, G., d'Angelo, C. A., Di Costa, F., & Solazzi, M. (2009). 'University–industry collaboration in Italy: a bibliometric examination', *Technovation, 29*, 6, 498-507.

Ahrweiler, P., Pyka, A., & Gilbert, N. (2011). 'A New Model for University-Industry Links in Knowledge-Based Economies', *Journal of Product Innovation Management, 28*, 2, 218-235.

Almeida, M. (2005). 'The evolution of the incubator movement in Brazil', *International Journal of Technology and Globalisation, 1,* 2, 258-277.

Beccatini, G. (2003). 'The Development of Tuscany: Industrial Districts', in: G. Beccatini, M. Bellandi, G. dei Ottati & F. Sforzi (Eds.), *From Industrial Districts to Local Development: An Itinerary of Research.* Edward Elgar, Cheltenham, UK/ Northhampton, MA, pp. 11-28.

Braczyk, H.-J., Cooke, P., & Heidenreich, M. (Eds.). (1998). *Regional Innovation Systems*. University College London Press, London/ Bristol PA.

Branscomb, L.M. (1993). 'The National Technology Policy Debate,' in: L.Branscomb (Ed.) *Empowering Technology: Implementing a U.S. Strategy.* The MIT Press, Cambridge MA.

Burt, R. S. (1982). *Toward a Structural Theory of Action*. New York, etc.: Academic Press.

Carayannis, E. G. (1999). 'Fostering synergies between information technology and managerial and organizational cognition: the role of knowledge management', *Technovation, 19*, 4, 219-231.

Carayannis, E. G., Alexander, J., & Ioannidis, A. (2000). 'Leveraging knowledge, learning, and innovation in forming strategic government–university–industry (GUI) R&D partnerships in the US, Germany, and France', *Technovation, 20*, 9, 477-488.

Carayannis, E.G., Campbell, D.F.J., 2009. ' 'Mode 3' and 'Quadruple Helix': toward a 21st century fractal innovation ecosystem', *International Journal of Technology Management* 46, 201-234.

Carlsson, B. (2006). 'Internationalization of Innovation Systems: A Survey of the Literature', *Research Policy, 35*, 1, 56-67.

Clark, B. R. (1998). *Creating Entrepreneurial Universities: Organization Pathways of Transformation*. Pergamom, Guildford, UK.

Cohen, W. M., & Levinthal, D. A. (1989). 'Innovation and Learning: The Two Faces of R & D', *The Economic Journal, 99,* 397, 569-596.

Cooke, P. (1992). Regional Innovation Systems: Competitive Regulation in the New Europe*, Geoforum*, 23, 3, 365-382.

Cooke, P., Leydesdorff, L. (2006). 'Regional Development in the Knowledge-Based Economy: The Construction of Advantages', *Journal of Technology Transfer* 31, 1, 5-15.

Dangelico, R. M., Garavelli, A. C., & Petruzzelli, A. M. (2010). 'A system dynamics model to analyze technology districts' evolution in a knowledge-based perspective', *Technovation, 30,* 2, 142-153.

dei Ottati, G. (2003). 'Local Governance and Industrial Districts' Competitive Advantage', in: G. Beccatini, M. Bellandi, G. dei Ottati & F. Sforzi (Eds.), *From Industrial Districts to Local Development: An Itinerary of Research*. Edward Elgar, Cheltenham, UK/ Northhampton, MA, pp. 184-209.

Etzkowitz, H. (1994). 'Academic-Industry Relations: A Sociological Paradigm for Economic Development', in: L. Leydesdorff & P. van den Besselaar (Eds.), *Evolutionary Economics and Chaos Theory: New Directions in Technology Studies*. Pinter, London, etc., pp. 139-151.

Etzkowitz, H. (2002). *MIT and the Rise of Entrepreneurial Science*. Routledge, London.

Etzkowitz, H. (2008) *The Triple Helix: University-Industry-Government in action.* Routledge, London

Etzkowitz, H., & Leydesdorff, L. (1995). 'The Triple Helix---University-Industry-Government Relations: A Laboratory for Knowledge-Based Economic Development', *EASST Review 14*, 1, 14-19.

Etzkowitz, H., & Leydesdorff, L. (2000). 'The Dynamics of Innovation: From National Systems and "Mode 2" to a Triple Helix of University-Industry-Government Relations', *Research Policy, 29*, 2, 109-123.

Etzkowitz, H., Webster, A., Gebhardt, C., & Terra, B. R. C. (2000). 'The future of the university and the university of the future: evolution of ivory tower to entrepreneurial paradigm', *Research Policy, 29*, 2, 313-330.

European Union (2011) *Connecting Universities to Regional Growth: A Practical Guide,* available from

http://ec.europa.eu/regional_policy/sources/docgener/presenta/universities2011/universities2011_en.pdf [accessed April 6, 2014].
Fagerberg, J., Mowery, D. C., & Verspagen, B., Eds. (2009). *Innovation, Path Dependency and Policy. The Norwegian Case*. Oxford University Press, Oxford.
Fire, A., Xu, S. Q., Montgomery, M. K., Kostas, S. A., Driver, S. E., & Mello, C. C. (1998). 'Potent and specific genetic interference by double-stranded RNA in *Caenorhabditis elegans', Nature, 391,* 6669, 806-811.
Foray, D. (2004). *The Economics of Knowledge*. MIT Press, Cambridge, MA/London.
Freeman, C. (1987). *Technology, policy, and economic performance: lessons from Japan*. Pinter, London.
Freeman, C., & Perez, C. (1988). 'Structural crises of adjustment, business cycles and investment behaviour', in: G. Dosi, C. Freeman, R. Nelson, G. Silverberg & L. Soete (Eds.), *Technical Change and Economic Theory*. Pinter, London, pp. 38-66.
Freeman, C., & Soete, L. (1997). *The Economics of Industrial Innovation*. Pinter, London.
Fujisue, K. (1998). 'Promotion of academia-industry cooperation in Japan—Establishing the "law of promoting technology transfer from university to industry" in Japan', *Technovation, 18*, 6, 371-381.
Gay, B. (2010). 'Innovative network in transition: From the fittest to the richest', available from http://papers.ssrn.com/sol3/papers.cfm?abstract_id=1649967 [accessed, April 2014].
Gibbons, M., Limoges, C., Nowotny, H., Schwartzman, S., Scott, P., Trow, M., 1994. *The new production of knowledge: the dynamics of science and research in contemporary societies*. Sage, London.
Godin, B., & Gingras, Y. (2000). 'The place of universities in the system of knowledge production', *Research Policy, 29*, 2, 273-278.
Hall, P. A., & Soskice, D. W. (Eds.). (2001). *Varieties of Capitalism: The Institutional Foundations of Comparative Advantage*. Oxford University Press, Oxford, etc.
Hallencreutz, D., & Lundequist, P. (2003). 'Spatial Clustering and the Potential for Policy Practice: Experiences from Cluster-building Processes in Sweden', *European Planning Studies*, *11*, 5, 533-547.
Ivanova, I. A., & Leydesdorff, L. (2013, in press). 'Rotational symmetry and the transformation of innovation systems in a Triple Helix of university–industry–government relations', *Technological Forecasting and Social Change*. doi: 10.1016/j.techfore.2013.08.022
Ivanova, I. A., & Leydesdorff, L. (2014, in press). 'Redundancy Generation in University-Industry-Government Relations: The Triple Helix Modeled,

Measured, and Simulated', *Scientometrics*. doi: 10.1007/s11192-014-1241-7

Jacob, M. (2006). 'Utilization of social science knowledge in science policy: Systems of Innovation, Triple Helix and VINNOVA', *Social Science Information, 45*, 3, 431-462.

Krippendorff, K. (2009a). 'W. Ross Ashby's information theory: a bit of history, some solutions to problems, and what we face today', *International Journal of General Systems, 38*, 2, 189-212.

Krippendorff, K. (2009b). 'Information of Interactions in Complex Systems', *International Journal of General Systems, 38*, 6, 669-680.

Kwon, K. S., Park, H. W., So, M., & Leydesdorff, L. (2012). 'Has Globalization Strengthened South Korea''s National Research System? National and International Dynamics of the Triple Helix of Scientific Co-authorship Relationships in South Korea', *Scientometrics*, 90, 1, 163-175.

Latour, B. (1987). *Science in Action*. Open University Press, Milton Keynes.

Lawton Smith, H., Ho, K. (2006). 'Measuring the performance of Oxford University, Oxford Brookes University and the government laboratories' spin-off companies', *Research Policy* 35, 10, 1554-1568.

Lengyel, B., & Leydesdorff, L. (2011). 'Regional innovation systems in Hungary: The failing synergy at the national level', *Regional Studies, 45*, 5, 677-693.

Lewontin, R., 2000. *The Triple Helix: Gene, Organism, and Environment.* Harvard University Press, Cambridge, MA/London.

Leydesdorff, L. (2006). *The Knowledge-Based Economy: Modeled, Measured, Simulated*. Universal Publishers, Boca Raton, FL.

Leydesdorff, L. (2010). 'The Knowledge-Based Economy and the Triple Helix Model', *Annual Review of Information Science and Technology, 44*, 367-417.

Leydesdorff, L., & Bornmann, L. (2012). 'Mapping (USPTO) Patent Data using Overlays to Google Maps', *Journal of the American Society for Information Science and Technology, 63*, 7, 1442-1458.

Leydesdorff, L., & Deakin, M. (2011). 'The Triple-Helix Model of Smart Cities: A Neo-Evolutionary Perspective', *Journal of Urban Technology, 18*, 2, 53-63.

Leydesdorff, L., & Fritsch, M. (2006). 'Measuring the Knowledge Base of Regional Innovation Systems in Germany in terms of a Triple Helix Dynamics', *Research Policy, 35*, 10, 1538-1553.

Leydesdorff, L., & Ivanova, I. A. (2014). 'Mutual Redundancies in Inter-human Communication Systems: Steps Towards a Calculus of Processing Meaning', *Journal of the Association for Information Science and Technology, 65*, 2, 386-399.

Leydesdorff, L., & Meyer, M. (2010). 'The Decline of University Patenting and the End of the Bayh-Dole Effect', *Scientometrics, 83*, 2, 355-362.
Leydesdorff, L., & Rafols, I. (2011). 'How Do Emerging Technologies Conquer the World? An Exploration of Patterns of Diffusion and Network Formation', *Journal of the American Society for Information Science and Technology, 62*, 5, 846-860.
Leydesdorff, L., & Sun, Y. (2009). 'National and International Dimensions of the Triple Helix in Japan: University-Industry-Government versus International Co-Authorship Relations', *Journal of the American Society for Information Science and Technology 60*, 4, 778-788.
Leydesdorff, L., & Strand, Ø. (2013). 'The Swedish System of Innovation: Regional Synergies in a Knowledge-Based Economy', *Journal of the American Society for Information Science and Technology, 64,* 9, 1890-1902.
Leydesdorff, L., & van den Besselaar, P. (Eds.), (1994). *Evolutionary Economics and Chaos Theory: New Directions in Technology Studies*. London, etc.: Pinter.
Leydesdorff, L., & Zhou, P. (2014). 'Measuring the Knowledge-Based Economy of China in terms of Synergy among Technological, Organizational, and Geographic Attributes of Firms', *Scientometrics, 98,* 3, 1703-1719.
Lowe, C.U., 1982. 'The Triple Helix—NIH, industry, and the academic world', *The Yale Journal of Biology and Medicine* 55, 239-246.
Luhmann, N. (1995). *Social Systems*. Stanford University Press, Stanford, CA.
Lundin, P. (2011). 'Is silence still golden? Mapping the RNAi patent landscape', *Nature Biotechnology, 29*, 6, 493-497.
Lundvall, B.-Å. (1988). 'Innovation as an interactive process: from user-producer interaction to the national system of innovation', in: G. Dosi, C. Freeman, R. Nelson, G. Silverberg & L. Soete (Eds.), *Technical Change and Economic Theory*. Pinter, London, pp. 349-369.
Malerba, F., Nelson, R., Orsenigo, L., & Winter, S. (1999). ' "History-firendly" Models of Industry Evolution: The Computer Industry', *Industrial and Corporate Change, 8*, 1, 3-35.
McGill, W. J. (1954). 'Multivariate information transmission', *Psychometrika, 19*, 2, 97-116.
Meyer, M., Grant, K., Morlacchi, P., & Weckowska, D. (2014). 'Triple Helix indicators as an emergent area of enquiry: a bibliometric perspective', *Scientometrics, 99*, 1, 151-174.
Mirowski, P., & Sent, E. M. (2007). 'The Commercialization of Science, and the Response of STS', in: E. J. Hackett, O. Amsterdamska, M. Lynch & J.

Wajcman (Eds.), *Handbook of Science, Technology and Society Studies*. MIT Press, Cambridge, MA/London, pp. 635-689.

MIT Technology Licensing Office (2006). Licensing for RNAi Patents, available from http://web.mit.edu/tlo/www/industry/RNAi_patents_tech.html [accessed April 2014].

Nelson, R. R. (Ed.). (1993). *National Innovation Systems: A comparative analysis*. Oxford University Press, New York.

Nelson, R. R., & Winter, S. G. (1982). *An Evolutionary Theory of Economic Change*. Belknap Press of Harvard University Press, Cambridge MA.

Noble, D. (1977). *America by Design*. Knopf, New York.

Nonaka, I., & Takeuchi, H. (1995). *The Knowledge Creating Company*. Oxford University Press, Oxford/New York.

Owen-Smith, J., Riccaboni, M., Pammolli, F., Powell, W.W. (2002). 'A Comparison of U.S. and European University-Industry Relations in the Life Sciences', *Management Science 48*, 1, 24-43.

Park, H. W., Hong, H. D., & Leydesdorff, L. (2005). 'A Comparison of the Knowledge-based Innovation Systems in the Economies of South Korea and the Netherlands using Triple Helix Indicators', *Scientometrics, 65*, 1, 3-27.

Petruzzelli, A. M. (2011). 'The impact of technological relatedness, prior ties, and geographical distance on university–industry collaborations: A joint-patent analysis', *Technovation, 31*, 7, 309-319.

Powell, W. W., White, D. R., Koput, K. W., & Owen Smith, J. (2005). 'Network dynamics and field evolution: The growth of interorganizational collaboration in the life sciences', *American Journal of Sociology, 110*, 4, 1132-1205.

Pyka, A., & Scharnhorst, A. (Eds.). (2009). *Innovation Networks: New Approaches in Modelling and Analyzing*. Berlin/Heidelberg: Springer.

Saad, M., Zawdie, G., & Malairaja, C. (2008). 'The Triple Helix strategy for universities in developing countries: the experiences in Malaysia and Algeria', *Science and Public Policy, 35*, 6, 431-443.

Sábato, J. (1975). *El pensamiento latinoamericano en la problemática ciencia–technología–desarrollo-dependencia.* Paidós, Buenos Aires.

Schumpeter, J. ([1939], 1964). *Business Cycles: A Theoretical, Historical and Statistical Analysis of Capitalist Process*. McGraw-Hill, New York.

Shinn, T. (2002). 'The Triple Helix and New Production of Knowledge : Prepackaged Thinking on Science and Technology', *Social Studies of Science, 32*, 4, 599-614.

Soete, L., & ter Weel, B. (1999). 'Schumpeter and the knowledge-based economy: On technology and competition policy', *Research Memoranda 004*. MERIT, Maastricht Economic Research Institute on Innovation and

Technology, available from http://www.merit.unu.edu/publications/rmpdf/1999/rm1999-004.pdf [accessed April 2014].

Storper, M. (1997). *The Regional World - Territorial Development in a Global Economy*. New York: Guilford Press.

Strand, Ø., & Leydesdorff, L. (2013). 'Where is Synergy in the Norwegian Innovation System Indicated? Triple Helix Relations among Technology, Organization, and Geography', *Technological Forecasting and Social Change, 80*, 3, 471-484.

Sung, J. J., & Hopkins, M. M. (2006). 'Towards a method for evaluating technological expectations: Revealing uncertainty in gene silencing technology discourse', *Technology Analysis & Strategic Management, 18*, 3, 345-359.

Ulanowicz, R. E. (1986). *Growth and Development: Ecosystems Phenomenology*. San Jose, etc.: toExcel.

Ulanowicz, R. E. (2009). *A Third Window: Natural life beyond Newton and Darwin*. Wesst Conshohocken: Templeton Foundation Press.

Venditti, M., Reale, E., & Leydesdorff, L. (2013). 'Disclosure of university research to third parties: A non-market perspective on an Italian university', *Science and Public Policy, 40*, 6, 792-800.

Vernon, R. (1979). 'The Product Cycle Hypothesis in a New International Environment', *Oxford Bulletin of Economics and Statistics, 41,* 4, 255-267.

Viale, R., & Campodall'Orto, S. (2002). 'An evolutionary Triple Helix to strengthen academy-industry relations:suggestions from European regions', *Science and Public Policy, 29*, 3, 154-168.

Whitley, R. D. (1984). *The Intellectual and Social Organization of the Sciences*. Oxford University Press, Oxford.

Windrum, P. (1999). 'Simulation models of technological innovation: a review', *American Behavioral Scientist, 42*, 10, 1531-1550.

Yeung, R. W. (2008). *Information Theory and Network Coding*. New York, NY: Springer.