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Synergy in Knowledge-Based Innovation Systems at National and Regional Levels: The Triple-Helix Model and the Fourth Industrial Revolution

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Abstract: Unlike national systems of innovation, a knowledge-based economy is grounded in the volatility of discursive knowledge enabling us to specify expectations. Expectations can be improved by testing them against observations. Furthermore, expectations can be codified in different ways; for example, in terms of market perspectives or technological opportunities. The Fourth Industrial Revolution entails a transition to the reflexive entertaining of expectations in terms of models as increasingly the sources of innovations. The Triple-Helix synergy indicator enables us to use institutional arrangements as instantiations of the knowledge dynamics and thus to assess the generation of options and the reduction of uncertainty in information-theoretical terms. Using this indicator, one can assess empirically—in terms of negative bits of information; that is, redundancy—in which innovation systems and to what extent a technological revolution is taking place.

Keywords: triple helix; innovation systems; reflexive turn; expectation; synergy

1. Introduction

Does the Fourth Industrial Revolution [1]—the theme of this special issue—introduce a new metaphor replacing and perhaps encompassing older models, such as "National Systems of Innovation" (NSI), the "Knowledge-Based Economy" (KBE), and the "Triple Helix of University–Industry–Government Relations" (TH)? Hitherto, the elaboration of the presumably pending transition—the Fourth Industrial Revolution—in terms of innovations has remained to a large extent programmatic. However, "industrial revolutions" can be expected with the development of capitalism ([2–4]; they are driven by technological innovations.

The program of studies in innovation studies and evolutionary economics has been to consider the technological dimension no longer as an external driver, but to "endogenize" the innovative dynamics into the models [5,6]. How can the process of innovation be explained in relation to industrial and technological developments? Building on the evolutionary theorizing by Nelson and Winter [6], the metaphor of NSI emerged in the late 1980s. KBE has elaborated on NSI from an evolutionary perspective [7] since the mid-1990s, whereas TH can be considered as an institutional elaboration [8]. In this contribution, I propose to further develop the TH into an evolutionary model.

NSI combines the claims that innovation is systemic [9], that innovation systems are evolving [10], and that they are organized institutionally, and therefore influenced by and susceptible to government policies at national or regional levels [11–13]. NSI thus seeks to combine the perspectives of policy analysis, institutional analysis, and (neo-)evolutionary theorizing. However, the metaphor is misleading: innovation is not taking place within administratively bordered nations and innovation is not necessarily systemic.

Sahal [14], for example, distinguished among (*i*) *material* innovations "that are necessitated in an attempt to meet the requisite changes in the criteria of technological construction as a consequence of

changes in the scale of the object", (*ii*) *structural* innovations "that arise out of the process of differential growth whereby the parts and the whole of a system do not grow at the same rate", and (*iii*) *systemic* innovations "that arise from integration of two or more symbiotic technologies". As an example of a systemic innovation, the author points to the integration of office automation with computing during the 1950s and 1960s; with a leading role played by IBM. More formally, one can distinguish innovations which deconstruct and reconstruct specific relations within a system from changes among clusters of relations at the systems level. Relations among clusters of relations can change technological regimes, while specific relations are reconstructed along technological trajectories.

The assumption of NSI that innovation systems would be "national" originated from Freeman's (1987) report entitled "Technology and Economic Performance: Lessons from Japan" [11,15]. NSI was embraced notably by scholars with a Scandinavian background who feared that the specific qualities of their respective national innovation systems might suffer from integration into a larger European framework (e.g., [9]). However, the terminology of "national systems" generated resistance among scholars with backgrounds in regions such as Catalonia or Wales claiming regional innovation systems (e.g., [16,17] and at the supra-national level of the European Union, where terminology such as the "knowledge-based economy" was favored [18,19].

The knowledge-based economy can be distinguished from a political or market economy as a systemic development made possible as a new regime after the demise of the Soviet Union in 1991 (e.g., European Committee, [20]). In a knowledge-based economy, organized knowledge provides a third coordination mechanism in addition to the market and political control. However, organized knowledge production and control [21,22] emerged as a structural dimension of the economy gradually during the late 19th and most of the 20th century. Marx [23], had considered whether science-based technological evolution might be an independent source of social wealth more than labor. Sahal [14], cites the young Marx' [23] *The Poverty of Philosophy*:

> The landmill gives you society with the feudal lord; the steam mill, society with the industrial capitalist) ([23] at p. 92).

After extensive study, including calculations, however, the older Marx of *Capital I* [24] concluded that the main contradiction at the time remained the one between capital and labor. In the footnotes as a subtext (e.g., p. 393, note 89), however, Marx repeated that "the technology shows us the active relation of the human kind to nature, the immediate production process of our lives . . . " If technology could enable us to free man from work sufficiently, the nature of capitalism would change, since "*the basis of this mode of production falls away*" (p. 709; italics in the original). In other words, Marx envisaged a regime change that would be different from and an alternative to the communist revolution.

Noble [25], argued that "the major breakthroughs, technically speaking, came in the 1870s"; in other words, after the publication of *Capital.* He dated what he calls "the wedding of the sciences to the useful arts" as the period between 1880 and 1920. Braverman [26] introduced the concept of a scientific-technical revolution to designate this same period when he described the regime change as follows:

> The scientific-technical revolution . . . cannot be understood in terms of specific innovations—as is the case of the Industrial Revolution, which may be adequately characterized by a handful of key inventions—but must be understood rather in its totality as a mode of production into which science and exhaustive engineering investigations have been integrated as part of ordinary functioning. The key innovation is not to be found in chemistry, electronics, automatic machinery, aeronautics, atomic physics, or any of the products of these science-technologies, but rather in the transformation of science itself into capital.

But the transition is gradual. While World War I has also been characterized as the war of chemistry and World War II as the war of physics, the return to a liberal democracy under peacetime conditions [27]

led to a focus on economic models where science and technology were considered first as exogeneous factors of an economy that was conceptualized in terms of the dynamics of production factors such as labor, capital, and land. The component of growth due to technological progress was long held to be a residual factor which could not easily be explained (e.g., [28–30]).

Theorizing about the role of technological knowledge [31,32] was elaborated in evolutionary economics by a school of scholars who have been characterized from the perspective of hindsight as "the neo-Schumpeterians" [33–35]. Schumpeter [36] provided a model of technological change in which he distinguished between innovations as changes in the shape of the production function reflecting the possibility to generate more output from less input, and changes along the production function as factor substitutions [37]. In the Schumpeterian model, the two mechanisms stand orthogonally in terms of shifts along or perpendicular to the production function (Figure 1).
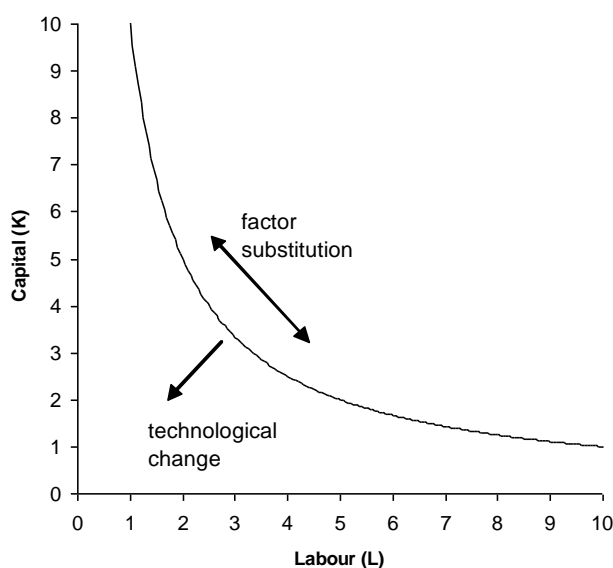

Figure 1. Schumpeter's model of technological change as a shift of the production function towards the origin while factor substitution is a shift along the production function.

In Nelson and Winter's evolutionary model [5,6], two other mechanisms were distinguished analytically: variation along trajectories versus selection mechanisms. These authors ([5] formulated their program as follows:

> We are attempting to build conformable sub-theories of the processes that lead up to a new technology ready for trial use, and of what we call the selection environment that takes the flow of innovations as given. (Of course, there are important feedbacks).

Freeman and Perez's [13] further elaborated a model of structural adjustments at the institutional level versus long waves in the technological evolution. This dialectic is reminiscent of Marx's distinction between production forces and production relations.

These various models have in common that *two* dynamics are postulated: adjustment with reference to an equilibrium, and the generation of innovation continuously upsetting the movement towards equilibrium. In processes of "mutual shaping" [38] between the two mechanisms, niches can be constructed as temporary and local suboptima. Note that the local suboptima in evolutionary economics are different from the global equilibria assumed in neo-classical economics.

2. From a Dialectics to a Trialectic

In the summarizing Epilogue [39] to the edited volume entitled *Evolutionary Economics and Chaos Theory: New directions in technology studies* [40]), I argued in favor of introducing organized

knowledge production as a *third* dynamic into the model in addition to and in interaction with market coordination and institutional control. The third dynamic makes the model so "complex" and non-linear that trajectories and regimes, self-organization, emergence, lock-in, etc., can be defined more clearly (e.g., [41,42]).

Henry Etzkowitz contributed a chapter to this edited volume entitled "Academic-Industry Relations: A Sociological Paradigm for Economic Development" [43]. In this chapter, Etzkowitz described the development of MIT into an entrepreneurial university since the 1930s. In the summer of 1994, Henry and I met again at a workshop in Abisko (Sweden) and discussed a follow-up project which would combine his interest in university–industry relations with my interest in the dynamics of science and technology. In the email conversations that followed, we developed the Triple-Helix (TH) model of university–industry–government relations [44].

This TH model was firmly anchored in both Etzkowitz's interest in the institutional dynamics of relations, on the one side, while on the other, it elaborated on my interest in the operationalization of an evolutionary model of the knowledge-based economy in terms of three (or more) social dynamics as against two. Whereas a co-evolution in a double helix can stabilize because of "mutual shaping" along a trajectory between the two selection environments, a third dynamic can be expected continuously to upset this tendency toward equilibrium to the extent that such a system becomes unstable. From this perspective, equilibrium needs to be explained, whereas a tendency towards equilibrium is assumed in neo-classical economics.

In an evolutionary theory of innovation, genotypes have first to be distinguished from phenotypes [45]. The genotypes operate as selection mechanisms on the observable (that is, phenotypical) variation. In the (neo-)institutional TH model, the institutional arrangements provide the variation, whereas selection mechanisms are genotypical and deterministic. The genotypes of non-biological systems, however, are not given as DNA—the observable code of biological evolution—but must first be specified [46].

Since non-biological selection is no longer "natural selection", more than a single selection mechanism can be expected to operate: market selection, technological selection, etc. The criteria for selection are based on (potentially different) codes constructed in the communication and developing in functionally different domains [47]. Using another semantics, one can consider the selection mechanisms also as social coordination mechanisms. In the TH model, we focus on three of them: markets, sciences, and politics.

Nelson and Winter's [5,6] distinction between market and non-market selection mechanisms can thus be generalized to selections in various dimensions. Since the selection mechanisms are not given but constructed, they can be expected to (co-)evolve by adapting to the complexity in the phenotypical variation. With a reference to Hayami and Ruttan [48], Nelson and Winter [5], were also aware that selections can operate upon selections and thus drive hyper-selection (cf. [49]): the trajectory of a technology provides a historical selection mechanism (stabilization) while developing along a life-cycle; the regime adds evolutionary selection (globalization). One needs a next-order systems perspective to "see" regime changes.

Thus, one obtains a system which is both vertically and horizontally differentiated: vertically, in terms of selections operating upon selections and thereby recursively generating stabilizations and globalizations; horizontally, in terms of different functionalities (academia, industry, and government). However, the resulting construct should not be considered as a "really existing" system; it remains a model, as the codes are not biological codes but codes of communication. Because of this volatility, the selections disturb one another continuously in different directions and at different levels so that the construct cannot be stabilized historically. One can recombine "infra-reflexively" [50] in different directions. Instead of a "system", one can thus expect a "fractal manifold" [51] composed of interacting triple helices. All higher-order helices can be decomposed in terms of triangles [51]. Such a construct does not "exist" as hardware—in the sense of the Latin *esse*—but we construct it as a model of latent genotypes using the phenotypes that we observe as a basis and testing ground for these inferences.

For example, Freeman and Perez' [13] above-noted model of structural crises and adjustment mechanisms in the institutional dimension *versus* technological paradigms generating long-term cycles is based on the premise of rapidly falling prices in specific production factors. Each new regime is based on a crucial factor, such as oil, or, more recently, micro-electronics. In my opinion, it is not the observable micro-electronics as hardware or as a commodity which drives the cycle(s), but the possibility to absorb knowledge into the production system in terms of computer routines and computer power, which is facilitated and mediated by the use of micro-electronics. The material component of "micro-electronics" opens a window on the knowledge dynamics which itself remains ideational. The surplus of possibilities generated in the knowledge dynamics can thus be appreciated and exploited.

When the knowledge dynamics is involved as a supra-individual coordination mechanism, "all that is solid, melts into air" [52]. However, the 19th century "air" is structured in the 20th century as the "hot air" of scholarly discourses decoding and recoding the knowledge bases of the economy [53]. Unlike air, one can expect this "hot air" to be structured at the above-individual level [54]: that is, as codes of communication. The codes provide the selection criteria; selection environments drive one another: horizontally as triple-helices and vertically because some selections are chosen for stabilization, and some stabilizations are chosen for globalization.

First, the information in the communications is provided with meaning and thus codified [55]. The codes of the communication can be generalized symbolically [56–58]. The cybernetic principle holds that the construction is bottom up (*genesis*) in history; but once constructed, control (*validation*) tends to be evolutionary and top-down [59]. For example, the market is not steered by individual transactions, but by more abstract market forces. The transactions provide the variation. Analogously, the sciences are not developing in terms of individual knowledge claims in manuscripts; the latter have to be validated in the light of theories. Social coordination mechanisms operating above the individual level contain the genotypes of society as the symbolically generalized codes of the communications. The codes both select and enable communications to be specifically reproduced and disseminated [60].

Symbolically generalized codes of communications can be considered as the eigenvectors of the communication matrix [56,57]. These eigenvectors can be spanned orthogonally shaping a vector space of possibilities. Although this vector space is generated in terms of relations—action (e.g., entrepreneurship) providing variation—the latent dimensions are not only relational but based on correlations between distributions of relations. This next-order level can function as the selection mechanism structuring follow-up communications. Without horizontal differentiation, the center of control would drift to the top-level (selection → stabilization → globalization). In the fractal manifold of a pluriform society, however, this hierarchical tendency—monopolization—is continuously "broken" by network interactions.

3. The Generation of Redundancy on Top of the Information Flows

The TH was first defined in terms of links among universities, industries, and government(s) as institutional relations. However, an essential element of the TH thesis is that the relations among institutions have become knowledge-based and have therefore grown into a network. In this constellation, institutions can substitute for each other's functionality to a certain extent. Universities, for example, can take on entrepreneurial roles (for example, by creating incubators and science parks), industry can organize academic education and research, and public–private relations between industry and government can be redefined in the light of new technological options.

The resulting overlay of relations and communications can develop a dynamic of its own [61]. The evolution of these relations, however, is not yet endogenized in the institutionally specified TH model. Under what conditions does the TH dynamic generate a surplus? Note that a TH overlay also generates overhead. Each configuration could have been different and is by definition sub-optimal so that it can almost always be improved.

From an evolutionary perspective, the institutional arrangements provide the retention mechanisms of solutions that have served us hitherto as "best practices". The observable institutions and their relations—the empirical case studies—provide us with a window on the knowledge dynamics in the same sense but in a direction opposite to that of the micro-electronic devices discussed above. The windows on the knowledge-based dynamics open a perspective in one direction and allow for the import of knowledge in the opposite direction from the perspective of hindsight. Can questions for further research be formulated?

Synergy among improved wealth generation in industry, novelty production in academia, and regulation and control by governmental authority may enable the networks (the nations, the regions) to construct competitive advantages by recombining differently coded communications [62]. In my opinion, the complexity in the relations among the codes is evolving and generating new possibilities of expectations.

The realizations provide the observable variation—which can be measured as information—whereas the not-yet-realized options provide redundancy—that is, possible realizations on top of the actual ones (Figure 2; [63]). The sum of information and redundancy is by definition equal to the maximum entropy [64].

Redundancy is generated in triple-helix relations because of partial overlaps in providing different meanings to the events from political, managerial, and technological perspectives. Patents, for example, are inputs to the economy, but patenting is output from an academic perspective. Thirdly, patents warrant intellectual property against litigation in the courts. The patent thus has a different meaning in each of these various contexts. Following a hypothesis of Herbert Simon [59], one can assume that there is an alphabet of such codes operating.
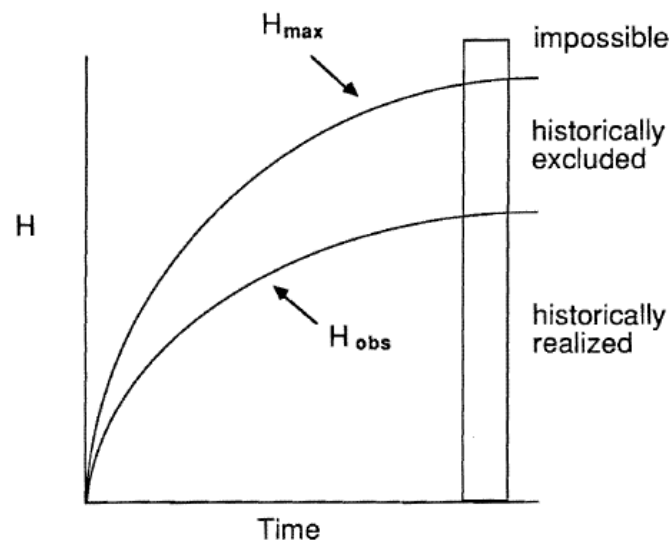

Figure 2. The development of information capacity, information content, and redundancy over time. Source: [63].

Knowledge-based innovations emerge from (re-)combinations of technological opportunities, market perspectives, and geographic endowments and constraints (e.g., [65,66]). The variously coded communications are interacting in relations among institutional carriers. Thus, a second-order dynamic of attributes to (first-order) communications is operating on top of the first-order dynamics of historical developments. The knowledge-based communications incur as a possible reconstruction on the historical arrangements that develop along the arrow of time. Storper [67] noted that an enormous leap in reflexivity has induced meta-capacities that can evolve faster than realizations at the institutional level.

4. Redundancy and the Further Perspective

In Shannon's (1948) *Mathematical Theory of Communication* [64], information is defined as probabilistic entropy (or uncertainty) and necessarily positive given the coupling with the Second Law of thermodynamics [68]. Whereas the Second Law states that uncertainty increases at the global level, pockets of negative entropy can occur locally when distributions resonate. These negative entropies can be considered as redundancies generated on top of the entropy flow as not-yet-realized options.

Negative information can only be produced in loops of communication generating a next-order layer in a non-linear model. Since redundancy is defined as the complement of the information to the maximum entropy, increases in redundancy lead to decreases of the relative information or, in other words, the uncertainty which prevails. The result is a net reduction of relative uncertainty, as in niches [69]. Reduction of uncertainty, furthermore, can be expected to improve the climate for investments [34].

Table 1 summarizes the differences between institutional and evolutionary TH models. A first difference is the unit of analysis: in the institutional model, this unit of analysis is agency; for example, entrepreneurship. Casson [70] argued that an institutional perspective on innovation eventually leads to a theory of the firm; in the case of TH theorizing, this perspective is extended with theorizing about the university as a pseudo-firm potentially operating as an entrepreneur in relevant (e.g., high-tech) markets [71].

Table 1. Summary of the differences between institutional and evolutionary Triple Helix of University–Industry–Government Relations (TH) models. Source: [72].

- University–Industry–Government relations
- (Inter-)institutional
- entrepreneurship (agents)
- network analysis; graphs;
- historical cases (*phenotypes*);
- inductive:

  ➢ *best practices*; comparative case studies;
  ➢ bottom-up;
  ➢ policy analysis

- Correlations among social coordination mechanisms
- evolutionary modeling of innovations (constructs)
- in the vector space:

  ➢ TH synergy indicator;
  ➢ redundancy (overlap) as a source of innovations;

[8,43,44,60,71]　　　　　　　　　　　　　　　　[51,55,72–75]

Innovations are the units of analysis in the evolutionary model on the right side of Table 1. One can expect the relations among the agents to be reconstructed by the dynamics of innovations. (In other words, the innovative dynamics is endogenized.) Because of these rewrites of the relations, positions based on correlations of distributions of relations are affected. The historical case is one among all possible ones; the historical trajectory, one among all possible reconstructions. (Yet, these are the ones to which we have access in empirical research.) The range of possibilities has to be hypothesized and this specification is knowledge-based; it can only be improved by developing discursive knowledge.

The hypotheses can be tested against observations: are the cases that actually happened also significant? The quality of the models thus becomes distinctive for the further development of the economy and therewith for society at large.

In the linear model, for example, innovation was first specified in terms of two dimensions: *technology push* versus *demand pull*. In non-linear models, feedback and feedforward arrows were added to co-determine longer-term developments. Relations were no longer fixed and given as in a channel between supply and demand [76]. The driving force in one phase may become a dependent variable in the next one [77]. Figure 3 illustrates the feedback and feedforward arrows shaping a non-linear system that operationally develops a third dimension of control mediating between supply and demand.
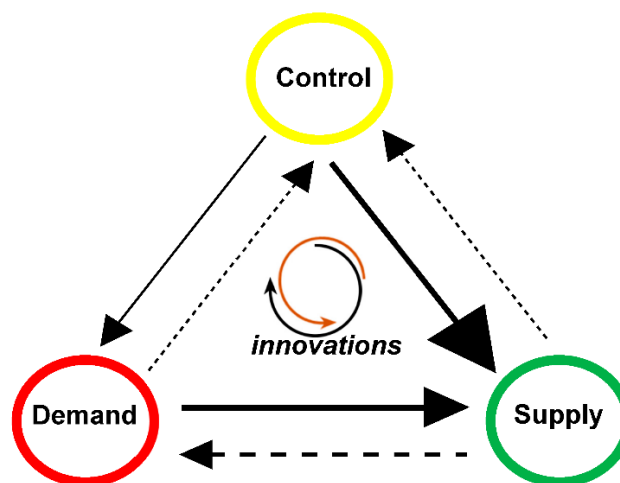

Figure 3. The generalized Triple-Helix model of innovations. Source: derived from [73].

While each forward arrow in Figure 3 models variation, a reverse arrow represents selective feedback. The process is complex because qualitatively different sources of variation are interacting, and so are the selection mechanisms: cycles can be interrupted, broken, and recombined. Combining a technological opportunity with a market perspective, for instance, may generate an invention, but the market must operate *as a selection environment* before the invention can be turned into an innovation.

When three or more feedbacks interact, loops are generated because of the possible transitivity of relations [78–80]. Triads can be either transitive or cyclic [52]. Whereas transitivity is a relational operation which can thus induce historical organization and relational hierarchy, the self-organization of markets, technologies, and control is based on cycles [67]. These cycles and the open triangles can develop in parallel [81]. The result is a complex system that is differentiated both horizontally and vertically; it is both hierarchical and heterarchical [59]. The loops may feed forward bringing the system into fruition—that is, structurally providing room for variation—or feed back, leading to lock-in and historical stagnation [74,82]. At each level, the one or the other direction can prevail.

The clockwise and counter-clockwise rotations (depicted in the center of Figure 3) precondition each other, since networks instantiated at the organizational level provide the retention mechanism for the self-organizing dynamics of the codes. Each variant may trigger an avalanche of restructuring [83,84]; the local equilibria are meta-stable. The codes can be expected to adapt to the opportunities provided in the historical layer. As noted, the codes can remain flexible and evolving, since they are not given and directly observable—as in the case of biological DNA—but have the status of hypotheses [58,62]. Consequently, one needs a measurement theory for testing assumptions about their interactions and evolution against appropriate data.

5. The TH Indicator of Synergy

Entropy statistics [85] enables us to model the trade-offs between variation and selection in the case of three or more analytically different dimensions. Mutual information in three (or more) dimensions can be positive or negative [86,87]; cf. [68]: when *positive*, this value suggests that the generation of information—that is, historically observable variation—prevails; when *negative*, the generation of redundancy—the complement of the information to the maximum entropy—prevails, and uncertainty is reduced. Uncertainty can be reduced to the extent that negative entropy is generated.

One can use the generation of negative entropy—that is, redundancy—as an indicator of synergy and systemness. We have applied this information-theoretic approach to studying the knowledge base in a number of country studies (listed in Appendix A and discussed in [75]). In these studies, we use firms as the units of analysis and specify three codes as most relevant in innovation systems: (1) firm addresses (ZIP or postal codes) in the geographical dimension; (2) NACE—*nomenclature statistique des activités économiques dans la Communauté européenne*—codes developed by the OECD as indicators of the technological capabilities of firms; and (3) size-classes as proxies for organizational formats, such as small- and medium-sized firms versus large corporations. ZIP codes, for example, vary over geographical regions; however, in reference to the other two dimensions, the distribution of ZIP codes indicates local constraints operating as a (non-market) selection environment.

A locus of negative information can also be considered as a niche in the entropy flow: more options are available than the realized ones. However, positive values of this indicator (mutual information in three or more dimensions) may indicate strength and adaptiveness in terms of past performance, since available options have been realized historically. In such a more mature stage of a cycle, the dynamics of innovation are very different from those in a configuration where not-yet-realized options prevail [4]. Following the distinction between Schumpeter Mark 1 and Mark 2, Soete and ter Weel [88], for example, distinguished "creative agglomeration" from "creative destruction". Abernathy and Clark [89], speak of "strategic vectors of industrial development" (see also [90]).

6. Further Perspectives

Contrary to the metaphor of Big Data, we argue that the knowledge is not in the data, but in the quality of our handling of the data using models. Using the metaphors of KBE and TH, the data is not "given" in nature (or by God) but constructed in previous cycles. For example, the garden of my house in Amsterdam is a current state where previously there were meadows and before that only the sea. Our knowledge-based capacity to change the "natural" environment is the source of innovations [91]. This capacity is stored in books and archives as footprints of codifications of communication.

The Fourth Industrial Revolution is not a natural event, but a metaphor which has been constructed by Schwab [1] and others on the basis of earlier "Industrial Revolutions". The articulation of this vision provides us with hypotheses that challenge us to consider the historical developments as instantiations of knowledge dynamics in the techno-economic evolution. Opening the black boxes of these drivers of the Fourth Industrial Revolution can make the results of innovation studies relevant for explanation [53,92]. The domain is then no longer specified only in terms of industrial development and political consequences, but also in terms of the three subdynamics of TH: knowledge production, wealth generation, and regulation.

A next crucial step is to consider observations as opportunities for specifying theoretically informed expectations that can again be tested against observations. The empirical design can thus become theoretical—expectation-driven—as different from historical and visionary [93]. Max Weber [94], already warned against the temptation of historicism:

> In the interest of the concrete demonstration of an ideal type or of an ideal-typical developmental sequence, one seeks to make it clear by the use of concrete illustrative material drawn from empiricalhistorical reality. The danger of this procedure which in itself is entirely legitimate lies in the fact that historical knowledge here appears as a servant of

theory instead of the opposite role. It is a great temptation for the theorist to regard this relationship either as the normal one or, far worse, to mix theory with history and indeed to confuse them with each other.

Expectations can be theoretically informed; interactions among different codifications generate new opportunities as options [55]. These options point to the potential domains of a Fourth Industrial Revolution as a pending regime of expectations.

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