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Conceptual definition of technology emergence: A long journey from philosophy of science to science policy

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ABSTRACT

Technology and innovation policy has been the core of economic development since the 1950s. Moreover, the increasing rate of technological developments allowed policy and strategy makers to think about technology emergence for proactive planning. In this sense, technological emergence became popular with different applications and foresight studies. However, even though it is a popular concept in the literature, an accepted formal definition is lacking. In this study, we propose a definition based on review as; "**Technological emergence** is a cyclic process in highly creative scientific networks that demonstrates qualitative novelty, qualitative synergy, trend irregularity, high functionality, and continuity aspects in a specified time frame". We discuss and explain the definition by demonstrating it in a multi-dimensional model to make it understandable and applicable for future studies. Finally, we discuss it with existing literature and propose future implications.

1. Introduction

"We dance 'round in a ring and suppose,

But the Secret sits in the middle and knows." By Robert Frost

Technology emergence has been subject to scholarly works since Schumpeter put technology at the center of economic development. Especially after Solow [1]'s discovery of the limited explanatory power of neoclassical principles, knowledge has been understood as an additional factor of production. Then, technological, organizational, and institutional changes were viewed by evolutionary economists as the core drivers of economic growth. In this respect, economic emergence, as well as technology emergence, became popular factors for decision makers to understand these shifts by examining time series data. Such data may be accepted as the more powerful explanation for present phenomena than any derivations from formal logic. Moreover, technology emergence attracts policy makers' attention for two reasons: 1) changing status quo capabilities [2] and 2) focus on early warning indicators, because of the long gestation periods of many emerging technologies [3].

Therefore, identifying, tracking, and conceptualizing ideas about emerging technologies have become popular research subjects since the twentieth century. At first, the emergence concept surfaced in science regarding understanding striking changes in biology, chemistry, and physics. Then, emergence became popular in the philosophy of science at the end of the twentieth century with discussions on the nature of emergence.

Increasing understanding of the concept in philosophy attracted different scientific groups. For instance, these discussions inspired complexity researchers to examine emergence in complex systems from the 1930s. Complexity theorists also tried to explain different aspects of the emergence concept with self-organizing and synergistic characteristics. In addition to philosophy of science scholars and complexity theory researchers, economists also discussed the same concept from an evolutionary economic perspective. Some economists asserted that "emergence" from an evolutionary economic perspective differed from that under study in the biological sciences.

As briefly reviewed, there have been on-going discussions for understanding emergence in literature of three different academic domains. In these literature, the emergence concept has been interpreted by considering the inherent dynamics. In this study, we aim to interpret emergence in a technical/technological context, considering its diverse

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aspects and applicability.

Many studies aim to conceptualize and model [4] emerging technologies. Moreover, while conceptualizing and modeling technology, many phrases appear in the literature for interpreting the technological change with “emerging technologies”, “disruptive technologies”, “innovation”, “invention”, etc. Rotolo, Rafols, Hopkins, and Leydesdorff [5] explained the differences and similarities among these concepts by evaluating them from the philosophical perspective. Based on his findings, the “emerging technologies” concept differs from others with its understanding from other disciplines [6]. It is also thought that the concept is mostly used with its dictionary definition, which might degrade its actual understanding.

It should be emphasized that these efforts are not solely on describing the nature of emergence and its aspects—except for Rotolo et al. [7]'s study. However, as Teran [6] stated, Rotolo et al. [7] considered “emerging technology,” not “technology emergence.” Moreover, we couldn't find any conceptual paper that describes the technology emergence concept by considering its theoretical background. Therefore, we define our research questions as follows:

1. What is technology emergence?
2. What are vital aspects of technology emergence?
3. How can technology emergence be interpreted for developing technology policy and business R&D strategy when scientific and technological change are considered?

By answering these questions, we aim to propose a definition for technology emergence and describe its aspects for future business strategies and for technology policy development. The study is outlined as follows. In the second section, we review the theoretical background of emergence by synthesizing different perspectives and describe emergence aspects in the abstract. Then, in the third section, we review scientific and technological change models for establishing a bridge between technology emergence and policy/strategy making. Finally, in the fourth section, we propose the definition of technology emergence through a process-oriented perspective and develop a model by considering theoretical foundations. Findings are summarized and discussed in the concluding section.

2. Theoretical background of the emergence concept

We review the concept in three different literature on emergence. Our rationale on reviewing these three academic streams is (1) understanding the nature of emergence by reviewing the philosophy of science literature; (2) exploring the emergence concept's systemic side with a complexity theory perspective; and finally, (3) solidifying the findings on technology and innovation literature by reviewing the related evolutionary economic studies. It is clear that the emergence concept was not considered from a technology point of view by philosophy of science and complexity scholars, but we believe that by understanding the nature of emergence the findings will convey us to interpret emergence concept for technology.

2.1. Philosophy of science perspective

Emergence as a concept has been discussed intermittently by philosophy of science scholars since the nineteenth century. Teran [6] proposed a schematic overview in his study and traced back emergence to Mill's 1843 study. Sartenaer [8] dated the emergence concept to 1875 [9] and expressed that the term was first coined by George Henry Lewes for distinguishing resultants and emergents.

Goldspink and Kay [10] and Sartenaer [8] divided “emergentism” in philosophy of science into four periods. The first period was in the nineteenth century, and included the works of John Stuart Mill (1843), Alexander Bain (1870), and George Henry Lewes (1875). Stephan [11] called the first period “proto-emergentist”. The second period was in the early twentieth century and concerned the attempt to offer an alternative to mechanism and vitalism by introducing a third theory called emergentism. Emergentism may be called “British emergentism,” with the seminal works of Samuel Alexander (Space, Time and Deity, 1920), Lloyd Morgan (Emergent Evolution, 1923), and C.D. Broad (The Mind and its Place in Nature, 1925). Sartenaer [8] added Whitehead to the second period and asserted that, with Morgan, they were the pioneers of British emergentism. They rejected vitalism and dualism, accepting the materialist ontology that only physical matter existed. The third period was in the 1940s, and during this period there were discussions on emergentism with novelty and non-predictability aspects by W.T. Stace, P. Henle, and G. Bergmann. The third period was also described using the studies on cognitivist rejection of behaviorism. This rejection conveyed a discussion with individualists' “mind is nothing more than the biological brain” proposition versus dualists’ “mind and brain are distinct.” Sawyer [9] described this period as a “reductionist interlude.” Notable works include Hempel (1948) and Nagel (1961). The fourth period was defined by Sartenaer [8] as taking place in the 1970s. He further defined this period with a discussion on psychophysical problems of emergence. Stephan [11] furthered this timeframe to include the 1990s and described this time period with studies that focused on core concepts in the computational modeling of complex systems, including connectionism, artificial life, and multi-agents of social systems subjects. Sawyer [9] pointed out that as for today, the conceptual landscape of emergence became very complex with its conceptual spread on different contexts.

Through this brief, chronological description of emergence, it can be asserted that emergentist philosophy understood the term “emergence” differently. At first emergentist theories made statements about the world using two aspects as synchronous: its compositional structure, and evolution (or “becoming”)—the diachronous aspect. The synchronous aspect could be characterized by the idea that a whole could have genuinely different properties than parts. It should be noted that some properties as a whole could not be explained by deducing from the properties of parts; such properties are called emergent, as opposed to resultant properties. In this sense, the diachronous aspect dealt with the appearance of new things with new properties over time. Through this perspective, qualitative novelty was important. It is thought that these new properties could not be predicted with even perfect knowledge of the old properties. Also, it should be emphasized that emergentism was interested in qualitative change and not just quantitative change.

According to Sartenaer [8] emergence would signify a kind of change. Based on his description, this change occurred in three different ways as the assertion of a cosmic irregularity; a shift where one character replaced another; or a cumulative change in which certain characteristics supervened upon other characteristics. Then, he emphasized that the emergent evolutionists should admit a thorough regularity in nature. Actually, Pepper [12] supported this idea by emphasizing Darwin's quote of “Law of Continuity” and incremental nature for evolutionary change. From this aspect, it could be expressed that “continuity,” “unexpectedness,” and “uncertainty” are important dimensions for detecting emergence when the subject is handled with evolutionary perspective.

Corning [13] summarized widely agreed characteristics of emergent entities as (1) characterization of higher-order descriptions; (2) obedience of higher order laws; (3) characterization of unpredictable novelty; (4) composition of lower level entities; and (5) lower level entities’ insufficient accountability of emergent entities.

Goldspink and Kay [10] first tried to describe the working definition of emergence by considering the relation between an emergent and its emergence basis. He said that an emergent might be ontologically determined by its emergence basis and understood as qualitatively novel or untraceable. Qualitative novelty was explained in the study as an ambiguous expression. Untraceability was defined as the failure of determinative traceability. Even if it was thought to be untraceable, Sartenaer [14] proposed that a higher degree of organizational complexity might exhibit novel properties. From this statement it can be asserted that these properties might not be predicted, but they might be expected based on the increasing measure of complexity in organizations or domains. Kim [15] supported the predictability proposition by dividing it by inductiveness, theoretical predictability, and emphasis on inductive predictability of emergent properties. These statements encouraged us to think more about predictors of technological emergence.

Because the technology context may be accepted as a social network, an emergence concept should also be examined from the sociological perspective. Kim [15] differentiated social systems from other fields with human agents' cognitive aspects and emphasized the theory of autopoiesis, which was described as humans coordinating their action by way of communication. They proposed the hologram analogy for describing the whole with consideration that the removal of every part (agents) might reduce the resolution, with this analogy stressing coherence in collaboration networks and pattern formation. Goldspink and Kay [10] emphasized that for all emergentists, interaction was a central issue and asserted that higher-level properties emerged from the interaction of individuals in a complex system. Also, the complexity of interaction among components might be another variable contributing to emergence. He also compared individualists and collectivists in his study; from the collectivists' perspective he explained irreducible systems with nonaggregativity, near decomposability, localization, and complexity of interaction characteristics. Sawyer [9] expressed that most social properties were not aggregative and thus they should be treated as emergent. He furthered that connectionist models suggested that the density of network connections was related to localizability and decomposability of the system and proposed that dynamic density increased as communication and transportation technology advanced.

Finally, we found that emergence in philosophy of science was described with different perspectives and did not reach a consensus on definition and aspects. Table 1 summarizes aspects.

When these aspects were examined, we could see that qualitative novelty, non-reducibility, and unpredictability were the features that came from scholars in this field with different definitions and criticisms. Therefore, we realized that these aspects might be reinterpreted and described based on the focused technology context. Moreover, in these discussions, the nature of emergence demonstrated to us that we needed to search in technological contexts for qualitative novel properties, which should also meet unexpectedness and irregularity.

2.2. Complexity theory perspective

Discussions on emergence and emergents inspired complexity theorists to interpret this notion from the adaptive systems perspective. As in the philosophy domain, there also was not a consensus on a definition in complexity theory For instance, Stephan [11] compared different definitions of emergence with different disciplines. He stated that it was hard to decide on a concrete and comprisable definition. However, as Corning [13] stated, the broader the concept's extension, the weaker its instructive value. Thus, we focused our research more on definitions and aspects of emergence.

Table 1
Summary of philosophy of science perspective on aspects of emergence.

Aspects of Emergence	Source
a. **Emergence is an empirical relation between two entities: an emergent and its emergence basis;** b. The emergent is dependent and autonomous from its emergence basis; c. The emergent is ontologically determined by its emergence basis and the emergent is qualitatively novel with regard to its emergence basis; d. Emergents are somehow untraceable from their base.	[9]
a. **Unpredictability,** b. Irreducibility.	[14]
a. **Downward causation,** b. Theoretically unpredictable but Inductively predictable, c. Not reductively explainable, d. Not resultant.	[12]
a. **Non-additive,** b. Novel, c. Non-predictable, d. Non-deducible.	[15]

Sartenaer [16] proposed that emergence was produced with “self-organizing” processes. He cited Doyne Farmer's quote on emergence to demonstrate the concept's high ambiguity as, “It's not magic… but it feels like magic.” Then, he proposed synergy as an important aspect of emergence. He defined synergy as, “the combined effects that are produced by two or more particles, elements, parts or organisms—effects that are not otherwise attainable.” He understood synergy as the “functional complementarities” perspective that has the ability to affect the whole with its new combinations. Therefore, he proposed emergent phenomena as “a subset of the vast (and still expanding) universe of cooperative interactions that produce synergetic effects of various kinds, both in nature and in human societies.” He added that “this definition would be limited to qualitative novelties, unique synergistic effects that were generated by functional complementarities, or a combination of labor.”

Corning [13] articulated synergism with his proposition of increasing the number of component units, which may increase the likelihood of emergent higher-level properties. However, Corning's definition should not be understood as implying that all synergistic effects would entail emergence without modifications, reshaping, or transformations. Then, he asserted that self-organization may not be understood as necessary for all conditions [17]. From these assertions, we realize that the synergistic effect might lead us to determine technological emergence in scientific databases when we apply a network perspective appropriately. However, we should keep in mind that this synergistic effect should be accepted with its qualitative form, which we assumed has potential for modification, reshaping or transformation.

From a different perspective in complexity research, Corning [13] characterized the levels of emergence as considering it as a new, natural kind. This new, natural kind might appear when science, mathematics, or philosophy would introduce new ways of looking at nature leading to the recognition of regularities not perceived before. From this assertion we thought that this perspective put forward the evolutionary perspective and might be applied to a technological context with Fisher-Pry trends based on technological substitutions. Under this assertion, the new, natural kind might become dominant in technical and technological contexts while it had potential to solve the existing technical/technological or societal problems. However, it was clear that this process has been cyclical and the nature of evolution has forced the dominant design continuously to transform the whole incrementally or radically with unexpected and unpredictable ways.

Goldstein [18] connected emergence to creativity processes in his study and proposed a thesis that emergent and creative processes that demonstrated collaboration and network characteristics [19], shared a common logic for novelty generation. In this sense, Lee, Walsh, and Wang [20] proposed an “artificial societies” concept, emphasizing the collaboration and negotiations of autonomous computational agents between each other in self-organizing fashion, without understanding it with a mechanistic perspective and preferred agent-based modeling. Sawyer [17] exemplified his proposal on a creativity relationship by demonstrating the use of emergence by scholars such as Bergson's “creative evolution,” C.L. Morgan's “creative synthesis,” Whitehead's “a general theory of creativity,” and Prigogine's description of self-organizing emergence as a creative process [19]. Therefore, from Goldstein's analogy we realize that tracking the creativity process in science, technology, and knowledge databases might lead to identify and track technological emergent properties. In support of his proposal, Goldstein [21] also claimed that radical novel outcomes might be reached after improvising or negating the past patterns. Hence, we thought that a paternalistic approach might work for identifying radical novelty. However, even as we focus on creative networks, we think that the qualitative nature of novelty might be again problematic and need experts'[1] judgments. Moreover, we proposed that in the judgment process, expert opinions might focus on newness, originality, and changing potential of a pre-existing pattern.

Munier and Ronde [22] explained five necessary characteristics of emergence with radical novelty (with consideration for the explanatory gap of emergence); coherence/collectivity/wholeness; global or macro level; ostensive; dynamical concepts; and proposed self-transcending constructions (STC) as a feature of emergence that considers the emergence phenomenon with a processual perspective. He also emphasized that if an emergent didn't display that it both followed and was discontinuous with the substrates from which it emerged, then it didn't warrant being labeled emergent. With this assertion, it can be interpreted that continuity may be accepted as an important component while tracking emergence. Goldstein [23,24] analyzed continuity with persistence and illustrated that research with greater staying power was deserving of special attention, by using different datasets. However, the arguments related the persistence with resultant properties, while aiming to identify emergence with a predictive approach. In this aspect, we should assert that persistence might not be considered as continuity, which was defined by complexity literature when the discussions in the old-new and whole-part relationships were considered [25].

Like the creativity analogy, Hofkirchner [26] proposed the discovery process analogy and explained emergence as a process that led to the appearance of a structure not directly described by the defining constraints and instantaneous forces that control a system. He emphasized "something new" for emergence and discussed "something" and "new" in his study separately. In this discussion, he proposed two new features as unpredictability and self-similarity, and emphasized the role of newness from the eye of the observer. With newness, novelty was also mentioned in his study and he ranged novelty spanning from "obvious" to "purposeful" on the spectrum. Crutchfield [27] questioned this newness problem in emergence because he posited that it was always referred to outside the system by some observer that anticipated the structures via a fixed palette of possible regularities. Finally, he summarized his findings with three notions of emergence as (1) the intuitive definition of emergence: "something new appears"; (2) pattern formation: an observer identifies "organization" in a dynamical system; and (3) Intrinsic emergence: the system itself capitalizes on patterns that appear.

Moreover, Crutchfield [27] distinguished discovery from emergence through two issues. First, discoveries are atemporal. This is because the change in state and increased knowledge of the observer are not the focus of the analysis activity, but emergence is dynamical in an evolutionary system. He stated that emergence concerns the process of discovery. Therefore, we considered that understanding the discovery process with its dynamics might lead us to understand technological emergence.

In a recent study, Crutchfield [27] defined the emergence principle through the complexity perspective as "new properties of systems [that] emerge with the increase of their complexity; these properties are qualitatively different from the properties of parts of the systems and irreducible to them." This definition implied that emergence should contain some aspects as qualitatively different and irreducible.

Finally, after explaining the definitions and aspects in literature and defining the main actors in the field, we summarize complexity theory approaches on emergence in Table 2.

[1] An expert was defined in Munier and Ronde [22]'s study by citing Paradiso as an individual with his/her qualitative and practical knowledge. They emphasized that it was his recognized knowledge, which guided his behavior and his choice between various possible orientations for a given subject.

Table 2
Summary of complexity theory perspective on aspects of emergence.

Aspects of Emergence	Source
a. **Something new appears, newness,**[a] b. Unpredictability, c. Self-similarity	[28]
a. **Radical Novelty,** b. Coherence/Collective/Wholeness, c. A global or macro level, d. Being the product of a dynamical process, e. Being ostensive (downward causation), f. **Self-transcending constructions**[b].	[21,23,24]
a. **Subset of the 'vast',** b. Continuity c. Unlike kind or Qualitatively Novel, d. Unique synergistic effects that are generated by functional complementarities, or a combination of labor.	[13,21]
a. **Presence in a macro-state and not in microstate,** b. Nonlinearity, c. Demonstrating Weak Emergence Properties, d. Novelty, e. Emergence as a process	[29]
a. **Serendipitous novelty** b. Inability to anticipate	[30]

[a] For Crutchfield [27]; newness was in the eye of the observer. However, he ranged the newness or novelty (he used these terms interchangeably) from "obvious" to "purposeful." Therefore, it can be asserted that observer dependency makes the novelty detection a qualitative process. From a different perspective, newness can be described as an index of sociocultural significance and transformative power [28].

[b] Goldstein [21] referred to self-transcending constructions as the dual nature of emergent, which were followed from, derived from, or continuous from which they emerge. Also at the same time, transcending the forms, dynamics, functionings, laws, and principles operating at a lower substrate level.

We thought that the aspects proposed by complexity theorists might be more applicable in a technology context. Therefore, in addition to a philosophy perspective we found additional aspects for emergence as a qualitative synergistic effect and a creativity analogy. Moreover, we understood that quantitative newness should be supported by expert judgments to convert these findings to qualitative newness, which was more appropriate for describing technological emergence.

2.3. Evolutionary economics perspective

Finally, evolutionary economics was the last academic stream we considered for analyzing the emergence concept in literature. The evolutionary concept was associated with economics due to Schumpeter's ideas on the importance of innovation in economic growth and creative entrepreneurship at its core. Holland [31]; whose seminal contributions were accepted as initial in a contemporary surge in evolutionary economics [32], identified evolutionary economics as "simply an attempt to look at an economic system, whether of the whole world of its parts as continuing process in space and time." In this respect, we asserted that the dynamism of the economic system made scholars handle economics with an evolutionary perspective. However, despite Boulding's definition of evolutionary economics and considerable influence of American Institutionalism [33], based on Foster [34]'s explanations, Schumpeter rejected applying biological selection metaphors to economics.

Beyond these discussions, there were limited studies applied with principles of emergence and complexity science to economics, while combining an evolutionary perspective to economics by interpreting them innovatively. We identified two main flows in economics regarding emergence research: the first one was complexity-inspired and the second one was philosophy-inspired.

Dawid [35] reviewed the relationship between complexity and evolutionary economics of innovation in their studies. They identified two pathways of complexity in economics history. First, the path focused on issues such as self-organization and self-transformation. The second path described concepts of feedback and divergence. Robert and Yoguel [36] maintained a complex adaptive system's approach to economics. He explained its application explicitly in his paper by emphasizing the role of emergence.

As Goldstein proposed, Foster [37] asserted that entrepreneurship would be accepted as a catalyst for emergence and tracking creativity, which couldn't succeed in isolation and might lead to economic emergence. Moreover, they emphasized that emergence occurred in an economic process starting with a novelty generation and ending with competitive selection. They added that economic order and emergence were inseparable, calling it a “continuity hypothesis” where economic evolution could not be viewed as analogous to biological evolution with its socioeconomic characteristics.

Actually, in evolutionary economics, economic agents were interacted and formed radically new bundles of rules, which could be called “genuine novelty,” and could take the form of capital goods, productive networks, contracting systems, and human skills. Foster and Metcalfe [38] proposed that enacting these bundles of rules would involve a process of “self-organization” and “unpredictability” with regard to patterns of structure that ultimately form. From their assertions, we might foresee that such unpredictability was diminished by a process of “competitive selection” with domination of new technological, organizational, or institutional rules. Thus, in this cyclic process, the current system consistently has changed and evolved and resulted with creation of an evolution in the economic system.

As stated in the philosophy part, unpredictability is an important aspect for emergence. Foster and Metcalfe [38] partially rejected the unpredictability rule and asserted that although innovations were accepted as uncertain, and for this reason in most evolutionary-economic models treated as stochastic, it would be incorrect to consider the process of innovation as totally random. They emphasized that innovations might be expected to occur in a systemic manner by tracking the cumulativeness of relevant technical advances. This assertion encouraged us to believe that with measuring cumulativeness of technological advances appropriately, we could predict or identify technological emergence and would help policymakers or strategy makers more on their future decision-making processes.

The first focused study on economic emergence with complexity inspiration was Antonelli and Ferraris [39]'s study. They studied the anatomy of emergence in economics by defining emergence as the outcome of self-organizing, bottom-up growth in agent-based models of complexity. Their perspective might be understood as a complexity-based approach. Based on their findings, evolutionary-institutional economics saw genuine novelty as the single most important hallmark of economic emergence, which was identified and conceptualized by Harper and Endres [40]; with Schumpeter's notions of adaptive and creative response. Moreover, emergent patterns and institutions might also exert downward causal effects at the micro-level through changing individuals' habits, purposes, and preferences [33]. For economic patterns, Hodgson [41] suggested four core characteristics to describe emergent properties. These are:

a. *Material Realization:* emergent patterns are realized in physical structures and processes;
b. *Coherence:* the pattern is not a mere aggregate, but a systemic whole (“a network”) whose components are connected and interact;
c. *Non-distributivity of systemic properties:* the entire pattern possesses at least one systemic (e.g., global) property that none of its components has;
d. *Structure-dependence of systemic properties:* systemic properties of the pattern depend upon the composition of the system (the set of its elements) and its connective structure (the organization of its elements).

They stated that these four core features were common to all forms of emergence in economics. Besides these core features, they proposed the following additional features because they expressed that economic patterns exhibited extra-strength versions of emergence in evolutionary economics:

a. *Genuine Novelty:* the pattern is a genuinely novel structure that is qualitatively different from the patterns from which it emerged;
b. *Unpredictability in principle:* the first-time appearance of a new type of economic pattern could not be predicted through a rational procedure;
c. *Irreducibility:* the systemic properties of the pattern did not follow from the properties of the system components in isolation or in simpler systems.

After proposing aspects of economic emergence and analyzing emergence structures for capital goods, Harper and Endres [40] concluded that emergence occurred every time, if there was an appearance of a qualitatively new good, technology, design, routine, organizational capability, firm, network, market, or industry. However, they emphasized that the emergence may have synchronic and diachronic aspects [40]. This means that emergent patterns may demonstrate irreducible features, and novel and unpredictable properties, by having a certain kind of causal history.

A second notable study on economic emergence by Harper and Endres [40] put forward four key concepts through a philosophy of science perspective:

a. *Supervenience:* A set of properties *A* supervened upon another set *B* just in case no two things could differ with respect to *A*-properties without also differing with respect to their *B*-properties;
b. *Irreducibility:* A systemic (higher level) property or phenomenon was said to be emergent if it was irreducible, that was it could not be reductively explained in terms of the properties of the system's lower-level constituent component parts;
c. *Self-organization:* The spontaneous (non-planned or non-imposed) emergence and dynamic self-production of spatio-temporal patterns, structures, or functions in systems arising from the actions and interactions of their lower-level components or elements.
d. *Downward causation:* The idea that higher level emergent properties, patterns, or phenomena cause, determine, regulate, or influence lower-level properties and parts, either in those component entities or in their interactions.

Through these aspects, Martin and Sunley [42] proposed that economic emergence might create two different outcomes – destroying existing trends or adapting them to new conditions. It might be interpreted as radical or incremental innovation.

Finally, notable aspects of economic emergence are summarized in Table 3.

According to Table 3, it is clear that we couldn't find more aspects than before because the inspirational roots of economics were philosophy and complexity. Upon review, we realized the importance of entrepreneurship in the creation of emergence in evolutionary economics, and, through this perspective, we thought that an analogy might be created considering scientists and patent assignees in knowledge databases for tracking technological emergence. In addition, with Martin and Sunley [42] assertion, we believed that we could ease the unpredictability aspect of the philosophy side for technological emergence search and prediction.

Consequently, through this review, we decided to propose aspects of technological emergence as (1) a qualitative novelty, (2) a qualitative synergistic, (3) an irregular trend, and (4) continuous. We discuss this definition more in explaining the proposed conceptual model.

Table 3
Summary of economics perspective on aspects of emergence.

Aspects of Emergence	Source
a. **Material Realization,**	[42]
b. Coherence,	
c. Non-distributivity of systemic properties,	
d. Structure-dependence of systemic properties	
e. Genuine Novelty,	
f. Unpredictability in principle,	
g. Irreducibility.	
a. **Supervenience,**	[40]
b. Irreducibility,	
c. Self-organization,	
d. **Downward causation.**[a]	

[a] Beyond these characteristics, Harper and Endres [40] put forward three orders of emergence: first order emergence, second order emergence (morphodynamic), and third order emergence (developmental or evolutionary).

3. Review of perspectives on scientific and technological change

To embed technological emergence in science, technology, and innovation policy discourse, we now review the scientific and technological change. Science and technology proceed in an evolutionary fashion with theories, tools, and applications continuously. One of the best known theories of scientific change is Thomas Kuhn's scientific revolutions [39]. Kuhn considered scientific progress through a series of revolutions. In these revolutions, paradigms were continuously replaced by new ones. Kuhn used paradigm as a broad concept covering all rules, methods, and consensus knowledge upon which a group of scientists agree, which is enough to employ regularly within a discipline. According to Kuhn's structure of scientific revolutions, science would advance in an iterative and cyclic process, which would consist of several stages: (i) pre-paradigmatic phase, (ii) normal science, (iii) crises, and (iv) revolutions. Current paradigm dominates the research in fields that were considered to be at the normal science stage. According to Kuhn [43]; Kuhn distinguished normal science from revolutions and thought that scientists worked to develop and deepen the paradigm by putting forward definitions and answering the outstanding questions. Usage of tools and solving the problems by utilizing the current paradigm helped scientists feel comfortable during this period. However, anomalies were recognized and became inevitable and they challenged the foundation of the current paradigm at the crisis stage. In this stage, disagreements were revealed and questions on the current paradigm arose. At the revolutionary stage, compelling evidence was accumulated and competing paradigms became mature enough to take over the existing paradigm that had been evidently incapable of handling the pressing crises. As a result, a new paradigm would replace the existing one and provide an overarching framework for the research community. This process repeats itself as the new paradigm becomes the norm. From now on scientists took this new norm as normal science. However, Kuhn had several criticisms with relativism and incommensurability in the reviewed literature and Paker [44] gave answers in his book defending his hypothesis. Although some criticisms remained unaddressed, his ideas should not be expected to measure revolutions, disruptions, or emergence through a positivist manner because of their recognized nature of ambiguity and complexity. Beyond these criticisms, we assert that technological emergence might be expected in the crisis stage.

Furthermore, Kuhn [43] proposed a post-Kuhnian perspective in their study on scientific change called “Repertoires.” They focused on collaboration intensity with an assertion that their approach permitted one to investigate the interrelation between various components of scientific practice. Through this perspective, they assumed that the concept would provide a framework that could facilitate a more comprehensive view of the drivers of scientific change [45]. From their assertion, we thought that a science mapping/visualization perspective might be compatible for understanding the scientific change properly, considering the collaboration focus of the authors. We also interpreted from their study that increasing scientific collaboration intensity might give clues on possible technological emergent outcomes.

Ankeny and Leonelli [45] challenged the Kuhnian paradigm shift model as an oversimplified view of complex reality. Therefore, Fuchs [46] proposed that task uncertainty and mutual dependence were the two variables that interacted to yield four types of scientific change. Task uncertainty referred to the level of uncertainty involved in the course of scientific inquiry. Task uncertainty was high in scientific frontiers where research was essentially exploratory in nature and there was a high amount of tacit knowledge involved. In contrast, task uncertainty was low in areas where tasks were routinized. Mutual dependence referred to the social and organizational dependencies between scientists and their competing peers. A combination of high task uncertainty and high mutual dependence would lead to original scientific discoveries. A combination of low task uncertainty and high mutual dependence would result in specialization to maintain the tension between scientists with high mutual dependence while they worked on routinized research. Through this perspective, we propose that the more competitive the scientific environment, the more possible to expect technological emergence.

Another theory on the evolution of scientific discipline was proposed by Fuchs [46]. Based on his proposal, the evolution of a scientific discipline was divided into four stages as (1) the conceptualization stage; (2) the tool and instrument development stage; (3) the investigation of the research questions supported by the newly developed enabling techniques stage; and (4) the transferring tacit knowledge to codified and routinized knowledge stage. We asserted that emergence might be seen in the fourth stage while creating and codifying the knowledge.

Shneider [47] proposed to use a self-organized criticality model, which they thought was different from the Kuhnian model for tracking paradigm transitions. They used entropy statistics to enable relating micro-developments in the data, theorizing about the sciences in terms of distributed change. They assumed that new knowledge claims in manuscripts continuously generated journal-journal citations potentially leading to an equivalent of “avalanches.” These avalanches could occur anywhere with different outcomes, but with local consequences within the discipline or specialty. They asserted that while it was impossible to say where change would occur, emergence would be expected. Sciences with continuities were needed for the accumulation of a knowledge base, but discontinuities provided options for reorganization.

After reviewing scientific change perspectives in literature, we see that technological change can be understood by evolutionary economists with cyclic perspectives (Loet [48], generally described by models of technology evolution incremental innovations punctuated by periods of radical innovations that spur the emergence of new technologies [49]. Cattani [50] discussed this cyclic perspective with path-dependence characteristics and proposed that evolutionary views take this issue with a process of understanding. In these cyclic perspectives, the concept of technology might be used differently in the literature that was discussed by Dosi [51]. They found that distinguishing technology from product was not possible through definitions. In their review of definitions, “technique” was included in all of them. Taylor and Taylor [52] commented on technology cycles by combining them with waves. They argued that cycles provided space for these waves, which could be considered as up and down fluctuations on a landscape that was evolving cyclically in terms of regimes. Moreover, they proposed that corresponding time cycles of knowledge-generating paradigms could be approximated with Fibonacci numbers for forecasting future changes at the systems level [49].

According to Ivanova and Leydesdorff [53]; the technology life cycle is related to the concept of technology paradigms and these paradigms designate technology platforms for successive generations of technology. From a network perspective, Kim [54] state that no technology works in isolation, and at each level it needs to coordinate and be compatible with other systems or products. This aspect made it a more complex process and with an increasing non-linearly related number of actors. External network relationships were also discussed by Suarez [55] with the technological speciation concept, and he asserted that technological speciation would occur when selection forces in a new domain were significantly different from those faced in the other domains. Cattani [50]'s proposition might be accepted through an adaptation perspective, and he discussed that novelty might be generated by selection acting upon existing variations. However, it was not explained how this variation was created in the first place.

The seminal work that might be accepted in technological change was Cattani [50]'s study in which they applied the evolutionary perspective. They proposed a cyclical model and put emphasis on the emergence of dominant designs, which were classified as competence-destroying and competence-enhancing technological discontinuities. They asserted that technological discontinuities would occur continuously through two phases, which were called an era of ferment and an era of incremental change. Dominant design differentiated these two phases through its emergence. By applying cases and testing their hypotheses, they found that the competitive environment changed in repeated patterns over time. This change was linked to systematic environmental change. From this cyclical model we could assert that even though it was not possible to identify and forecast technological emergence beforehand, it might be possible to track its development in an era of incremental change.

Anderson and Tushman [56] offer another technology life cycle model. Their model was designed with three phases: the fluid phase, transitional phase, and specific phase. Based on Abernathy and Utterback [57]; Utterback added the discontinuity phase later as a fourth dimension. Roberts and Liu [58] asserted that the emergence of dominant design was expected to start a transitional phase. Therefore, for searching and predicting technological emergence, it might be useful to understand the weak signals of the fluid phase's end and antecedents of the dominant design. Because the proposed model was based on the product life cycle with consideration for the market dynamics, we could propose it to utilize patent data and economic statistics for technological trend detection and prediction [59–61]. While using patent data, some shortcomings stated by Jarvenpaa, Makinen, and Seppanen [62] should be kept in mind.

B. Kim [54] was uncertain on the technology life cycle context since "unpredictability" was in terms of performance, utility, and economics associated with utilizing the technology. Then, he asserted that consumers of the economy adopted a technology with low uncertainty much faster than that with high uncertainty. He described this issue as a less uncertain technology life cycle that would reach its natural maturity earlier than a more uncertain technology life cycle. With this description, it can be said that uncertainty or unpredictability depend on inherent characteristics. Beyond B. Kim [54]'s unpredictability proposition, Cattani [50] introduced a pre-adaptation concept and asserted that in the course of technology, evolution could identify the existence of an ideal cut-off point. In that case, firms accumulated knowledge without forecasting its subsequent applications. The phase in which firms leveraged that knowledge in a new domain had new environmental conditions and possible uses for information.

When distributions were considered, it could be noted that technology progression had been mostly tracked by using the general form of an S-curve, which is thought to reach saturation at maturity. Taylor and Taylor [52] asserted that at this point a new disruptive technology may emerge to replace the old one and the cycle began again. This substituted characteristics of technological progression that might be interrupted with the replacement technology, which demonstrated higher performances than the old ones. From these aspects, it can be asserted that incremental innovations make the S-curve continuous with substitutions and radical innovations having their own S-curves. Therefore, emergence research in technology may have two objectives when the S-curve and its substitutive characteristics are concerned. The first one is tracking and predicting substitutive technologies, and the second one is searching weak signals of radically innovative technologies. This substitutive perspective is studied in literature as the substitution model, which was prepared by Fisher and Pry [63] and tested in tracking three different technological change cases. Before tracking technological emergence, the goodness-of-fit to the Fisher-Pry model may be searched.

Finally, we assert that technological emergence should be handled with a processual perspective as described in scientific and technological change. Moreover, the crisis stage and competitive environment for scientists should be expected as pre-conditions for analyzed domains. We should also consider the cyclical aspect of scientific networks by describing time windows based on quantitative and qualitative outcomes.

4. Conceptual model proposal of technology emergence

After analyzing different, and sometimes contradictory, perspectives in literature, we come to the conclusion that technology emergence could be classified as an "unknown-unknown," as described in decision making literature. However, according to Feduzi and Runde [64]; even emergence and epistemic constraints limit imagining unknown-unknowns by decision makers. Unknown-unknowns could be divided in two with knowable-unknowns and unknowable-unknowns, theoretically. Therefore, we accept technology emergence as knowable-unknowns, which could be transformed from unknown-unknown into knowable-unknowns at some point in time when we considered its cyclic and path-dependent characteristics and accumulative nature of knowledge production.

Furthermore, from a reductionist and individualist approach, we could infer that macro system properties might be tracked via components and parts. In this sense, knowledge and its accumulative nature might rationalize this mechanistic perspective, which was criticized by Sawyer [17] (with citations from Bunge, Hedström and Swedberg) as mechanistic explanations couldn't predict, but only explain. However, by considering qualitative and quantitative models together it was thought to overcome this criticism with incomplete determinism [26] and partly reject the purely mechanistic perspective.

Finally, when we combined three academic perspectives on emergence and scientific change literature, we formed this definition for technology emergence:

"**Technology emergence** is a <u>cyclic process</u> in <u>highly creative scientific networks</u> that demonstrates <u>qualitative novelty, qualitative synergy, trend irregularity, high functionality, and continuity aspects</u> in a specified time frame."

In this definition, we emphasize the importance of qualitative aspects in distinguishing technology emergence with a processual perspective. For a discussion on the components of this definition and proposal of a conceptual model, we depict technology emergence and its aspects, as shown in Fig. 1.

We factorize the technology emergence concept with functionality, qualitative synergy, and qualitative novelty aspects, as shown in Fig. 1. We didn't formulate irregularity or continuity as dimensions in Fig. 1, but we define them as aspects, too. We assume that a higher qualitative novelty, qualitative synergy, and functionality should produce technology emergence, which will demonstrate irregularity and continuity when it is compared with its alternatives. Through this definition, we describe the technology emergence process in a three-phase cycle, which is demonstrated in Fig. 2.

As demonstrated in Fig. 1, we create the cycle sequentially. This cyclic process is inspired by the scientific and technological change literature. Kuhn [43]; Fuchs [46]; and Shneider [47] proposed cyclic structures for explaining scientific change. Moreover, Anderson and Tushman [56] also proposed a cyclic model for technological change.

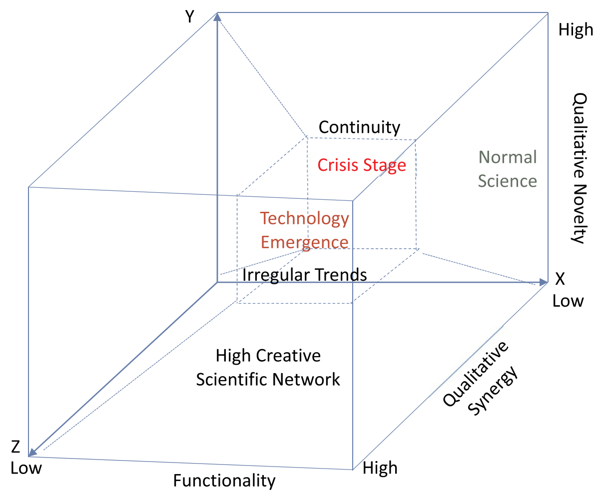

Fig. 1. Conceptual model of technology emergence.

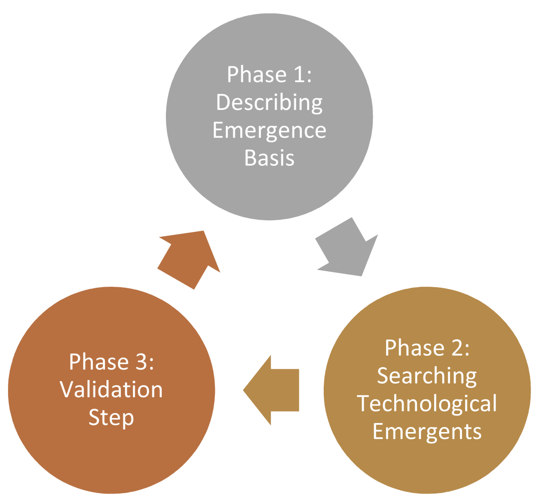

Fig. 2. Three-phase cycle for extracting the technological emergence process.

Because we are looking for novel and irregular changes in scientific domains, we think cyclic models would be more appropriate for searching technology emergents. Although the arrows make us think of a linear model, we reject this thought with consideration for a high interdependence of phases and accept holistic perspectives for increasing future planning adaptiveness.

With this cyclic representation, actually, we divide the process to explore emergence and emergence basis separately, as discussed previously by philosophy of science scholars [14,16]. We assert that to reduce random outputs and decrease irrelevancies in technological emergence, we should describe the emergence basis appropriately.

Therefore, in the first phase (Fig. 2), we assume that without describing the emergence basis appropriately, we might frame [65] our future thinking while coming up with new ideas and concepts because of the randomness of outcomes and the bias of findings. As stated by L. Leydesdorff, Cozzens, and Vandenbesselaar [66]; different perspectives and different inputs might create different outcomes. For overcoming these bottlenecks, we assert that the emergence basis should demonstrate two distinctive aspects – highly creative and highly synergistic. We believe that all scientific networks demonstrate these aspects, but as stated in the scientific change literature, there are some time frames that show that these aspects reach their highest points in Kuhn's crisis stage, or Fuch's high task uncertainty and high mutual dependence period. In an evaluation of the first phase, we aim to determine the state of focused scientific domains before beginning technology emergence research. As stated by complexity researchers Goldstein [19] and Corning [13]; technology emergence might be expected from synergistic and creative networks. Therefore, when taking these assumptions into consideration, we can assert that if we parse the creative scientific network or weigh the products of creative networks higher, then we might increase the probability of finding technology emergence. It is clear that science publication networks are already creative, but as L. Leydesdorff [67] mentioned, it can be divided into two, as parametric and qualitative steering of science. We believe that we should focus on qualitative change for science as proposed by L. Leydesdorff [67]. With these propositions we produce the following priori assumptions as:

A.1 . In highly cited publication networks, the probability of extracting relevant technological emergence would increase (Creative Network).

A.2 . In highly collaborative networks the probability of extracting relevant technological emergence would increase (Synergistic Network).

Measuring creativity might be described as challenging, but for science and economic networks, there are some models and approaches proposed in the literature [65,68]. Moreover, we believe that highly cited papers might be accepted as demonstrating partial creativity. When we examine creativity from the knowledge exchanging perspective and the autopoietic operation of science system, as stated by Lucio-Arias and Leydesdorff [69]; we have seen that citation is a selection process and that it transforms knowledge claims from scientists to accredited knowledge. Therefore, we assume that with this transformation, an evolutionary selection process would take place and “citing” and “being cited” actions further and qualify the future knowledge production process. This idea was also supported with the “creative accumulation” term by L Leydesdorff and Rafols [3]. In addition to the creativity perspective, interdisciplinarity of the emergence basis should also be focused based on the findings of L. Leydesdorff and Schank [70]. It should also be stated that new developments in science may be accepted as a focus point for technology emergence research.

For A.2, we assume that high-collaboration research networks have higher probability to produce technological emergent outputs. This assertion is supported by complexity theory scholars and sociologists. For instance, Sawyer [17] stated that increasing the number of component units may increase the likelihood of emergent higher-level properties. He also emphasized that interaction was a central issue for finding emergence. Moreover, he asserted that higher-level properties emerged from the interaction of individuals in a complex system and the complexity of the interaction among components might be another variable contributing to emergence. Furthermore, as stated by Rotolo et al. [5]; while the dynamics of emergence could be roughly traced by using co-authorship data, it should be noted that many collaborations were not formalized into co-authorship relations. For the collaboration issue, L Leydesdorff and Rafols [3] proposed to utilize a “small worlds” perspective by using slope in degree distributions as indicators of preferential attachment. The rationale was the expectation of newcomers attaching themselves preferentially to leading centers. Finally, we assert that if the emergence basis is low on these aspects, it might produce popular concepts as the outcome, but not emergents. Therefore, phase one might be understood as a verification step for initiating technological emergence research and a layer of qualitative aspect.

After coming to two assumptions on the emergence basis, the second phase (Fig. 2) is searching technology emergence in this emergence basis. In this phase, we aim to find emergent properties that demonstrate qualitative novelty, qualitative synergism, functionalism, irregularism (in trends), and continuity aspects on the specified emergence basis. Here, we explain these aspects one by one.

4.1. Qualitative novelty

As stated in the philosophy of science literature, novelty is the most common aspect of emergence. Newness should be searched in the emergence basis with its qualitative aspect, as emphasized by L. Leydesdorff et al. [66]. L. Leydesdorff et al. [66] tracked new journals and distinguished them with their qualitative aspects in their study. Moreover, some of the researchers claimed that these qualitative novel properties could not be predicted, even with perfect knowledge. However, because science networks were collaborative and agglomerative knowledge systems, J. Kim [15] asserted that these properties might not be theoretically predictable, but inductibly predictable. Moreover, a supportive idea came from Goldstein [19]; as radical novel outcomes might be reached after improvising or negating past patterns. In light of these assertions, we assume that qualitative novelty might be reached through considering highly cited papers first. As Crutchfield [27] stated, novelty might be accepted in a range from "obvious" to "purposeful" and depended mostly on observers' evaluations. Taking into consideration highly cited publication networks, we aim to decrease the intermediation level of observers to avoid subjective judgments from experts that might also be decreased by using fuzzy decision-making models. In addition to our proposal, we reviewed some methodology proposals to measure and define novelty in science networks [20,71]. These models might also be applied for determining novelty.

4.2. Qualitative synergy

The synergistic effect was Corning [13] proposal for describing emergence. He defined it as the combined effect of units for emergence. Sawyer [17] also supported this synergism idea with his sociological perspective. When we search existing literature, we see that synergistic effects could be calculated by utilizing appropriate social network measures. Applications in scientific convergence [72,73] might be good for partially understanding the synergistic effect. Also, the synergistic effect should be applied not only to categorical levels but also on the author, organization, or country level to strengthen the accuracy in knowledge networks.

4.3. Functionality

In scientific networks, researchers exchange information through using citations or being cited. We assume that every new paper improves older ideas. This accumulation of knowledge perspective makes us think about functionality as an important aspect for the selection process. This aspect is considered for literature in terms of applicability, utility, and practicability concepts. Besides these terms, we assert that functionality might be considered with its complementarity aspect as Corning mentioned in his articles. We claim that functionality could be the link between the whole and partial relationships with their complementarity aspect. We found in some theoretical foundations in the technology management literature [74] that functionality had a great impact in new product development. The functionality concept was mainly discussed in technology management and in technology evaluation models discussed since the 1960s [75].

4.4. Continuity

We think that the "whole is greater than the sum of its parts." As Holland [31] stated, emergence in agent-based models should be considered as patterns of interaction. Thus, while analyzing parts of the technology context, we also need the analysis for their interrelationships to demonstrate coherence and continuity. We assert that technological emergents might be highly centralized in term co-occurrence networks when they emerge. Based on this assertion, term co-occurrence networks should be prepared on a yearly basis and persisting terms that are highly centralized should be examined for predicting technological emergents.

4.5. Trend irregularity

Pepper [12] found emergence with a change, and he emphasized its irregular character. Moreover, Martin and Sunley [42] assumed that emergence trends would create two different outcomes – destroying existing trends or adapting old properties to new conditions. In both situations, we thought there would be discreteness in trends. In the technology life cycle literature, these discontinuities were examined in Anderson and Tushman [56]'s model as dominant designs, and in Abernathy and Utterback [57]'s model as a phase. We assume that in technology emergence research there are two types of trends. The first one is radical or dominant emergent which occurs surprisingly without a background and creates an unexpected trend. The second one is incremental emergent, demonstrated substitutive characteristics and can be traced by Fisher-Pry models. In this sense, while evaluating trends of technology emergents, trend characteristics of technology emergents should also be stated for classifying them appropriately.

The third phase (Fig. 2) is the validation step. We believed that validation for technology emergence should be evaluated based on Holland [31]'s statement on exploratory models. Holland [31] asserted that these de-mystifying models should be validated with their suggestions to scientists, who are familiar with the area and new avenues. He claimed that these models should provide an explanation of complex phenomena in terms of a limited set of mechanisms.

5. Conclusions

It is clear that in the cases of technology emergence, business strategists and policy-makers have incomplete knowledge of the boundaries and the direction that technology is moving [5]. In this uncertain environment, converting unknown-unknowns to known-unknowns is a challenging task (L [3] for tool developers. For us, the starting point for this challenging task is defining the ambiguous technology emergence concept properly. Podsakoff, MacKenzie, and Podsakoff [76] emphasized the importance of concept definitions by demonstrating different case studies with a lack of conceptual clarity in the social sciences. They assert that the lack of clarity might lead to overlapping concept proliferation and high measurement errors. They propose that before focusing on measurements, a development of definitions of concepts should be the main focus. We agree with Podsakoff et al. [76]'s arguments, and before measuring technology emergence we first attempt to clarify the technology emergence concept properly to contribute to current theories and fill the existing gaps.

Through this perspective, after tracking the emergence concept with a 150-year timeline and three different, but conceptually connected, theoretical backgrounds, we propose a new definition for the technology emergence concept, taking into consideration the scientific and technological change literature. We detail our definition by demonstrating it as a three-phase model and describe the phases and aspects to be considered, in the previous section. In reviewed emergence literature, we ascertain that there has been a high dependency among emergent and emergence bases. Therefore, technology emergence is very sensitive to its emergence basis and needs a combination of qualitative and quantitative approaches.

This definition and proposed methodology may enhance the technology policy-making procedure by combining and embedding the concept in adaptive policy-making. Through the cyclic approach, we assert that every technology domain should be considered as a dynamic network and should be tracked continuously for policy orientation. This continuous perspective may be understood as periodical, but the duration of periods should be calculated based on the inherent dynamics of focused scientific domains. It should be noted that there is no one-size-fits-all situation. By meeting emergence basis assumptions for every period, we assume that accuracy in identifying technology emergence will increase, and this may help policy makers form a process drawing on this adaptive perspective.

We should emphasize that our proposal is different from Rotolo et al. [7]'s study with two propositions. Our first proposition is; Rotolo et al. [7]'s "emerging technology" definition is a macro understanding of emergence. They described emerging technology but not technology emergence. Technology emergence concept is different because our focus is understanding the individual technology in micro-state. When these technology emergents combined in one field, then the aggregated findings may be interpreted by using Rotolo et al. [7]'s definition whether it becomes emerging technology or not. Our second proposition is about underlying theoretical frameworks. Even emergence concept was partially reviewed in Rotolo et al. [7]'s paper, some of the components and their qualitative aspects neglected because of the macro perspective. Because we focus on micro state and individual technology emergents, we include qualitative aspects in our definition for proposing distinguishing arguments to researchers. However, we believe that our proposal may be understood as complementary to the emerging technology concept with considering micro-macro relationship.

Based on our literature review, our definition was the first attempt for defining the technology emergence concept based on theoretical foundations. We believe that it might inspire science, technology, and innovation policy researchers to understand technology emergence more and develop case studies in the future building upon our proposed definition.

For further studies, we plan to operationalize the proposed conceptual definition and extract statistically significant discriminant variables to distinguish emergents from others. The first point is to decide on the analysis unit. Words,[2] sentences, paragraphs, articles, authors, organizations, and countries are all different levels of research in scientometric studies. We assume that testing the definition at different levels may inspire others to create a hybrid and reliable methodology for technology emergence research.

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