EDICIONES Universidad de Valladolid

Intermediate forms and technological change: Exploring the links between technology and topology*

Formas intermedias y cambio tecnológico: Explorando los vínculos entre tecnología y topología

VÍCTOR GÓMEZ VALENZUELA
Institute of Public Goods and Policies (IPP)
Spanish National Research Council (CSIC)
Email: victor.gomez@cchs.csic.es
Instituto Tecnológico de Santo Domingo (INTEC)
Av. Los Próceres No. 10, 10602. Los Jardines del Norte, Santo Domingo, The Dominican Republic
E-mail: victor.gomez@intec.edu.do
ORCID: https://orcid.org/0000-0002-4225-4389

RECIBIDO: 03/04/2022
ACEPTADO: 30/06/2022

DOI: https://doi.org/10.24197/st.2.2022.96-123

Resumen: El estudio de la tecnología y el cambio tecnológico es un campo dinámico donde convergen diversas disciplinas de las ciencias sociales y las humanidades. Es posible encontrar varias ontologías que incorporan referentes topológicos como metáforas heurísticas y dispositivos metodológicos simples en los estudios tecnológicos. El artículo examina dos conceptos topológicos relacionados, continuidad y convergencia sustentados en las nociones de acumulación de conocimiento y de combinación de tecnologías preexistentes, para llegar a las nociones de convergencia e inflación. El artículo concluye con algunas pautas para futuras investigaciones que exploren en términos formales el potencial de la topología en los estudios de la tecnología y del cambio tecnológico.

Palabras clave: tecnología, cambio Tecnológico, topología, ontologías CTS

Abstract: The study of technology and technological change is a dynamic field where diverse disciplines from the social sciences and the humanities converge. It is possible to find several ontologies that incorporate topological referents as heuristic metaphors and simple methodological devices in technological studies. The paper examines two related topological concepts, continuity and convergence, based on the notions of accumulation of knowledge and a combination of pre-existing technologies to arrive at the notions of convergence and inflation. The paper concludes with some future research guidelines that formally explore the potential of topology in technology and technological change studies.

Keywords: technology, technological change, topology, STS ontologies

* No funding was reported for the preparation of this paper.

1. INTRODUCTION

This conceptual paper explores topological referents in technology and technological change studies to contextualise the potential academic contribution of topology to understand the dynamics of technological change. Thus, this is a more exploratory conceptual-based paper than an empirical one, describing the possibility of an alternative topological narration of the technological change emphasising concepts: of continuity and convergence. Of course, it cannot be discharged its potential to lift-up further analysis which a more substantial empirically-based topological basis. Therefore, a key research question arises: How can technological change be explained based on its topological interpretation departing from the notion of *intermediate forms*? To answer the posted research question at least in a preliminary way, it is proposing for this paper the following approach:

1. Exploring the various and related ontologies from which topological references emerge to analyse technological change.
2. Overviewing some basic topological notions
3. Approaching technology as a fluid construct
4. Approaching technological change since continuity and convergence

In methodological terms, this paper is based on reviewing the relevant literature to explore the potential of topology for the analysis of technology and technological change. The proposed approach does not seek to exhaust the exploration of topology but rather to lay a reflective basis to call the attention of other researchers to explore the analytical potential that the topological approach to technological change would offer. It also may contribute to the rich literature of interdisciplinary fields such as social construction of technology (SCOT), science, technology, and society studies (STS), innovation studies, or more specific approaches such as actor-network theory (ANT).

This paper hopes to contribute to the analysis and use of topology in interpreting technological change and defining a future research agenda for future inquiry and researchers interested in using the topological perspective to explore the diversity of processes and dynamics of technological change.

2. SELECTED ONTOLOGIES AND TOPOLOGICAL REFERENTS

It is possible to discover referents and approaches incorporating topological references as heuristic metaphors and straightforward methodological devices (Marres, 2012). Some explicit references to topology that can be traced through the literature of technology studies are terms such as *networks*, *exchanges*, *technological trajectories*, *transitions*, *clusters* and *accumulation* (Bettencourt, Kaiser, & Kaur, 2009; Cerulli, 2014; Dosi, 1982; Nachum & Keeble, 2003; Valverde, Solée, Bedau,

& Packard, 2007). These terms are part of the episteme of archaeology, anthropology, sociology, and economics disciplines.

At this point, it is necessary to state that the relationship between science (technology), method and society has always been complex to decipher and that from the perspective of the social studies of science and technology, what is clear is that this relationship is dynamic and that is interwoven in the social, political, economic, and institutional. It means that science and technology, like scientific methods, are shaped by society and shape society and the social relations that determine them. This deep imbrication supposes a theoretical and methodological challenge for the different areas and ontologies that study these relationships from the broader perspective of STS studies. Therefore, a selection of ontologies is presented in a very schematic way, looking at them at the end to locate the topological elements related to an explanation of the technology and technological change.

2.1. Selected ontologies

In S.C. Gilfillan's publication of 1952 entitled: *The Prediction of Technical Change*, he wrote: '…men tend to talk and think alike, and to standardise their manufactures instead of building all the intermediate forms, such as those that might unite a ship and the aeroplane by a continuous series of the intermediate form.' (Gilfillan, 1952: 371). It suggests that it is possible to link the design of a ship and an aircraft in a relationship of continuity through the intermediate forms that connect them. It immediately references the fascinating world of topology and thus to an impressive variety of concepts that belong to the strange world of the qualitative properties of mathematical objects. Topology is among the youngest fields in mathematics and concentrates on the equivalence of objects. Two objects, such as Gilfillan's ship and aircraft, are considered equivalent to the extent that they can deform each other in space without breaking, tearing or adding parts; the main interest of topology is those qualitative properties unchanged by such continuous deformation (Waldmann, 2014). The search for intermediate forms between a ship and an aeroplane is based not only on the original materials with which the first aircraft were manufactured but also on maritime and area navigation, applying similar principles of the physics of fluid mechanics. Sovacool & Hess (2017) accounted for ninety-six approaches to socio-technical change, including socio-technical transitions, large technical systems, the social construction of technologies, innovation studies, and other technical change approaches. It is possible to find topological references metaphorically (2017). In at least 14 of them, it is possible to find referents to technological changes pointing out terms such as networks, continuity, and discontinuity.

The constructivist approach conceives technology as a socially and economically determined phenomenon, subject to the influence of human agency and affected by context and social, economic, political, and ideological structures. In such a way, technology causes and is prosecuted for social purposes that may be explicitly or implicitly suggested (Klein & Kleinman, 2002). The deterministic conception prescribes an omniscient character to technology and has been criticised by various social sciences and humanities authors. A comprehensive review of these two views, their common boundaries and their relationship as part of an academic continuum is found in Allan Dafoe's paper On Technological Determinism (2015).

The socio-constructivist approach has played a critical role in STS studies, pointing out the weight of systems and social and economic structures in modelling technology and how social preferences shape the innovation cycle and technological change in general (Dotson, 2015). One fundamental but not unique source of the influence of the socio-constructivist approach comes from the Strong Program in STS studies, mainly sustained by the Edinburg School. Among the different lines of constructivist thought, the social construction of the technology approach stands out. The contemporary perspective on this approach is based on Trevor Pinch and Wiebe Bijker (1984). They define the four main concepts underpinning the social construction of technology (SCOT) approach as 1) interpretive flexibility, 2) relevant social group, 3) closure and stabilisation, and 4) the broader social context (Klein & Kleinman, 2002).

The concept of *interpretive flexibility* suggests that the emergence of technology or its *design* is an *open* process that can generate different results depending on concurrent circumstances. The concept of the *relevant social group* refers to the social agents and their *shared* interpretations of the meanings given to technologies and artefacts and the effect their actions have on technology development. The concept of *closure and stabilisation* is very similar to the notion of *dominant design*. In the stabilisation phase of a dominant design, a convention is generated regarding the interpretation and design of the technology that will finally break into the society or market involved (Utterback, 1996: 24). The concept of 'broader social context' refers to the network of political, social, economic, and institutional conditions that serve as the context of technology development. It also includes the dynamics and influences on technological development can be direct, indirect, implicit, and explicit, such as labour market regulations or cultural gender biases.

These four ideas suggest that technology is built on and defined in social terms subject to a social and cultural feedback loop, starting from the various interpretations that different social groups make of technological artefacts and media (Pinch & Bijker, 1984). Pinch and Bijker use the bicycle development in the last half of the 19th century as a paradigmatic case. Their analysis sheds light on the complex socio-technical dynamics behind the social shaping of technology (Pinch & Bijker, 1984: 411-418). From the STS perspective, technology is understood as a socio-technical system rather than simply aggregating parts and components or specific artefacts. Thus, human agency is broadly understood as the related socioeconomic contexts and environments imprinting the logic of technological change. However, considering the fundamental role of human agency in STS ontologies, especially in the socio-constructivist approach, terms such as social networks, social groups, interactions, proximity, and elements make at least a symbolic reference to topological analysis.

It is essential to highlight the contributions of the influential but little-known William F. Ogburn, who contributed in the first half of the 20th century (Godin, 2010). In his 1922 book, *Social Change concerning Culture and Original Nature,* he proposed four phases of technological change: invention, accumulation, diffusion and adjustment (Ogburn, 1922). According to Ogburn, accumulation results from increasing new knowledge and technologies available and accessible in social groups. In contrast, diffusion refers to disseminating various social groups and different sectors. Adjustment, however, refers to the time a culture takes to respond to and accept new technology, generating 'cultural lag' (Ogburn, 1922). SC Gilfillan is akin to Ogburn in terms of ideas. In 1935's *Sociology of Invention*, Gilfillan postulated a set of 38 propositions explaining technological change as a socially conditioned process (Gilfillan, 1970[1935]). However, Ogburn and Gilfillan's ideas were neither as well-known nor as widely disseminated as Joseph Schumpeter's; despite sharing the evolutionary influence, they can be considered legitimate precursors of contemporary thought on innovation (Godin, 2010; Volti, 2004).

One of the most exciting derivations of these ideas is the notion of technological differentiation, which is of interest when explaining the phenomenon of variation and diversity as part of technological evolution (Schiffer, 2002). This concept refers to the variations that certain technologies can undergo as they transfer from one group of users to another. Each group of users adapts it to satisfy different needs as a dynamic process (Pel, 2014). The coordinates of space and time and the relational mapping of technological variations are essential to explain the differentiation and variability of technologies and the combination of elements that gain complexity until they become new devices or technologies (Pel, 2014). Thus, differentiation, diversity, convergence, and other aspects play an essential role in this process (Etzkowitz, 2003).

Another interesting ontology is the Action Network-theory or ANT, which lay in artefacts and technical objects integrated with social relations as agents. It gave it an agency role linked to a socio-material network (Latour, 1996), making this theory a natural space for a topological-based approach to technological change. Latour's most conspicuous representative, the ANT approach, is based on a comprehensive epistemological approach of a monistic, hybrid and fluid nature that treats people and objects alike (Latour, 1996). This approach highlights the importance of associations and interactions between actants (persons and objects, objects and persons and objects with objects), endowing them with agency power (Latour, 2007). Therefore, from the perspective of ANT theory, the analytical emphasis is centred on the framework of relationships, assemblages, mediations, or heterogeneous, fluid, and extended associations instead of finished essences or substances (Latour, 2007, Elder-Vass, 2015).

Consequently, the emphasis shifts from human subjects and actors (persons and social institutions) to agents defined as actants or participants, both human and non-human, and their interactions, in such a way that the social world can understand in material terms and the material world (the world of objects and artefacts), in social terms (Larrión, 2019). However, this perspective reveals a critical bias of the ANT consisting of the explanatory weight of non-human agency (material objects) in social processes. It means that social causality cannot be explained solely as the result of the assembly networks of material objects, nor as the result of the interactions of the human and non-human components of said networks, but as a more complex issue in which social and economic relations and the institutional and political framework are fundamental in the social shaping of technology (Elder-Vass, 2015; Larrión, 2019). Therefore, the monism inherent in the ANT perspective prevents approaching the specificity of the social (political and economic) as an explanatory domain by itself, affecting a better understanding of the multiplicity of links underlying technology and the dynamics of technological change.

From the above concisely depicted ontologies, the notion of technology is built on diversity, continuity, combination, convergence, discontinuity, and more. In the case of diversity, these terms refer to the availability and variability of technologies in certain territories and the social, institutional, and economic networks that support interactions between innovators and social actors (Funk & Owen-Smith, 2017; P. P. Saviotti, 2018[1991]). Continuity (i.e., gradual change) refers to the process that relates technologies or families of technologies and their combination over time and space. It is a more complex process allowing the aggregation of technologies on a hierarchical structure to create a product or service, an idea equivalent to the notion of convergence (Arthur, 2009; Hacklin, Marxt, & Fahrni, 2010; P. Paolo Saviotti & Metcalfe, 2018[1991]). The case of discontinuity (i.e., the disruption of new technologies or the emergence of a new one) is a process conceived related to technological transitions to explain socioeconomic and institutional dynamics in which lay socio-technical change (Basalla, 2011[1988]p. 40; Geels, 2009, 2010).

In most cases, this terminology is used as heuristic metaphors rather than as epistemological resources on their own. There is nothing wrong with this metaphorical use. Maybe it may reflect a latent relationship that has not received more attention.

2.2 Selected ontologies

In S.C. Gilfillan's publication of 1952 entitled: The Prediction of Technical Change, he wrote: '…men tend to talk and think alike, and to standardise their manufactures instead of building all the intermediate forms, such as those that might unite a ship and the aeroplane by a continuous series of the intermediate form.' (Gilfillan, 1952: 371). It suggests that it is possible to link the design of a ship and an aircraft in a relationship of continuity through the intermediate forms that connect them. It immediately references the fascinating world of topology and thus to an impressive variety of concepts that belong to the strange world of the qualitative properties of mathematical objects. Topology is among the youngest fields in mathematics and concentrates on the equivalence of objects. Two objects, such as Gilfillan's ship and aircraft, are considered equivalent to the extent that they can deform each other in space without breaking, tearing or adding parts; the main interest of topology is those qualitative properties unchanged by such continuous deformation (Waldmann, 2014). The search for intermediate forms between a ship and an aeroplane is based not only on the original materials with which the first aircraft were manufactured but also on maritime and area navigation, applying similar principles of the physics of fluid mechanics. Sovacool & Hess (2017) accounted for ninety-six approaches to socio-technical change, including socio-technical transitions, large technical systems, the social construction of technologies, innovation studies, and other technical change approaches. It is possible to find topological references metaphorically (2017). In at least 14 of them, it is possible to find referents to technological changes pointing out terms such as networks, continuity, and discontinuity.

The constructivist approach conceives technology as a socially and economically determined phenomenon, subject to the influence of human agency and affected by context and social, economic, political, and ideological structures. In such a way, technology causes and is prosecuted for social purposes that may be explicitly or implicitly suggested (Klein & Kleinman, 2002). The deterministic conception prescribes an omniscient character to technology and has been criticised by various social sciences and humanities authors. A comprehensive review of these two views, their common boundaries and their relationship as part of an academic continuum is found in Allan Dafoe's paper On Technological Determinism (2015).

The socio-constructivist approach has played a critical role in STS studies, pointing out the weight of systems and social and economic structures in modelling technology and how social preferences shape the innovation cycle and technological change in general (Dotson, 2015). One fundamental but not unique source of the influence of the socio-constructivist approach comes from the Strong Program in STS studies, mainly sustained by the Edinburg School. Among the different lines of constructivist thought, the social construction of the technology approach stands out. The contemporary perspective on this approach is based on Trevor Pinch and Wiebe Bijker (1984). They define the four main concepts underpinning the social construction of technology (SCOT) approach as 1) interpretive flexibility, 2) relevant social group, 3) closure and stabilisation, and 4) the broader social context (Klein & Kleinman, 2002).

The concept of interpretive flexibility suggests that the emergence of technology or its design is an open process that can generate different results depending on concurrent circumstances. The concept of the relevant social group refers to the social agents and their shared interpretations of the meanings given to technologies and artefacts and the effect their actions have on technology development. The concept of closure and stabilisation is very similar to the notion of dominant design. In the stabilisation phase of a dominant design, a convention is generated regarding the interpretation and design of the technology that will finally break into the society or market involved (Utterback, 1996: 24). The concept of 'broader social context' refers to the network of political, social, economic, and institutional conditions that serve as the context of technology development. It also includes the dynamics and influences on technological development can be direct, indirect, implicit, and explicit, such as labour market regulations or cultural gender biases.

These four ideas suggest that technology is built on and defined in social terms subject to a social and cultural feedback loop, starting from the various interpretations that different social groups make of technological artefacts and media (Pinch & Bijker, 1984). Pinch and Bijker use the bicycle development in the last half of the 19th century as a paradigmatic case. Their analysis sheds light on the complex socio-technical dynamics behind the social shaping of technology (Pinch & Bijker, 1984: 411-418). From the STS perspective, technology is understood as a socio-technical system rather than simply aggregating parts and components or specific artefacts. Thus, human agency is broadly understood as the related socioeconomic contexts and environments imprinting the logic of technological change. However, considering the fundamental role of human agency in STS ontologies, especially in the socio-constructivist approach, terms such as social networks, social groups, interactions, proximity, and elements make at least a symbolic reference to topological analysis.

It is essential to highlight the contributions of the influential but little-known William F. Ogburn, who contributed in the first half of the 20th century (Godin, 2010). In his 1922 book, Social Change concerning Culture and Original Nature, he proposed four phases of technological change: invention, accumulation, diffusion and adjustment (Ogburn, 1922). According to Ogburn, accumulation results from increasing new knowledge and technologies available and accessible in social groups. In contrast, diffusion refers to disseminating various social groups and different sectors. Adjustment, however, refers to the time a culture takes to respond to and accept new technology, generating 'cultural lag' (Ogburn, 1922). SC Gilfillan is akin to Ogburn in terms of ideas. In 1935's Sociology of Invention, Gilfillan postulated a set of 38 propositions explaining technological change as a socially conditioned process (Gilfillan, 1970[1935]). However, Ogburn and Gilfillan's ideas were neither as well-known nor as widely disseminated as Joseph Schumpeter's; despite sharing the evolutionary influence, they can be considered legitimate precursors of contemporary thought on innovation (Godin, 2010; Volti, 2004).

One of the most exciting derivations of these ideas is the notion of technological differentiation, which is of interest when explaining the phenomenon of variation and diversity as part of technological evolution (Schiffer, 2002). This concept refers to the variations that certain technologies can undergo as they transfer from one group of users to another. Each group of users adapts it to satisfy different needs as a dynamic process (Pel, 2014). The coordinates of space and time and the relational mapping of technological variations are essential to explain the differentiation and variability of technologies and the combination of elements that gain complexity until they become new devices or technologies (Pel, 2014). Thus, differentiation, diversity, convergence, and other aspects play an essential role in this process (Etzkowitz, 2003).

Another interesting ontology is the Action Network-theory or ANT, which lay in artefacts and technical objects integrated with social relations as agents. It gave it an agency role linked to a socio-material network (Latour, 1996), making this theory a natural space for a topological-based approach to technological change. Latour's most conspicuous representative, the ANT approach, is based on a comprehensive epistemological approach of a monistic, hybrid and fluid nature that treats people and objects alike (Latour, 1996). This approach highlights the importance of associations and interactions between actants (persons and objects, objects and persons and objects with objects), endowing them with agency power (Latour, 2007). Therefore, from the perspective of ANT theory, the analytical emphasis is centred on the framework of relationships, assemblages, mediations, or heterogeneous, fluid, and extended associations instead of finished essences or substances (Latour, 2007, Elder-Vass, 2015).

Consequently, the emphasis shifts from human subjects and actors (persons and social institutions) to agents defined as actants or participants, both human and non-human, and their interactions, in such a way that the social world can understand in material terms and the material world (the world of objects and artefacts), in social terms (Larrión, 2019). However, this perspective reveals a critical bias of the ANT consisting of the explanatory weight of non-human agency (material objects) in social processes. It means that social causality cannot be explained solely as the result of the assembly networks of material objects, nor as the result of the interactions of the human and non-human components of said networks, but as a more complex issue in which social and economic relations and the institutional and political framework are fundamental in the social shaping of technology (Elder-Vass, 2015; Larrión, 2019). Therefore, the monism inherent in the ANT perspective prevents approaching the specificity of the social (political and economic) as an explanatory domain by itself, affecting a better understanding of the multiplicity of links underlying technology and the dynamics of technological change.

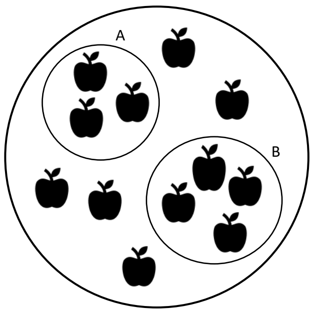
From the above concisely depicted ontologies, the notion of technology is built on diversity, continuity, combination, convergence, discontinuity, and more. In the case of diversity, these terms refer to the availability and variability of technologies in certain territories and the social, institutional, and economic networks that support interactions between innovators and social actors (Funk & Owen-Smith, 2017; P. P. Saviotti, 2018[1991]). Continuity (i.e., gradual change) refers to the process that relates technologies or families of technologies and their combination over time and space. It is a more complex process allowing the aggregation of technologies on a hierarchical structure to create a product or service, an idea equivalent to the notion of convergence (Arthur, 2009; Hacklin et al., 2010; P. Paolo Saviotti & Metcalfe, 2018[1991]). The case of discontinuity (i.e., the disruption of new technologies or the emergence of a new one) is a process conceived related to technological transitions to explain socioeconomic and institutional dynamics in which lay socio-technical change (Basalla, 2011[1988]p. 40; Geels, 2009, 2010).

In most cases, this terminology is used as heuristic metaphors rather than as epistemological resources on their own. There is nothing wrong with this metaphorical use. Maybe it may reflect a latent relationship that has not received more attention.

2.3 Topological referents: Sets, subsets, continuity, and convergence. An elementary approach

Topology deals with abstract sets of elements that could also be a construct and their interactions. It opens an enormous possibility for the analysis and interactions of the elements and the sets it makes (Aluja & Lafuente, 2012; Manetti, 2015; Waldmann, 2014). For example, let us take the imaginary set of twelve apples in Figure 1 to call the set P.

Figure 1. The set "P” of apples



Source: Own elaboration

In general terms, the twelve apples are the elements that are part of the set P. However, it is not exactly like that since P and other sets call it subsets. Subset A has three apples, and subset B is composed of four. These subsets, in turn, are elements of the set P. Therefore, the set P is a collection of seven objects: five apples and the subsets A and B. The representation of the set P would be as follows:

ISSN: 1989-8487

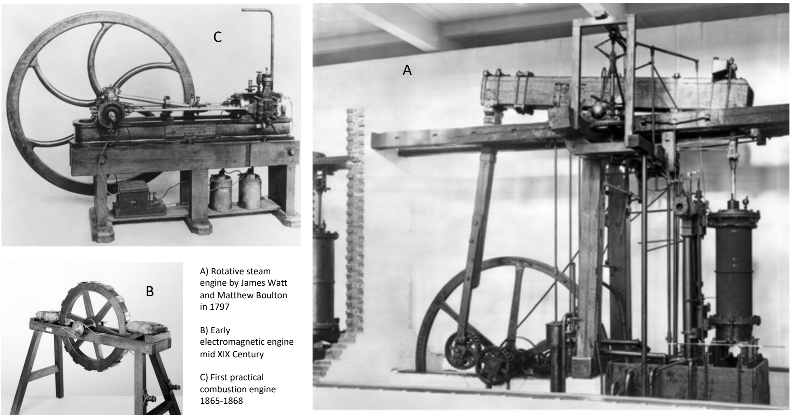
Then is possible to express the relationship between the set P and the subsets A and B in different ways. For example, set A is included in "P" or, more directly, that set A belongs to P. The set P and its relationship with elements can be considered a primary topological space from the previous perspective. The above ideas make it possible to review continuity and convergence as critical metaphorical topological referents in analysing technological change. Continuity is a way of thinking about how close the elements of a set are. Thus in continuity but especially in convergence, it is necessary to think about the idea of distance and proximity; that is, it is necessary to reduce the distances between the subsets and their elements from near to very close, for which it is necessary to specify what would be the tiny in-between spaces (Manetti, 2015; Waldmann, 2014).

Finally, a type of continuity function is the so-called homeomorphism, defined as a bijective function $f: X \to Y$ in which each point in X corresponds to a point in Y and vice versa. In other words, the function f and its inverse f^{-1} are continuous (Waldmann, 2014). Two homoeomorphic spaces cannot be differentiated, suggesting that they are equivalent to one another and become fluid. It implies no differences between triangles, squares, and circles (Manetti, 2015; Waldmann, 2014). These ideas about general topological spaces can define invariant properties as those conserved by homeomorphisms. Therefore, an object can be extended, squashed, shrunk, and stretched again without these deformations' intrinsic properties being changed.

3. TECHNOLOGY AS A FLUID CONSTRUCT.

The ideas of continuity and convergence are interesting tools to examine technologies as fluid constructs, and even those discrete technologies are considered artefacts. An example can be found in the case of the rotary steam engine of Watt and Boulton of the late 18th century (Basalla, 2011[1988]: 45). The idea of technology as a fluid construct refers to its flexibility and plasticity based on its potential for combination with other technologies or technological sets with different affinity degrees. Continuity and convergence allow us to appreciate the common and distinct elements that give meaning to technology and bring the notion of the technological distance closer. As an illustration, Figure 2 shows the electromagnetic engines of the first half of the 19th century and the first internal combustion engines of the 1860s. These engines share common elements with their predecessor, the steam engine, such as pistons, connecting rods and wheels that transform back and forth movement into a rotary movement based on oscillating steam (Basalla, 2011[1988]: 60). Here, continuity presupposes that technology evolves, incorporating elements and forms from previous technologies. Although it is impossible to define a bijective relationship, it helps us understand how the forms change and are affected and how the elements are adjusted and modified until a new technology is configured.

Figure 2. Continuity and convergence in steam engines and early electromagnetic engines



Source: Science and Society Picture Library. Manchester, UK. https://www.ssplprints.com

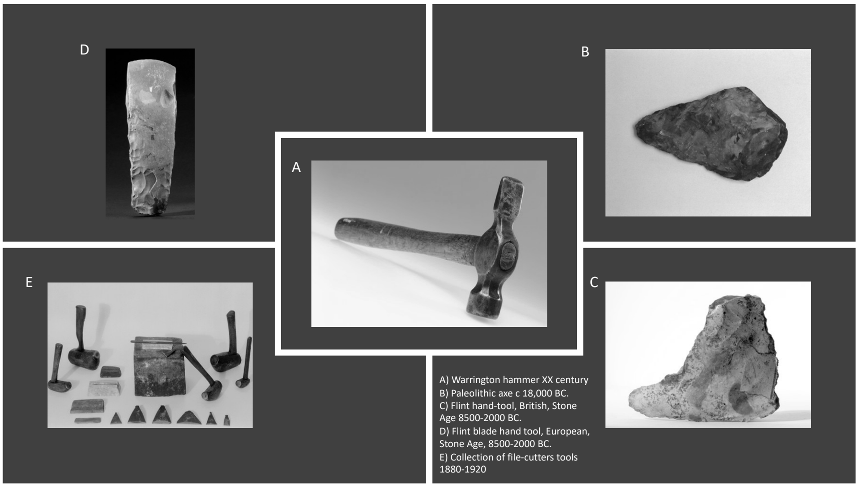
Taking Gilfillan's concept of 'intermediate forms (1952), one might wonder if the bicycle could have been one of the intermediate forms between ships and the first biplane and triplane aircraft. Figure 3 shows the common elements that link the first aeroplane with bicycles, including similar fabric for sails.

Figure 3. Related forms and materials between bicycles and planes

Source: Science and Society Picture Library. Manchester, UK. https://www.ssplprints.com

From a topological perspective, or rather one of equivalence (thinking of a homeomorphism), there are no differences between a palaeolithic axe of Mode I and a contemporary hammer (see figure 4). Their differences will disappear just as there are no differences between a square and a circle since it is possible to establish the correspondence between the different points between them (the quadrature o the circle). Considering the palaeolithic axes and modern hammers as topologically equivalents is possible to imagine them as abstract objects since the theoretical deformation would make the nearby points correspond to other nearby points (Hagan, 2007; Moore, 2007). Thus, building a bijective function between an axe and a hammer would be possible and shows the plasticity of the technological representation of cultural material to act (Hagan, 2007).

Figure 4. Hammers and axes: homeomorphism?



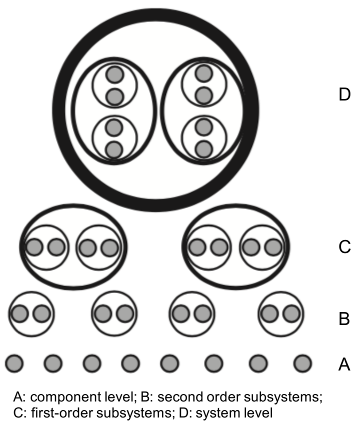
Source: Science and Society Picture Library. Manchester, UK. https://www.ssplprints.com

Thus, technology in terms of objects and artefacts can be considered a fluid object from which the analysis of technological change becomes an invariable property of them as an abstract representation of the artefact. Therefore artefacts as abstract technological objects can be defined as the product of the collective memory or an object that has been transformed for particular purposes within the culture (Hagan, 2007). Therefore, it becomes inherent to the technology, distinguishing between technology as a discrete phenomenon or a fluid phenomenon insubstantial. The topological referents in this area are particularly interesting; the studies on the emergence of the so-called dominant designs are a crucial concept from innovation studies (Abernathy & Utterback, 1978; Utterback, 1996).

A dominant design is proven when the market accepts a given product's design and its primary technological attributes as the standard for the industry within its product category (Brem, Nylund, & Schuster, 2016: 79). One of the most interesting theoretical works in studying dominant designs is the paper of Murmann and Frenken (2006). They propose a theoretical synthesis with inputs from the perspective of complex systems with explicit heuristic purposes for constructing the concept and its analytical approach. A dominant design emerges within a *technological class* when the central components share the same technologies due to their high *pleiotropy*. The *interfaces* are essential since they can be core components (Murmann & Frenken, 2006p. 944). Consequently, the unit of analysis is the technological artefact, which can be understood as a complex hierarchical system. The lower levels constitute a nested hierarchy of subsystems.

For Murmann and Frenken (2006), the concept of the nested parts hierarchy supposes that in a complex system such as an aeroplane, each of the elements or components - such as wings, landing gear, the engine, or the fuel tank, among others - can be represented as first-order subsystems. It further supposes that each of these subsystems includes smaller, second-order subsystems. At the same time, there are additional levels of increasingly smaller subsystems, down to the level of fundamental elements such as rivets. In this nested logic, each level of the hierarchy of artefacts goes through its technological cycle of variation, selection, and retention. Figure 5, taken from Murmann and Frenken's paper, explains the hierarchies that illustrate *inclusion* and *control hierarchies*, describing a complex technological artefact such as a modern aircraft.

Figure 5. Complex nested hierarchies



Source: Murmann & Frenken (2006)

In the case of the dominant designs, their evolution until they become established in the market offers an exciting opportunity to review the role of intermediate forms in the dynamics of technological change. A conclusion from the analysis of dominant design may be that technology evolves through a complex sequence of intermediate forms defined by interactions of different sets of technologies of varying degrees and affinity levels, including additional levels of increasingly smaller subsystems.

4. EXPLORING A TOPOLOGICAL APPROACH TO TECHNOLOGICAL CHANGE.

In topological terms, convergence and continuity are intertwined. Convergence is a function of continuity in which two points or elements are incredibly close. The notion of continuity is key to analysing technological change from a topological perspective since it lays the foundations to address them more formally. Mainly when the analysis is applied to the combination of technologies, which allows the connection of pre-existing knowledge bases and practices to accelerate the processes of technological change (Arthur, 2009: 172-174; Brem et al., 2016).

On the other hand, acceleration refers mainly to the gestation time of a given technology as an innovation process. When the technology is considered from its arrival on the market, it can take years to achieve a process that depends on the sector (Sood & Tellis, 2005). It means that not all technologies presented as innovations will be successful. Once on the market, design and format standards will compete until a dominant format or design emerges in the industry, and, in some cases, the most efficient technology or technology with better performance for society or consumers will not necessarily win due to the manoeuvres, coalitions and strategies of competitors (Shapiro & Varian, 1999; Spulber, 2013).

From the family of products, goods and services perspective, the dynamics of change appear to result from incremental modifications punctuated by discontinuities that we can understand as advances and evolutionary rather than revolutionary technical leaps. In this way, the accumulation of knowledge and combination of technologies and the pre-existing knowledge in a particular technological domain, together with the context's selective pressures, can explain the processes of technological change at an aggregate level. The accumulation of knowledge and pre-existing technologies is a complex dynamic that consists not only of the linear increase in the stock of available knowledge but also has important practical implications, including maturity in knowledge management at the firm level (Niemi, Huiskonen, & Kärkkäinen, 2009). The accumulation of knowledge implies improvements in an economy's absorptive capacity or a specific industry to increase the possibilities of combining existing technologies for new or derived technologies (Kuo, Wu, & Lin, 2019). Therefore, accumulating existing knowledge and technologies is, from the outset, a necessary condition for the dynamics of technological change and the amplification of the impact of scientific knowledge. However, beyond this, questions about the details and specificities of the dynamics of technological change remain open.

The idea of a process of convergence and inflation is attractive as an explanation for the processes of accumulation, combination, and acceleration of innovations in the domain of the continuous function of technological change. A. Sood and G.J Tellis (2005) analyse the emergence and evolution of four technologies: desktop memory, display monitors, desktop printers and data transfer, considering accumulation, combination and acceleration as a synergic process. They propose the idea of technology as an 'innovation platform,' in which processes and integration occur and from which the emergence and evolution of technologies begin (Sood & Tellis, 2005: 153). This function can be comparable to the domain of the technological change function. In this area, the smartphone breakthrough constitutes an interesting example of convergence and inflation from the emergence of innovation from a technological platform resulting from the accumulation, combination and acceleration of pre-existing technologies with a disruptive effect on the conventional cell phone market (Shi & Zhang, 2018).

In innovation systems literature, the accumulation of knowledge is one of its most distinctive functions, which is related to the increase in the stock of knowledge, as well as to learning processes and knowledge transmission within the economic system (Fagerberg & Srholec, 2008; Lundvall, 2007; Metcalfe & Ramlogan, 2008). The combination of technologies is a factor that defines the connection between innovation, knowledge, and pre-existing technologies. It also defines the acceleration of processes of technological change arising from the emergence of specific technologies, usually stabilised by a dominant design (Arthur, 2009: 172-174; Brem et al., 2016). Acceleration refers mainly to the gestation time of an innovation that, depending on the sector, can take years to reach the market as a new product (Sood & Tellis, 2005). The dynamics of knowledge accumulation, combination and acceleration can be understood more clearly when socio-cognitive processes mature and *converge*. It generates what studies are known in STS as 'closure and stabilisation' (Pinch & Bijker, 1984: 424), marking what F.W. Geels defines as a technological transition (Geels, 2010: 500).

The history of technology is full of design and format standards wars, such as the case of the electricity distribution war of the late nineteenth century. It was the war between the direct current and alternating current systems of Thomas Edison and George Westinghouse, respectively, winning the worse performance system of the direct current. A second but lesser-known format war is the decline of electric automobiles declined their presence in the market from what is known as its "golden era" between 1890 and the beginning of the 20s of the twentieth century, before the preeminence of the internal combustion engine initiated with the Ford Model "T" in 1909 (Høyer, 2008). The third example is the war between the Betamax and VHS video formats. The latter triumphed (Cusumano, Mylonadis, & Rosenbloom, 1992) until Google's recent and failed attempt to introduce its glasses.

More technologies fail as products and innovations than manage to enter the market, with a more conservative approach of incremental and gradual innovations of existing technological products, goods, or services prevailing. Therefore, the dynamics of knowledge accumulation, combination and technological acceleration can be understood more clearly when socio-cognitive processes mature and *converge*, stabilising new technological proposals and allowing them to reach the market. The emergence of the first iPhone model in 2007 marked a disruptive change in the industry. Still, when examining systems (sets) and subsystems (subassemblies) and their elements, its level of technological innovation was relatively low since, in essence, it was the combination of a significant number of pre-existing technologies, which later may converge in new products and services.

The smartphone industry innovations are much older than imagined and can be traced back to the nineteenth century with Maxwell's equations on electromagnetism, followed by hertz's discovery and the radio waves. After the advances of Alexander G. Bell with the telephone in the late nineteenth century or William Marconi with the invention of wireless telegraphy, the same at the end of the same century. The above milestones must be added to the mid-twentieth century's advances in computational processing systems and the invention of silicon-based integrated circuits in the 1960s. As we know them in the twenty-first century, Telecommunications would not be possible without this progress. It allowed Jack S. Kilby to be awarded the Nobel Prize in Physics in 2000 for his contributions to developing integrated circuits and advanced semi-conductive materials. A similar process occurs in almost all technologies, such as in "x-rays" and Magnetic Resonance Imaging machines MRI. Therefore, technological change can be understood as a sequence of continuity and convergence in which different technologies combine to give rise to socio-technical transformations that affect industry and society equally, although with different rhythms.

The above reflection applies to almost all technologies. If we go back in time, we think of the first steam trains and locomotives of the First Industrial Revolution. We will see a straightforward process of continuity and convergence of pre-existing technologies from areas that are differentiated from each other in many cases. The rails and tracks are of medieval origin, even older, in their wooden beginnings and perfected from activities such as mining, driven first by human and animal traction. Watt's steam engine originates precisely in need of an efficient solution for the drainage of deep mines. Finally, the crossing rails, technologies, and related artefacts, in history in a particular place allowed their combination giving rise in 1804 to the invention of the locomotive by the British engineer Richard Trevithick (Mason, 1931).

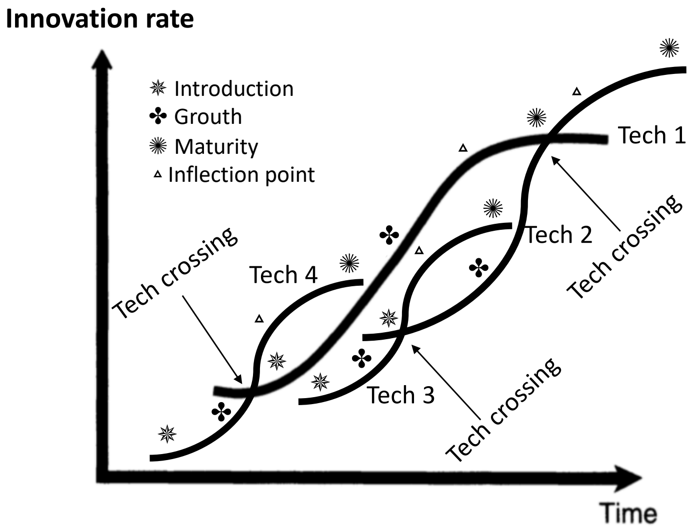
It can be stated that convergence and continuity based on the combination, acceleration, and stabilisation are elements of a complex process of high hierarchy that explains the pace of technological change that can be considered in two hypothetical moments. The first moment is the continuity function of technological change, which can be understood in cumulative terms. It suggests that the function can be drawn in the plane of X, Y. In a second moment, and related to the accumulation processes, the different technologies can be combined under certain conditions that allow it, from which the continuity function can experience the behaviour of inflation or acceleration like that of an exponential function (in the form of a smooth *J*).

Once again, situated in the two hypothetical moments of accumulation and combination that allow acceleration and then inflation, a base of knowledge and related technologies is needed to support it (Kuo et al., 2019). This accumulation and combination process can occur synchronously or asynchronously, or in a particular place with suitable institutional and socioeconomic conditions, and can occur on a small, medium or large scale, generating new technologies and processes that will be selected based on market dynamics or by the effect of the network of political, economic and institutional forces in interaction (Nelson & Nelson, 2002; Solée et al., 2013).

The form of smooth J is related to the introduction and growth stages of new technology in the market before reaching its maturity stage, when it takes an S shape and is well known in the literature on diffusion, adoption, and technological change, particularly since the works of Abernathy and Utterback (Abernathy & Utterback, 1978; Sood & Tellis, 2005; Utterback, 1996). The "S" curve behaves as a cumulative distribution function, in which the effect of the accumulation of knowledge and existing technologies are highlighted from the perspective of the diffusion of technologies (Anderson & Tushman, 1990). Similarly, when we take an expression of the type x^2, x^3, or x^4, the exponents are constant, such as $2^3= 8$, but nothing prevents a specific function from having variable exponents such as 2^t or 3^x. It means that when factors or independent variables, such as accumulation and combination, appear in the exponent of the function, we would be facing an exponential function of technological change.

Based on the interpretation of Sood and Tellis of the S curve (2005), it would be a generalised exponential function of the kind $A = ab^{ct}$ where A represents the rate of technological change, a and *c* are the multiplier factors that can compact or expand the function, b would be the theoretical basis of available knowledge and technologies. The *t* is the variable exponent that can accelerate the technological dynamics of accumulation and combination. Therefore, the continuity function of technological change would hypothetically grow to a specific power, always with a positive sign. It assumes that the exponential function of technological change would be monotonous. It would have an inverse function of logarithmic type (in the form of a smoothed S) in which each value of M corresponds to a value in T in the topological space that they conform. This description of the dynamics of technological change in topological terms has limitations but allows a least feasible hypothetical understanding of the dynamics of technological change. This notion of technological change (as intertwined functions of technological change diffusion) is an assumption to simplify the analysis of the crossovers of technological diffusion functions of different types of technologies. Figure 6 shows the points of convergence of several "*S*" shaped curves corresponding to different technologies with their respective diffusion stages and possible crossing between them.

Figure 6. Dynamics of diffusion and technological change



Source: Own elaboration based on Sood and Tellis (2005)

Figure 6 presents the crossing or combination of four hypothetical technologies that may sometimes rival technologies. One of the interesting conclusions is that technologies evolve by interacting with more than one S-shaped curve whose interaction improves the technologies' performance. It could also increase the rate of technological change and the number of new technologies that can arise over time, initiating new cycles of accumulation, combination and acceleration, a dynamic defined as inflationary convergence. These interactions, often of a probabilistic type, suppose their occurrence in spaces and networks of information with certain proximity and in scenarios in which access to knowledge and technologies is possible by the economic and social agents involved in the processes of innovation and technological change. With a certain degree of rigour, it is possible to characterise these interactions topologically, which is already being done, for example, in analysing innovation patterns and their organisation over time (Valverde et al., 2007).

One of the key findings in Sood and Tellis (2005) is the co-evolution and interaction of the four technologies studied, highlighting that technologies evolve by interacting with more than one S-shaped curve, in which rival technologies participate. This interaction improves the performance of the technologies involved, increasing the rate of technological change and the number of new technologies that may emerge over time. In this way, new cycles of accumulation, combination and acceleration are initiated in a dynamic defined as inflationary convergence.

The interactions and convergences of different S-shaped curves occur in networks and spaces of information and knowledge that can be characterised in topological terms, opening exciting research possibilities. These interactions are probabilistic, and the analysis of innovation patterns resulting from the exchange of information and the capacity of innovators to combine existing technologies and designs is already being explored (Valverde et al., 2007). Based on the crossovers of the technological change functions, inflationary convergences can start as inflexion and acceleration in different spaces and levels of interaction of the technological change functions as the technologies spread. These convergences can occur in an ecosystem where the different topologies or sets interact, meaning that the ecosystem approach is comparable with topological spaces (Solée et al., 2013; Valverde et al., 2007).

Such processes of convergence and inflation are experienced regularly, only due to the scale on which they occur. They may not be as striking or have the transformative consequences they have had in social, political and economic terms of the steam engine of the first industrial revolution of the second half of the eighteen century. It is also de case of the social and economic impact derived from the presentation of the first successful personal computers on the market (the Apple II in 1977 and the IBM in 1981), as well as the impact of the first generation of smartphones since 2007, to mention just two cases that can be defined as the result of convergence and inflation processes from the accumulation and combination of pre-existing technologies. Therefore, inflationary convergences occur from the crossings of the diffusion functions of different technologies, giving rise to tipping points and acceleration in different spaces and levels of interaction of the diffusion functions of these technologies in the ecosystems in which they interact, so factors such as proximity and access are critical (Solée et al., 2013; Valverde et al., 2007).

Of course, topology is much more than set theory and homeomorphisms. Without a doubt, it will not allow us to exhaust research programs on technology and technological change. However, it does offer us the opportunity to look differently, at least in the metaphors derived from the contributions that can make to the study of technology from the strange world of deformed objects while maintaining their invariant properties. How do the market and the socioeconomic context influence this dynamic of accumulation-combination-acceleration and technology selection?

The literature on innovation systems is key to understanding the dynamic role of the market, policies and institutions (rules of the game, regulations, incentives, among others), especially for those technologies that generate a significant social and economic impact (Lundvall, 2007; Solée et al., 2013).

The typical examples of how specific technologies were imposed thanks, in some cases, to the questionable role of market selection and the prevailing institutional arrangement of the moment have it in the cases of the triumph of direct current over alternating current or of the internal combustion engine over the electric motor in the automotive industry in the twenties and thirties of the last century (Høyer, 2008). Similarly, certain technologies are not selected at a given time due to regulatory or ethical issues that affect the set of prevailing societal values. We have recent examples in the smart glasses introduced by Google in 2013 and that despite their innovative nature as convergence technology, they failed at the time as a socio-technical experiment (Kudina & Verbeek, 2018).

The same logic applies to social resistance to broader experimentation with stem cells and other technologies that may be ethically and socially questionable. Therefore, the thrust of the convergence and inflation processes is usually moderated not only by the market and the economic forces that act as selecting agents of the technologies that result from the convergence and inflation processes, but the selection process also concerns the set of social actors, the value system and the institutions that embody them.

Therefore, what interactions between technologies will the future look like, and what impact will they have? Innovation studies already provide a perspective on innovation as a multidimensional and multi-actor process of distributed logic. The joint evolution of technologies, social, economic, and financial networks and institutions plays a determining role in the innovation dynamics of technological change as a more global explanatory framework of socio-technical transitions.

Likewise, in the different ontologies referred to in this paper as the evolutionary ontology, actor-network theory, and innovation studies, discontinuity is one of the most basic approaches to describing technological change and its effect of 'creative destruction. It can be understood in the sense of radical innovation. As a type of technological change, whose magnitude moves a sector forward thanks to a technical advance that represents a new state of the art, discontinuity changes the way of doing things, and that usually entrenches a new standard or dominant design in the market (Anderson & Tushman, 1990; Brem et al., 2016). This notion is key to analysing the issue of technological transitions from a topological approach, as it lays the groundwork for addressing them more formally, mainly when the analysis is applied to specific technologies.

Because of the global emergency caused by the 2020 global COVID-19 pandemic and its structural consequences for economic, educational, and health systems worldwide, it is not easy to venture any ideas or guesses regarding the technological convergence processes. However, in the medium- to long-term, it would be expected that frontier technologies such as nanotechnology, super high internet speed as 5G, artificial intelligence, quantum computing and materials science would cross. As much as their independent evolution already offers significant disruptive potential, crossings could initiate a new stage of technological change, allowing us to confront global challenges of equity and sustainable development successfully.

5. CONCLUDING REMARKS.

This paper has focused on two basic topological notions: continuity and convergence, and from them, the fundamental ideas of convergence and inflation are based on the basic notions of accumulation of knowledge and combination of technologies. As indicated in several ontologies related to the study of technology and technological change, it is possible to find topological referents. In this paper, two of them were briefly reviewed: continuity and convergence departing from the notion of topological space. However, this metaphoric use can be extended to other disciplines and interdisciplinary fields, such as archaeology, sociology, and economic studies. A comprehensive and detailed literature review is a pending task to be embraced later.

The outlined approach of technology as a fluid construct, including the study of dominant designs and the evolution of certain technologies as subsets of hierarchical and nested technologies formalising their relation, could yield exciting results. In the analytical base of technology as a fluid construct are notions such as variability, variety, distance, proximity, continuity, and convergence, which could be helpful in the analysis of dominant designs with new perspectives. These perspectives would allow technology and technological change to be treated as a complex domain incorporating elements of the context through operations of combination (union, intersection) and acceleration (inflexion points) of the open elements that make up technological sets considered as topologies. The evolution of technology through a complex sequence of intermediate forms and the interactions of different sets of technologies of varying degrees and affinity levels opens analytical possibilities for topology in collaboration with established ontologies like STS perspectives and innovation studies.

The idea of convergence and continuity could be extended to the analysis of technological transitions since the ideas of accumulation, combination, and acceleration in domains related to technologies whose diffusion functions can intersect at certain times. This crossing of functions can occur in different phases of the technology diffusion process (introduction, growth, and maturation), generating processes that we call inflationary convergences. Such convergences can emerge spontaneously and probabilistically at different levels and scales of the systems or sets (topologies), including developing a specific technology. The above reflections conclude that the two contributions foreseen in this work have been achieved, at least in part. First, it has been shown that topological referents are present in established ontologies related to STS studies and innovation. In addition, the possibility of developing an eventual research agenda about the potential contribution of topology has been outlined. The two contributions allow us to deduce that topological referents have a background with methodological possibilities beyond the mathematical language of heuristic metaphors.

Limitations

This article has limitations that derive from its purpose. However, it can open Pandora's box of topology and their eventual contribution to analysing technology and technological change. Therefore, at least in the first phase, the purpose could be to apply topology analysis to the objects and artefacts as abstract entities to test the feasibility of topology at different levels and analytical scales. A second analytical phase could include a more paused and detailed exploration of the topological referents in different theoretical and methodological ontologies. It can be helpful to see its significant implications beyond their metaphoric use and define a viable research agenda. The formal application of topology to the analysis of specific technologies should point towards this analysis. More than a new understanding of technology and technological change, this article seeks to attract attention and point out an area whose exploration is a subtle and persistent call. Finally, Gilfillan's conception of the latent relationship between topology and technology through "intermediate forms" shows the need to understand the nature and impact of technology and technological change beyond heuristic metaphors. Further research should recognise the initial scope of this work.

REFERENCES.

Abernathy, W. J., & Utterback, J. (1978). Patterns of Industrial Innovation. *Technology Review*(50), 41-47.

Aluja, J. G., & Lafuente, A. M. G. (2012). Topology. In *Towards an Advanced Modelling of Complex Economic Phenomena: Pretopological and Topological Uncertainty Research Tools* (pp. 71-106). Berlin, Heidelberg: Springer Berlin Heidelberg.

Anderson, P., & Tushman, M. L. (1990). Technological Discontinuities and Dominant Designs: A Cyclical Model of Technological Change. *Administrative Science Quarterly, 35*(4), 604-633. doi:10.2307/2393511

Arthur, W. B. (2009). *The Nature of Technology*. New York, USA.: Free Press.

Basalla, G. (2011[1988]). *La Evolución de la Tecnología*. Barcelona, España: Editorial Crítica.

Bettencourt, L. M. A., Kaiser, D. I., & Kaur, J. (2009). Scientific discovery and topological transitions in collaboration networks. *Journal of Infometrics, 3*(3), 210-221. doi:https://doi.org/10.1016/j.joi.2009.03.001

Brem, A., Nylund, P. A., & Schuster, G. (2016). Innovation and de facto standardisation: The influence of dominant design on innovative performance, radical innovation, and process innovation. *Technovation, 50-51*, 79-88. doi:https://doi.org/10.1016/j.technovation.2015.11.002

Cerulli, G. (2014). The Impact of Technological Capabilities on Invention: An Investigation Based on Country Responsiveness Scores. *World Development, 59*, 147-165. doi:https://doi.org/10.1016/j.worlddev.2014.01.019

Cusumano, M. A., Mylonadis, Y., & Rosenbloom, R. S. (1992). Strategic Maneuvering and Mass-Market Dynamics: The Triumph of VHS over Beta. *The Business History Review, 66*(1), 51-94. doi:10.2307/3117053

Dafoe, A. (2015). On Technological Determinism: A Typology, Scope Conditions, and a Mechanism. *Science, Technology, & Human Values, 40*(6), 1047-1076. doi:https://doi.org/10.1177/0162243915579283

Dosi, G. (1982). Technological paradigms and technological trajectories: A suggested interpretation of the determinants and directions of technical change. *Research Policy, 11*(3), 147-162. doi:https://doi.org/10.1016/0048-7333(82)90016-6

Dotson, T. (2015). Technological Determinism and Permissionless Innovation as Technocratic Governing Mentalities: Psychocultural Barriers to the Democratization of Technology. *Engaging Science, Technology, and Society, 1*, 98-120. doi: http://dx.doi.org/10.17351/ests2015.009

Elder-Vass, D. (2015). Disassembling Actor-network Theory. *Philosophy of the Social Sciences, 45*(1), 100-121. doi:10.1177/0048393114525858

Etzkowitz, H. (2003). Innovation in Innovation: The Triple Helix of University-Industry-Government Relations. *Social Science Information, 42*(3), 293-337. doi:10.1177/05390184030423002

Fagerberg, J., & Srholec, M. (2008). National innovation systems, capabilities and economic development. *Research Policy*(37), 1417-1435. doi:10.1016/j.respol.2008.06.003

Funk, R. J., & Owen-Smith, J. (2017). A Dynamic Network Measure of Technological Change. *Management Science, 63*(3), 791-817. doi:10.1287/mnsc.2015.2366

Geels, F. W. (2009). Foundational ontologies and multi-paradigm analysis, applied to the socio-technical transition from mixed farming to intensive pig husbandry (1930–1980). *Technology Analysis & Strategic Management, 21*(7), 805-832. doi:10.1080/09537320903182280

Geels, F. W. (2010). Ontologies, socio-technical transitions (to sustainability), and the multi-level perspective. *Research Policy, 39*(4), 495-510. doi:https://doi.org/10.1016/j.respol.2010.01.022

Gilfillan, S. C. (1952). The Prediction of Technical Change. *The Review of Economics and Statistics, 34*(4), 368-385. doi:10.2307/1926864

Gilfillan, S. C. (1970[1935]). *The Sociology of Invention*. Cambridge, Massachusetts, USA: MIT Press.

Godin, B. (2010). Innovation Without the Word: William F. Ogburn's Contribution to the Study of Technological Innovation. *Minerva, 48*(3), 277-307. doi:10.1007/s11024-010-9151-1

Hacklin, F., Marxt, C., & Fahrni, F. (2010). An evolutionary perspective on convergence: inducing a stage model of inter-industry innovation. *International Journal of Technology Management 49*(1/2/3), 220-249. doi:10.1504/IJTM.2010.029419

Hagan, S. M. (2007). The Imagined And The Concrete: What is an Artifact? . *Artifact, 1*(1), 23-25. doi:https://doi.org/10.1080/17493460600610855

Høyer, K. G. (2008). The history of alternative fuels in transportation: The case of electric and hybrid cars. *Utilities Policy, 16*(2), 63-71. doi:https://doi.org/10.1016/j.jup.2007.11.001

Klein, H. K., & Kleinman, D. L. (2002). The Social Construction of Technology: Structural Considerations. *Science, Technology, & Human Values, 27*(1), 28-52. doi:https://doi.org/10.1177/016224390202700102

Kudina, O., & Verbeek, P.-P. (2018). Ethics from Within: Google Glass, the Collingridge Dilemma, and the Mediated Value of Privacy. *Science, Technology, & Human Values, 44*(2), 291-314. doi:10.1177/0162243918793711

Kuo, C. I., Wu, C. H., & Lin, B. W. (2019). Gaining from scientific knowledge: the role of knowledge accumulation and knowledge combination. *R&D Management, 49*(2), 252-263. doi:https://doi.org/10.1111/radm.12322

Larrión, J. (2019). Teoría del actor-red. Síntesis y evaluación de la deriva postsocial de Bruno Latour / Actor-Network Theory. Synthesis and Evaluation of Bruno Latour's Post-Social Drift. *Revista Española de Sociología, 28*(2), 323-341. doi:10.22325/fes/res.2019.03

Lundvall, B. Å. (2007). National Innovation Systems—Analytical Concept and Development Tool. *Industry and Innovation, 14*(1), 95-119. doi:10.1080/13662710601130863

Manetti, M. (2015). *Topology*. Cham Heidelberg New York Dordrecht London: Springer.

Marres, N. (2012). On Some Uses and Abuses of Topology in the Social Analysis of Technology (Or the Problem with Smart Meters). *Theory, Culture & Society, 29*(4-5), 288-310. doi:https://doi.org/10.1177/0263276412454460

Mason, W. W. (1931). Trevithick's First Rail Locomotive. *Transactions of the Newcomen Society, 12*(1), 85-103. doi:10.1179/tns.1931.007

Metcalfe, S., & Ramlogan, R. (2008). Innovation systems and the competitive process in developing economies. *The Quarterly Review of Economics and Finance, 48*(2), 433-446. doi:https://doi.org/10.1016/j.qref.2006.12.021

Moore, G. H. (2007). The evolution of the concept of homeomorphism. *Historia Mathematica, 34*(3), 333-343. doi:https://doi.org/10.1016/j.hm.2006.07.006

Murmann, J. P., & Frenken, K. (2006). Toward a systematic framework for research on dominant designs, technological innovations, and industrial change. *Research Policy, 35*(7), 925-952. doi:https://doi.org/10.1016/j.respol.2006.04.011

Nachum, L., & Keeble, D. (2003). Neo-Marshallian Clusters and Global Networks: The Linkages of Media Firms in Central London. *Long Range Planning 36*(5), 459-480. doi:https://doi.org/10.1016/S0024-6301(03)00114-6

Nelson, R. R., & Nelson, K. (2002). Technology, institutions, and innovation systems. *Research Policy, 31*(2), 265-272. doi:http://dx.doi.org/10.1016/s0048-7333(01)00140-8

Niemi, P., Huiskonen, J., & Kärkkäinen, H. (2009). Understanding the knowledge accumulation process—Implications for the adoption of inventory management techniques. *International Journal of Production Economics, 118*(1), 160-167. doi:https://doi.org/10.1016/j.ijpe.2008.08.028

Ogburn, W. F. (1922). *Social change with respect to culture and original nature*. New York: B. W. Huebsch, Inc.

Pel, B. (2014). Intersections in system innovation: a nested-case methodology to study co-evolving innovation journeys. *Technology Analysis & Strategic Management, 26*(3), 307-320. doi:10.1080/09537325.2013.850656

Pinch, T. J., & Bijker, W. E. (1984). The Social Construction of Facts and Artefacts: or How the Sociology of Science and the Sociology of Technology might Benefit Each Other. *Social Studies of Science, 14*(3), 399-441. doi:https://doi.org/10.1177/030631284014003004

Saviotti, P. P. (2018[1991]). The Role of Variety in Economic and Technological Development. In P. P. Saviotti & S. Metcalfe (Eds.), *Evolutionary Theories of*

Economic and Technological Change (Vol. 44, pp. 172-208). London & New York: Routledge. Taylor & Francis Group. Harwood Academic Publisher.

Saviotti, P. P., & Metcalfe, S. (2018[1991]). *Evolutionary Theories of Economic and Technological Change* (Vol. 44). London & New York: Routledge. Taylor & Francis Group. Harwood Academic Publisher.

Schiffer, M. B. (2002). Studying Technological Differentiation: The Case of 18th-Century Electrical Technology. *American Anthropologist, 104*(4), 1148-1161. Retrieved from http://www.jstor.org/stable/3567103

Shapiro, C., & Varian, H. R. (1999). The Art of Standards Wars. *California Management Review, 41*(2), 8-32. doi:10.2307/41165984

Shi, X., & Zhang, Q. (2018). Inbound open innovation and radical innovation capability: The moderating role of organisational inertia. *Journal of Organizational Change Management, 31*(3), 581-597. doi:10.1108/JOCM-07-2017-0262

Solée, R. V., Valverde, S., Casals, M. R., Kauffman, S. A., Farmer, D., & Eldredge, N. (2013). The evolutionary ecology of technological innovations. *Complexity, 18*(4), 15-27. doi:10.1002/cplx.21436

Sood, A., & Tellis, G. J. (2005). Technological Evolution and Radical Innovation. *Journal of Marketing, 69*(3), 152-168. doi:10.1509/jmkg.69.3.152.66361

Sovacool, B. K., & Hess, D. J. (2017). Ordering theories: Typologies and conceptual frameworks for socio-technical change. *Social Studies of Science, 47*(5), 703-750. doi:10.1177/0306312717709363

Spulber, D. F. (2013). INNOVATION ECONOMICS: THE INTERPLAY AMONG TECHNOLOGY STANDARDS, COMPETITIVE CONDUCT, AND ECONOMIC PERFORMANCE. *Journal of Competition Law & Economics, 9*(4), 777-825. doi:10.1093/joclec/nht041

Utterback, J. M. (1996). *Mastering the Dynamics of Innovation*. Boston, Massachusetts: Harvard Business School Press.

Valverde, S., Solée, R. V., Bedau, M. A., & Packard, N. (2007). Topology and evolution of technology innovation networks. *PHYSICAL REVIEW E, 76*(5). doi:https://doi.org/10.1103/PhysRevE.76.056118

Volti, R. (2004). William F. Ogburn "Social Change with Respect to Culture and Original Nature". [Social Change with Respect to Culture and Original Nature, William F. Ogburn]. *Technology and Culture, 45*(2), 396-405. Retrieved from http://www.jstor.org/stable/40060750

Waldmann, S. (2014). *Topology. An Introduction* Cham, Heidelberg, New York, Dordrecht, London: Springer

ISSN: 1989-8487