THE COMPLEXITY OF TECHNOLOGY
How the science of complexity explains technological activities

OCTOBER 2021

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ABSTRACT
This paper shows the importance of the science of complexity to explain processes and structures of technological activities clearing various aspects of the complexity of technology. In a first part of the paper are described some fundamental aspects of the science of complexity and its relation with technology starting from the difference among simple, complicated and complex systems, and a brief history of the formation of the science of complexity. We discuss after the question of measure of the complexity, the concepts and the studied phenomena that makes this science transdisciplinary, and the various types of complex systems: chaotic, auto-organized, adaptive and networks. After the paper describes some complex processes of interest for technology that are the autocatalytic and the phase transition processes, and those based on cyclic systems. It follows a presentation of models of complex systems of interest for technology, such as the small world network model, the NK model, the fitness landscape and the complex adaptive systems. In a second part of the paper we discuss the contribution of the science of complexity to the understanding of the technology innovation process in its phases of generation of innovative ideas, development of technologies and use of technologies. The paper is terminated discussing the advantages deriving by the complexity of technology due to the spontaneous development of valid organizational structures for innovation, and concerning the great number of potential new technologies that may emerge from the enormous chaotic field of technology knowledge. That makes technology a potential solution for economic or environmental problems, and that a sustainable technologic growth is possible by technological developments and right use of technologies.

KEYWORDS: Technology, technology innovation, technology dynamics, science of complexity

JEL CODES: D83, E17, O30, O33,

CONTENTS

1 INTRODUCTION

The study of technology dynamics (Bonomi 2020) and the process of technology innovation (Bonomi 2021) has shown the importance of the science of complexity in supplying general concepts, structures, processes and models in explaining technological activities. It is then of interest to discuss the complexity of technology through this science and to have a general view of technology dynamics seen from the point of view of the science of complexity. This science has been developed in particular by the Santa Fe Institute, founded in 1986 by George Cowan, former scientist at Los Alamos National Laboratories and first President of the Institute, and Murray Gell-Mann, Nobel Prize in physics, and having also many supporters in particular Kenneth Arrow, Nobel Prize in economy (Waldrop 1992). In fact, this science has a key role in treating the description of technology seen as an enormous set of physical, chemical and biological phenomena that produce the effects that may be exploited for various human purposes. In this case the science of complexity supplies the concept of technological operation, able to generalize the sets of physical phenomena composing a technology, leading to consider a technology as a time-oriented structure of technological operations. This application of the science of complexity is at the base of a general model of technology from which it is possible to derive the various processes and structures of a technological activity independently of its purposes, such as economic purposes, and able to explain some fundamental aspects of technology (Bonomi 2020). The science of complexity is transdisciplinary, and that means it defines concepts, describes structures and processes, and develops models that are valid for many disciplines. In this way it gives a support in understanding many phenomena of various nature including those observed in technology dynamics. An example of an important transdisciplinary approach is the model of technology, derived from a previous biological model of genes interactions (Kauffman 1993), and obtained by substituting genes with technological operations (Auerswald et al. 2000).

It is not the objective and possibilities of this paper to discuss the development of further applications of the science of complexity to the study of technology, and its scope is limited to description of concepts, processes and models of the science of complexity applied to processes and structures of technology innovation. The Santa Fe Institute, has carried out studies on complexity of technology between the end of 80' and the beginning of 90', in particular with the contribution of two of its scholars: Brian Arthur and Stuart Kaufmann (Waldrop 1992), leading to the development of the general model of technology cited previously. After these works, the Santa Fe Institute did not continued studies of application of science of complexity to technology, and a recent review edited by this institute on the research activity between 1984 and 2019 (Krakauer 2019a) reports many fields of study of this science, but it does not include the field of technology and makes only an indirect reference considering the case of emergent engineering that may be reframed by the science of the complexity (Krakauer 2019b). Actually, by describing the relations existing between technology and the science of complexity, this article has also the aim to renew the interest of this science in the field of technology and its innovation for a better understanding of this complex activity.

The study of complexity, implies the abandonment of the description of systems in term of existence of a direct relation between cause and effects, and the adoption of a new not linear way of thinking. Furthermore, it is necessary to abandon the easy, but not suitable, view of existence of a possible forecasting of evolution of the complex systems, substituted by a multiplicity of scenarios and accepting the associated uncertainness. The study of problems in this manner means to be able to integrate different types of information, recognize the hidden connections and possible evolutions, determine the factors of instability and possible useful variations.

After this introductory section in a second section we define the difference among simple, complicated and complex systems. In a third section we give a brief historical description of the formation of the science of complexity. In a fourth section we discuss the measure of the complexity. In a fifth section we define the various concepts and phenomena, and in a sixth section the various types of complex systems. In a seventh section we describe the various processes and in the eight section the models developed by this science interesting technology. In a ninth section we discuss the applications of the science of complexity to the technology innovation process and in the tenth section we conclude citing applications and discussing the advantages of technology due to its complexity.

2 DEFINITION OF THE VARIOUS TYPES OF SYSTEMS

From the point of view of the complexity, it is possible to define three general types of systems: the simple systems, the complicated systems and the complex systems.

Simple systems
They are of simple nature and ready understandable in its functioning, for example a pendulum, and a perturbation has typically a linear behavior in which we have generally an effect that is proportional to the magnitude of the perturbation.

Complicated systems
These systems, not readily understandable, are governed by established laws making possible forecasting or to have solutions based on analytic-deductive procedures. An example is the clock in which it is not possible to visualize immediately the functioning but it is possible to give its full description and the laws for its functioning. As in the case of simple systems, the complicated ones have typically a linear behavior in which a perturbation has generally an effect that is proportional to its magnitude.

Complex systems
These systems are characterized by the fact that it is not possible to establish deterministic laws for their behavior and are then unpredictable. Their behavior is not linear and in certain case they may be subject of great perturbations but with little effects or, on the contrary, have very great effects caused by little perturbations. These systems are of various types and are the object of study of the science of complexity.

3 BRIEF HISTORY OF THE SCIENCE OF COMPLEXITY

Historically the birth of the science of complexity may be attributed to the great French mathematician and physicist Henry Poincaré that observed analytically for the first time the limits of forecasting of behavior of complex systems. He reported in his book *Science and Method*, written in 1903, the possible existence of systems in which small differences in the initial conditions may generate enormous differences in the final resulting phenomena, making impossible a forecasting and then resulting in a casual behavior. The observations of Poincaré cannot be confirmed before the development of computers allowing the modelling of natural phenomena with sufficient calculation power and accuracy. That happened in 1961 following the works of Edward Lorenz, an American meteorologist, studying a global meteorological model on a computer, and finding that very small difference in the initial meteorological conditions were able to generate, after a certain time, very different meteorological situations. The history of this discovery has been reported in a book about chaos (Gleick 1987) and described as the result of a repetitive running of a meteorological model on the computer, casually using as input the printed initial data limited to three decimals. Actually, the computer used six decimals but not entirely printed to save space. Lorentz thought that this difference would not have effects on forecasting, but in fact it was not the case and gave after a certain time a very different meteorological situation, a behavior called later the *butterfly effect*. Following this discovery on behavior of chaotic systems there was an increased interest in the study of these systems and also other complex systems leading to the formation of the science of complexity in which the Santa Fe Institute, cited previously, has taken a great role (Waldrop 1992).

4 MEASURE OF THE COMPLEXITY

In the study of the complexity it would be of interest to have the possibility to measure the complexity of the various systems. While it is possible to measure the disorder of a system through the concept of entropy, and also to describe the various configurations of ordered systems, it is not possible to define a general measure of the complexity of a system but only to elaborate some measures on certain types of complex systems. This argument has been presented in a simplified manner in a book on complexity written by Murray Gell-Mann, one of the founders of the Santa Fe Institute cited previously (Gell-Man 1994). In informatics, for example, it is possible to define the *computational complexity* as the minimum time necessary to a computer to solve a certain class of problems independently of their dimension, however this measure depends also on the choice of the computer. Another aspect of the complexity of a system is the fact it depends also on the scale with which are considered its elements. For example, in a biological ecosystem is different whether we consider only plants and animals or we take account also of insects and microbiologic organisms. In technology, its modelling will be different following the detail we describe the structure of technological operations considering or not also the various sub-operations. It is then evident that the complexity varies following the scale of the elements considered for a system. Actually, any real complex system may be in principle modelled on a computer and described as a binary string. The complexity of this string may reflect, in a certain way, the complexity of the system. That will depend on the used model for the computer, that represents necessarily a simplification of the system, in carrying out an acceptable simulation in the considered scale of details. Now, comparing two strings, it may appear that one string contains regularities while the other may appear irregular. Actually, it is possible to define in informatics the regularity of a string using a parameter called *algorithmic contents of information* (ACI) or *algorithmic randomness* defined as the shortest length of time of a program able to print the string and terminate the program on a computer with a memory enough big for the treatment of the string. In fact, in presence of regularities in a string, the program will be able to compress the description of the string allowing a more rapid printing while, with a completely irregular string, the program will take time to print each of all elements of the string. However, the ACI cannot be measured accurately, in fact the Chaitin's theorem has shown that, given a string apparently disordered, it does not exist any algorithm able to identify all the possible regularities existing in the string and then compressing the program in order to measure accurately the ACI. This theorem has important implications on our concept of disorder, in fact, a string that appears completely disordered, may contain in the reality some regularities that however would be too complex to be identified, then the definition of a system as disordered may be simply the result of our ignorance on the system. Nevertheless, the ACI may give some indications about the complexity of a system. That may be explained for example considering three types of text of the same length represented by strings: a first text composed only by the same letter, a second text composed by a disordered list of letters, and a third text composed by a chapter of a book. The value of ACI will be very low for the first text, very high for the second disordered text and intermediate for the third text that in fact appearing more complex than the ordered text, and containing grammatical or syntactic regularities. In other words, the ACI does not represent a measure of the complexity but a property of a system that, starting from an ordered situation, increases the ACI in generating complexity reaching a point that corresponds to a transition from order to what it appears as a disordered system. This fact is important and it is observed in many real cases in which the formation of complex structures occur at the edge of chaos, for example, in the change of phases of water, the ordered molecular structure of ice may melt and form the complex molecular structure of liquid water and then a transition to the chaotic system of vapor molecules. In technology such transition is observed in generation of a new technology, considered as a form of complex system, and obtained by a formation of an order constituted by the combination of previous technologies existing in the chaotic system of the technological knowledge in the generation of new technologies, in fact the formation of order at the edge of chaos (Bonomi 2020).

5 COMPLEXITY CONCEPTS AND PHENOMENA

The science of complexity assumes that seemingly disparate phenomena, both natural or social, can be understood using a common conceptual view, and that it is possible to elaborate metaphors, analogies and finally develop models for these phenomena (Gray, Macready 2019). Used concepts and described phenomena in the science of complexity are for example: emergence, adaptation., evolvability, robustness, co-evolution, learning, self-organization, networking, phase transition and feedback loop. These concepts and phenomena are associated to various processes existing in a complex system and then in technology and are described as follows:

Emergence is a concept corresponding to a process forming an ordered system from the chaos. This concept was used for example in the case of biology to explain self-organization and selection processes in biological evolution (Kauffman 1993), and in technology to explain the generation process of innovative ideas from available knowledge (Bonomi 2020).

Adaptation is a concept corresponding to a process of modification of a system under the effect of externalities in order to maintain its fitness. In technology it corresponds to modification of technological parameters or technology structure to conserve the efficiency of technology under the effects of externalities.

Evolvability is a characteristic process of a system that continuously evolve with time modifying its structure under the effect of internal or external factors. This process occurs either in biological or technological evolutions and, in this last case, it is characterized also by the formation of organizational structures for technological innovations such as the R&D system, the startup-venture capital (SVC) system and the industrial platform system (Bonomi 2020).

Robustness is a phenomenon represented in natural systems by the resistance to disruption because of various externalities that act on the system. In artificial or technological engineered systems robustness represents the resistance to disruption although under the effect of externalities not considered in the design of the system.

Co-evolution is an evolutionary concept corresponding to a process observed for example in biology and concerning the genetic evolution of the prey-predator system. If a predator modifies its genetics improving efficiency in hunting a prey, it is observed also the formation of a genetic modification in the prey to compensate the increased efficiency of the predators. Such phenomenon observed in biological evolution has been called *Red Queen Regime* (Van Valen 1973), and it is observed also in technological competition among firms of an industrial district or sector in which the competitivity obtained by an incremental innovation of a firm is readily eliminated by innovations obtained by the other firms. That leads to a continuous development of technological innovations of incremental type but without important economic growth or emerging of dominating firms (Bonomi 2020).

Learning is a general concept covering a phenomenon existing either in natural or artificial systems in which specific behaviours necessary to maintain the fitness of a system, in respect to various externalities, are memorised and made available when necessary. A typical learning activity in technology is observed for example in facing externality effects and consequent acquisition of knowhow during the use of a technology, and also in learning by doing (LbyD) activity leading to improvements or even new incremental technologies (Bonomi 2020).

Self-organization is a phenomenon linked to emergence in which chaotic elements become self-organized forming an ordered system and observed, as cited previously, in biology (Kauffman 1993). In technology this phenomenon is represented by the formation of an innovative idea for a new technology based on a self-organization of pre-existent technologies through a combinatory process exploiting or not exploiting new or never used phenomena discovered by science. The formation of organizational structures for innovation may be also considered as the result of a self-organization of fluxes of knowledge and capitals (Bonomi 2020).

Networking is a typical behaviour of elements of a system that enter in connection forming a network. In the science of complexity networks are studied by specific models taking account of a phenomenon existing in real networks and called *small world effect.* That is based on the observation that are necessary in real networks only a very small number of passages to link two distant elements even in a great real network. The small world effect is largely exploited by rapid communications in internet. The formation of networks of relations is typical of either biological or technological ecosystems. The networking of actors interested in technology innovation and the existence of the small world effect is important in the diffusion of knowledge useful for generation of innovative ideas for new technologies. Interesting examples of networking and small world effect are reported in technology dynamics study in the examples of use of the general knowledge generated by R&D activities (Bonomi 2020).

Phase transition is a phenomenon consisting in a drastic change observed in a system because of evolution of certain parameters of the system. A phase transition is not a time dependent phenomenon but dependent on changes in the structure and processes of a system. Many cases of phase transitions are known in physics concerning for example melting/solidification, vaporization/condensation processes and also transition from magnetic/not magnetic behavior as a function of temperature. Phase transitions in technology are also observed in the evolution of territories from technology stagnation or decline to technology development because of an increase of R&D activities above a critical threshold of magnitude (Bonomi 2020).

Feedback loop is a phenomenon in which the caused effects of a system influence the factors that are the cause of the observed effects. It is formed in this way a feedback loop that determines the behaviour of the system. In technology feedback loops are observed in the generation of innovative ideas from R&D activities or during the use of technologies that are both in fact originated by previous innovative ideas. Important feedback loops exist in technology dynamics in the intertwining process between R&D activity and scientific research (Bonomi 2020), and in the relation between science and technology (Bonomi 2021). In the first case scientific results are useful for R&D activities, but R&D may trigger sometime scientific research to obtain results useful to verify possibilities of new applications. In the second case technology is needed to make new scientific discoveries, but science supplies new discovered phenomena exploitable for new technologies. Another important feedback loop exists in industrial platforms that supply improvements and new technologies to peer consumers that return knowledge of use of technologies useful to the platform for improvements and new technologies. (Bonomi 2020). These three feedback loops in the field of science and technology are presented in Fig.1.

6 TYPES OF COMPLEX SYSTEMS

It is possible to consider four types of complex systems: the chaotic system, the auto-organized critical system, the complex adaptive system and the network system that are described as follows:

6.1 Chaotic system

This is a disordered system that presents neither casual phenomena statistically correlated nor adaptative behaviors. However, in many cases, observing its chaotic evolution with time, it may show some regularities. In fact, representing this system with its variables in the so-called *space of the phases*, it may be observed an approach with time of the system, often thorough a repetitive behavior, to specific values of variables constituting what it is called an *attractor basin*. In another case a chaotic system reaches a dead point ending its evolution, and it is then called a *terminated system*, or it is not observed any arrest and the system is called *progressive*. It may be observed that the fact that attractors or termination behaviors are not observed in a chaotic system, it is not a demonstration that the system does not have these behaviors because they may appear after a time greater than that used for the observations. All these phenomena have been noted in the study of many chaotic systems (Gleick 1987), such as the study of the chaotic meteorological system made by Lorentz cited previously. The knowledge associated to technology, and including the enormous number of technologies that are in use or have been used, may be considered as a chaotic system from which new technologies emerge through combinatory processes.

6.2 Auto-organized critical systems

This type of systems with a chaotic behavior, presents however casual phenomena that are statistically correlated. That has been observed first in 1956 by Charles Richer, an American seismologist, studying statistically the occurring of earthquakes and their energy. Richter observed that the frequency and the intensity of earthquakes, in a determined vast area for a length of time enough high, were correlated with an inverse proportional relation between the logarithm of the frequency and the logarithm of the intensity of earthquakes. This type of correlation has been observed in many other casual phenomena occurring with time, and in 1987 Per Bak, a Danish physicist, gave a demonstration of this law in an experiment using a heap of sand of critical dimension producing avalanches by addition of further sand. It was found in this case that dimensions of avalanches followed the same logarithmic law of Richter for earthquakes. He found also that their distribution has a fractal dimension being the same for the various scales of sand heaps. He called these systems *critical auto-organized* systems (Bak, Tang, Wiesenfeld 1987), It has been also observed that in these systems the appearing of phenomena of extraordinary great dimensions, when considering a sufficient long lapse of time, occurs within irregular intervals of time, and they may appear coupled in a short period especially after a long period in which they have not appeared. The existence of critical auto-organized systems following the Richter law has been observed also in economic field considering the variation of cotton price in stock markets for which it exists a record of prices since a long time. In this case it has been observed also a fractal type distribution that appears the same considering many various periods of time of different length (Gleick 1987). In technology the auto-organized critical systems are represented by environments in which the generation of grouped new technologies may appear suddenly in small or great number within a short time in specific fields during the technological evolution. The same may occur for appearing with of externalities with small or great effects on the use of a technology modifying sensibly for example its economy.

6.3 Complex adaptive systems

The *complex adaptive systems* (CAS) are the most important among the various complex systems and find many applications also in technology dynamics. This complex system is characterized by a structure composed by a set of elements that interacting makes the emergence of a certain behavior (Holland 2019) or, in alternative, a system that, on the base of its behavior in respect to its environment, carries out a specific treatment of the received information (Gell-Man 1994). These two different views of CAS, have been the object of two different models of this system described later in the section on modelling of complex systems.

6.4 Network systems

Network systems are the result of a networking activity producing networks with ordered or casual connections. From the mathematical point of view, a network may be ordered, for example the linking of atoms in a crystal, or casual in which the elements of the network are linked in a disordered way. Real networks are mostly a mixture of both presenting, as cited previously, the so-called small world effect consisting in the existence of only a small number of connections to join even two very far nodes of the network (Newman 1999).

7 PROCESSES IN THE COMPLEX SYSTEMS

The science of complexity has studied a certain number of processes that may operate in complex systems and two of particular interest for technology are: the autocatalytic processes linked to phase transitions and processes based on cycles and hypercycles.

7.1 Autocatalysis and phase transition

The process of autocatalysis occurring in a complex system may be explained considering the relation existing between the number the elements of a system and the number of their interactions. An autocatalytic process may occur when there is a sufficient high number of positive interactions among the elements reaching and overturning a certain threshold that is high enough to provoke an autocatalytic process of growth. The overturning of the threshold represents in fact a phase transition of the system from a subcritical stagnant situation to an autocatalytic development. This situation is represented in general by the curve reported in Fig. 2 separating a subcritical area from the autocatalytic area. In this figure the curve represents also the phase transition from a subcritical to an autocatalytic situation of the complex system. In biology it has been proposed that the formation of the first living cells occurred when there was formed an enough high number of complex interactive networks among molecules with a biologic potential, generating auto-sustained protometabolic networks, and forming what it may be considered a phase transition from groups of simply interacting molecules to living organisms (Kauffman 1993). The process of phase transition has been observed also in technological activities and for example shown by studies on R&D. In fact, developing a mathematical simulation model of this activity, it has been shown the formation of a phase transition between a situation of technology stagnation or decline to a situation of technology development. That has been done studying the starting of a variable number of initial R&D projects in a territory vs. the efficiency of the territory in exploiting the available knowledge, and showing that an autocatalytic technology development is formed when there is an enough high number of initial R&D projects started in the territory and sufficient efficiency in exploiting of available knowledge (Bonomi 2020).

7.2 Cycles and hypercycles

Cycles in complex systems are phenomena characterized by a sequence of events, the last one forming anew the initial status quo event or generating a development or decline and arrest of the cycle. In a certain way cycles may be considered an evolution of feedback loops in which are introduced factors producing a connected sequence of effects in the loop. Often a cycle is started by an initial triggering factor that put it in activity. This activity may reach an equilibrium (status quo) or a continuous growth or, on the contrary, a decline until its arrest as previously noted. The growth of the activity may be the consequence of an autocatalytic effect produced in the cycle, on the contrary, the decline may be produced if the trigger magnitude is not enough effective to sustain the activity of the cycle causing in this way its arrest. A schematic view of the cycle with the possible evolutions is presented in Fig. 3. In technology dynamics there are various important types of cycles concerning knowledge in the R&D and startups activity, and the financial cycle of the SVC system (Bonomi 2020). Hypercycles are in fact cycles in which the elements of the cycle sequence are themselves cycles. They have been observed in many natural phenomena for example in biochemistry (Eigen, Winkler 1975) but not until now in technological activities.

8 MODELS OF COMPLEX SYSTEMS

The science of complexity has developed various types of models to explain the various behaviors of the complex systems. Such models, for the transdisciplinary characteristic of this science, may find applications in many fields of science and technology. The models interesting technology dynamics concern: the small world network model, the NK model, the fitness landscapes and the complex adaptive system (CAS) models

8.1 Small world network model

As previously discussed, real networks may be considered composed by a mixture of ordered and casual connections among their elements and presenting the previously explained small world effect. It is then of interest to develop a mathematical model simulating the real networks presenting this effect. One of these models is for example the Watts and Strogatz model in which in a special ordered network are introduced some random connections between nodes of the ordered part and presenting by running the model a small world effect (Watts, Strogatz 1998). The small world effect has for example an important role in diffusion of knowledge concerning technology or innovative idea in networks of researchers involved in a same field of R&D.

8.2 NK model

The NK model is constituted by a Boolean network of N points each connected with other points with a K number of connections. The activated or disactivated state of a point will depend on the state of the K points with which it is connected through logic relations (AND, OR, NOT, etc.) chosen for the connection. A simple example of Boolean network of model NK may be formed by 3 points (N = 3) each with 2 connections (K = 2) as reported in Fig. 4. The state of point 1 of the figure (activated or disactivated) will depend on the points 2 and 3 and by the chosen Boolean relation. For example, if the relation is AND, the point 1 will be activated only when both points 2 and 3 are activated. In this way it is possible to build up quite complex networks that may assume various sets of activated or disactivated states evolving with time in a variable way, or, in certain cases, forming more or less ample zones that remain activated or disactivated or rather oscillating with time in two states. The NK model has been originally developed in physics to explain the magnetic behavior of spin-glasses. In technology the NK model has been employed by Stuart Kauffmann in studying LbyD. In fact, Kauffman, starting from his application of the NK model to analyze asexual biological genetic evolution (Kauffman 1993), extended this approach to analyze the dynamics of manufacturing costs in LbyD activities by substituting genes with technological operations. The dynamics of manufacturing costs in LbyD activities through the NK model was presented first in a working paper published in 1998 by the Santa Fe Institute and then published in 2000 on the Journal of Economic Dynamics and Control (Auerswald et al. 2000). The idea existing in this work to see technology as a set of operations, deriving concepts such as the technological space and the technological landscape, was, as previously noted, of great importance for the development of a general model of technology introducing also the concept of space of technologies (Bonomi 2020). Another application of the NK model in technology has been also developed by Koen Frenken in 2001, but considering technology as an artefact composed by a set of components and not as a process composed by a set of operations as in the Kauffman's model (Frenken 2001).

8.3 Fitness Landscape

The fitness landscape may be derived from the NK model and represents a powerful tool in explaining the evolution of complex systems. The fitness landscape is used in particular to visualize relations between the various configurations of a system and their corresponding fitness. Considering that each configuration of a system may be described considering all the elements of the system, each with its various parameters with their various values or choices, it is possible to represent all the configurations in a multidimensional discrete space in which each point corresponds to a specific configuration. If we associate to each point or configuration the scalar value of its fitness, we obtain a fitness landscape. It is possible to explain the construction of a very simple fitness landscape starting from two points of the NK model that may assume each two possible states corresponding to 1 or 0. In this case the various configurations of the system composed by the two points may be represented in the space of configurations by four points corresponding to the four possible strings. If we associate the scalar value of fitness for each of the four points, we obtain the fitness landscape of the system represented in Fig. 5. This tool has found applications especially in theoretical biology in the study of genotypes. In technology dynamics a fitness landscape may be used to represents the efficiency of a technology as a function of values or choices of the various parameters of each operation constituting the structure of a technology in what it is called a technological landscape. The case reported in Fig. 5 corresponds in fact to a simple technology composed by two operations each with only one parameter that may assume only the values 0 or 1. The indicated space of configuration corresponds to the technological space, and the fitness landscape to the technological landscape of this simple technology (Auerswald et al. 2000).

8.4 Complex adaptive system models

Adaptation phenomena are studied in the science of complexity in the so-called complex adaptive systems (CAS) previously presented and that may be modelled finding applications in many fields including technology. A CAS may be described, as previously explained, on the base of its structure as a set of elements that interacting makes the emergence of a certain behavior. In alternative a CAS may be described on the base of its behavior in respect to its environment as a system that carry out a specific treatment of the received information. The first model, has been developed by John Holland (Holland 2019), and it is composed by a set of agents that have the freedom to act in a not totally fully predictable way on the base of own schemas, and their actions are interconnected in such a way that an action of an agent influence the actions of the other agents. The behavior of the system emerges from the interactions of the various agents under the influence of the environment in which the CAS is embedded. The agents may be individuals, firms, families, etc. following the nature of the system. In the Fig. 6 we have reported a simplified schematic representation of such system model. The second type of CAS model, described by Murray Gell-Mann (Gell-Man 1994), is composed by a system that receives and treats the information acting in consequence and it is presented schematically in Fig. 7. The process is cyclic and starts considering an initial existence of anterior data concerning behavior, effects, etc. that the system identifies in term of regularities and forming, through compression and simplification, a description of the forecasting behavior, and putting in this way the system in action. The operation of the system in the real world is influenced by an input of external factors that make a change of the behavior with the corresponding consequences. That has also a selective effect on the schematic structure followed by a memorization of data and experience that influence the future action of the system. This second model is of particular interest in technology as it describes the process of adaptation of a technology under the influence of externalities through improvements or generation of innovations during its use, as for example in LbyD activities.

9 SCIENCE OF COMPLEXITY AND TECHNOLOGY INNOVATION

In the previous sections we have seen how the various concepts, processes, structures and models of the science of complexity are in relation with various aspects of technology dynamics. It is of interest to see also the relation between technology and the science of complexity from the point of view of the innovation process. Therefore, considering that the concepts, structures, processes and models are in relation with the main phases of the innovation process i.e. the generation of innovative ideas, the technological development including feasibility, development and industrialization steps, and the use of technology.

9.1 Generation of innovative ideas

The process of generation of innovative ideas is based on the available knowledge concerning an enormous quantity of technologies, that are in relation and interacting among them. This system may be considered a *chaotic system,* that may have also the behaviour of an *auto-organized system* in certain case of generation of small or great waves of new ideas for new technologies. It is then characterized by the phenomenon of *emergence* of an idea from available knowledge, and consisting in a *self-organization* of pre-existent technologies in imagining a possible new technology exploiting or not exploiting new or never used phenomena discovered by science. This process of generation is favoured also by the existence of *networks* of people exchanging knowledge boosted by the *small world effect*. The factor controlling the emergence of innovative ideas is represented by the efficiency in exploiting the available knowledge generating more or less R&D projects or startups proposals. This efficiency, as we have seen previously, is also one of the parameters that determines the *phase transition* from a technological decline to an autocatalytic development in territorial innovation systems. Finally, the formation of the innovative idea may be seen also as formation of an order at the *edge of chaos* as discussed about the measure of complexity and the meaning and properties of the *algorithmic contents of information* (ACI) parameter.

9.2 Development of the technology

This phase of development is characterized by the presence of R&D and startups activities and for this phase are available a model of R&D based on a *knowledge cycle,* and a model of the SVC system following the VC *financial cycle*. In Fig. 8 we have reported as example the knowledge cycle of R&D projects or startups in technology dynamics. This phase of the innovation process is also concerned by the auto-organization of structures for innovation such the R&D system, the SVC system and the industrial platform system. Furthermore, it is possible the formation of a *phase transition* from technological decline to development in a territory through *autocatalytic processes* as a function of the amount of technology innovation activity and efficiency of exploitation of available knowledge. This phenomenon may be highlighted by running the R&D model cited previously (Bonomi 2020).

9.3 Use of the technology

During the use of technology there are numerous concepts and processes derived from the science of complexity that may characterize this activity such as: processes of *adaptation*, degree of *robustness* vs. external factors, *evolvability* with formation of new incremental innovations and *learning* through the formation of a knowhow by LbyD. An important model of the science of complexity explaining the activities during the use of a technology is a specific type of *fitness* *landscape* called technological landscape, that presents the efficiency of a technology as a function of its various operational conditions. A technology is normally operated in the optimal conditions represented in the landscape. Externalities may modify the form of the landscape and new optimal conditions of operation shall be found through an exploration of the new form of the landscape. Sometimes the effects of externalities cannot be eliminated by a search of new conditions in the landscape and it is necessary a technology innovation, generally of incremental type, associated to a new technological landscape. An important model of the science of complexity interesting the use of a technology is the *complex adaptive system* (CAS) following the Gell-Mann's view as a system treating information and acting in consequence. It may explain the way with which the use of a technology faces the influence of the various externalities. A simplified view of the Gell-Mann's model applied to the use of technology is reported in Fig. 9. In this model the process starts with existence of optimal conditions of operation of a technology associated with a predictive system on the behaviour of the technology constituted by the technological landscape and existing knowhow. Under the effects of an external factor the used optimal conditions may be disrupted and it is necessary an action to modify the operative conditions of the technology considering the landscape and accumulation of new knowhow. That occurs normally by modifying the operative conditions and possibly by introducing an incremental innovation. The new operative conditions close the CAS cycle with a possible modification of the predictive system. The interpretation of the improvements of a technology through the CAS model may explain also because a knowhow of a technology cannot be transferred completely by simply oral explanations or in the written form of manuals. In fact, a technology cannot be considered a simple deterministic system for which it is possible to give a complete description of its operative conditions. That because it is operated in a chaotic environment undergoing to unpredictable externality effects that must be considered in order to maintain its efficiency, and practically that cannot be completely included in manuals or oral descriptions, but treated as described in the CAS model. This situation well explains the necessity of LbyD in the improvement or transfer of a technology

9.4 Feedback loops in technology innovations

There is a process described by the science of complexity, the *feedback loop*, that in fact involve all the three stages of the innovation process. In the process of technology innovation there are two phases involved in the generation of knowledge, the first one concerns the R&D and startup activity, and it is constituted by general knowledge formed in successful or abandoned projects or startups, the second one is represented by knowledge generated during the use of a technology that may lead to incremental innovations in response to externalities or LbyD, although rarely forming radical innovations. Both sources may feed knowledge, especially in the case of R&D activities, to the stage of generation of innovative ideas that enables the starting of the following development phase.

The feedback loops completed with indications of concepts, processes, structures and models derived from the science of complexity, and involved in the various phases of the innovation process, are indicated in Fig. 10.

10 THE COMPLEXITY ADVANTAGE OF TECHNOLOGY

The interpretation of technological activities through concepts, structures, processes and models of the science of complexity has allowed to clear some fundamental aspects of technology that may have applications in technology management and policies for technology innovation. These aspects have been used in technology dynamics to describe the innovation process, to suggest new statistical studies for research and innovations and actions for the promotion of innovation activities (Bonomi 2020). Furthermore, the study of a general model of technology innovation has given also interesting considerations about the relation between science and technology, between technology and economic growth, between technology and the environment and also the importance of intermediate scientific and technical education in the process of generation of new technologies (Bonomi 2021). Actually, there is an important aspect of processes and structures studied by technology dynamics, and linked to the science of complexity, consisting in the fact that they have been originated and evolved historically mostly as spontaneous phenomena, and not resulting by a design developed in business schools or by a forecasting in the academic field, in fact both active essentially only in their study after knowing their existence. The spontaneous evolution of technological structures and processes may be considered as the result of a Darwinian selection of various attempts to satisfy the various technological needs of the society. The derived technological innovation system appears consequently robust, in the sense this concept is defined by the science of complexity, assuring the continuity of activities for example of the various organizational structures for innovation. Actually, the fact that technologies are the result from an innovation system formed mostly spontaneously, submitted to a Darwinian selection, based on efficiency of its processes and organizational structures for the innovation, constitutes one of the important advantages of technology resulting from its complexity, characterized by the emerging of new technologies from the chaotic system of technological knowledge, an emergence occurring through the self-organization of structures for innovation such as the R&D, SVC and platform systems. Furthermore, the neutrality of technology vs. its purposes of use, derived from its nature based on physical phenomena, and not defined in term of relations with the economic or social system, shows that environmental problems attributed to certain technologies are in fact ascribable to the purposes of their use and not to the basic nature of technology, and the same technology may be useful or dangerous depending on purpose and conditions of its use (Bonomi 2020). On the other side the enormous chaotic availability of technologies, and the progress in scientific discoveries, makes possible an enormous number of potential new technologies through the combinatory process of their formation. All that allows to conclude that technology shall not be considered a source of problems, but a potential solution for economic or environmental problems, and that a sustainable technologic growth is possible by a right development and use of technologies.

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12 FIGURES

Fig. 1. Feedback loops in technology dynamics

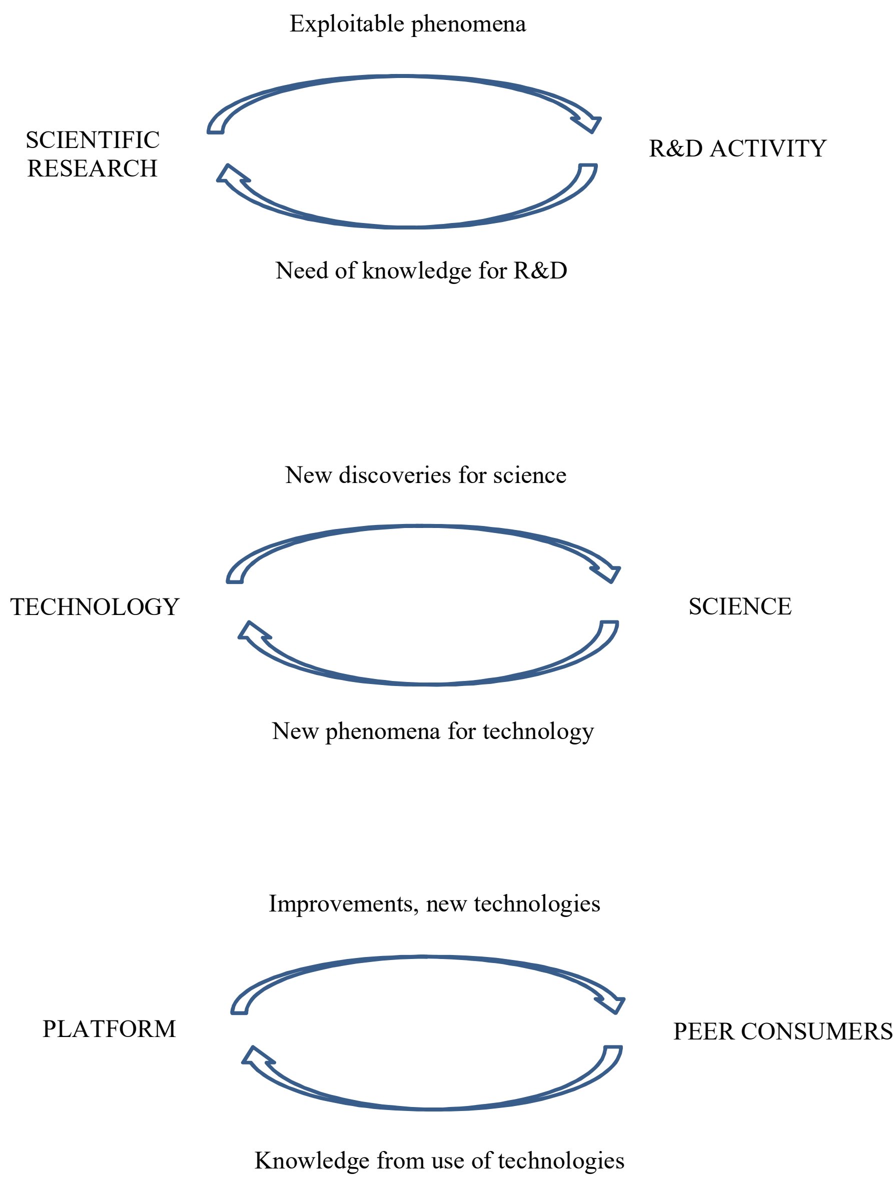

Fig. 2. Autocatalysis and phase transition

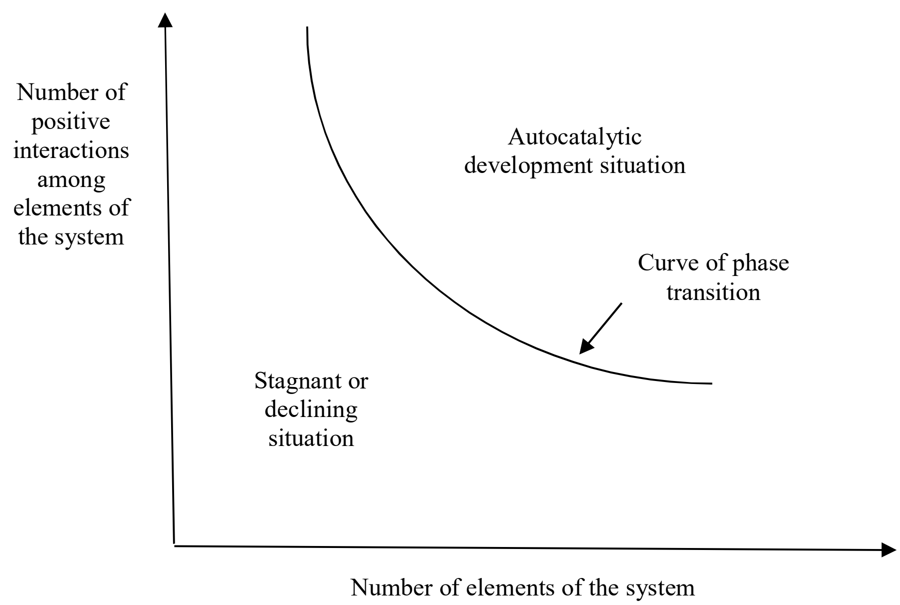

Fig. 3. Example of a complex system cycle

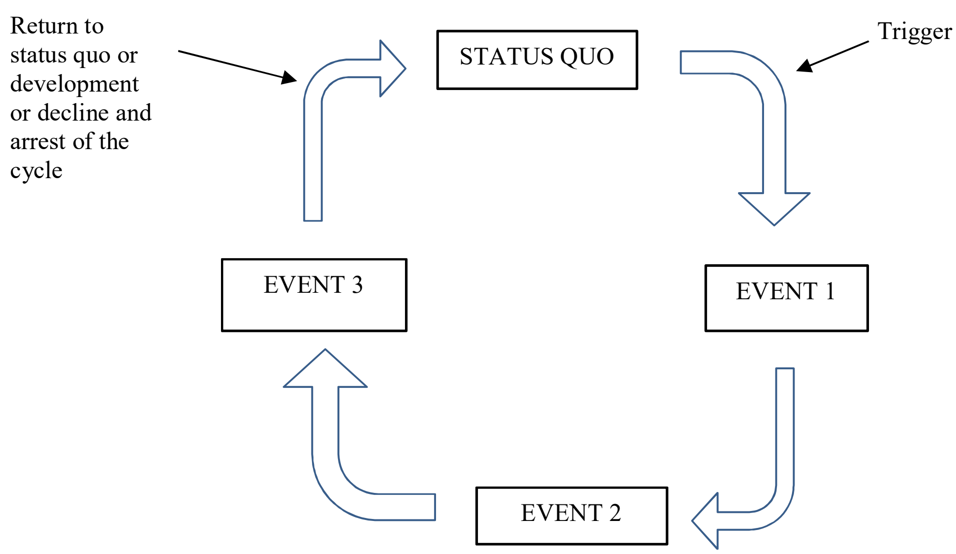

Fig.4. Schematic view of NK model with N = 3 and K = 2

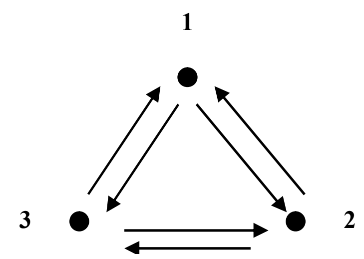

Fig. 5. Fitness landscape of two elements of a string each with two possible figures: 0 and 1

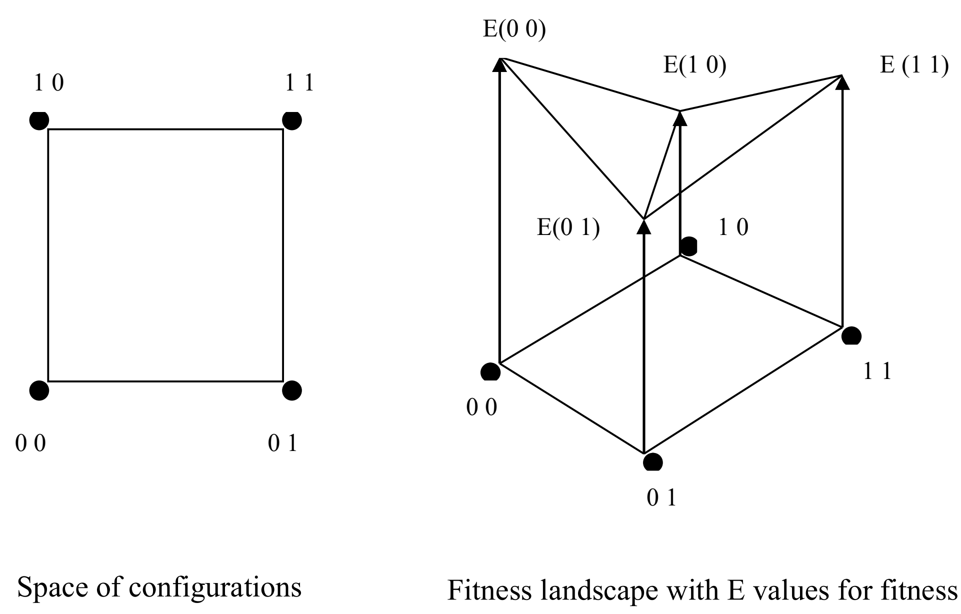

Fig. 6. Holland's model of a complex adaptive system

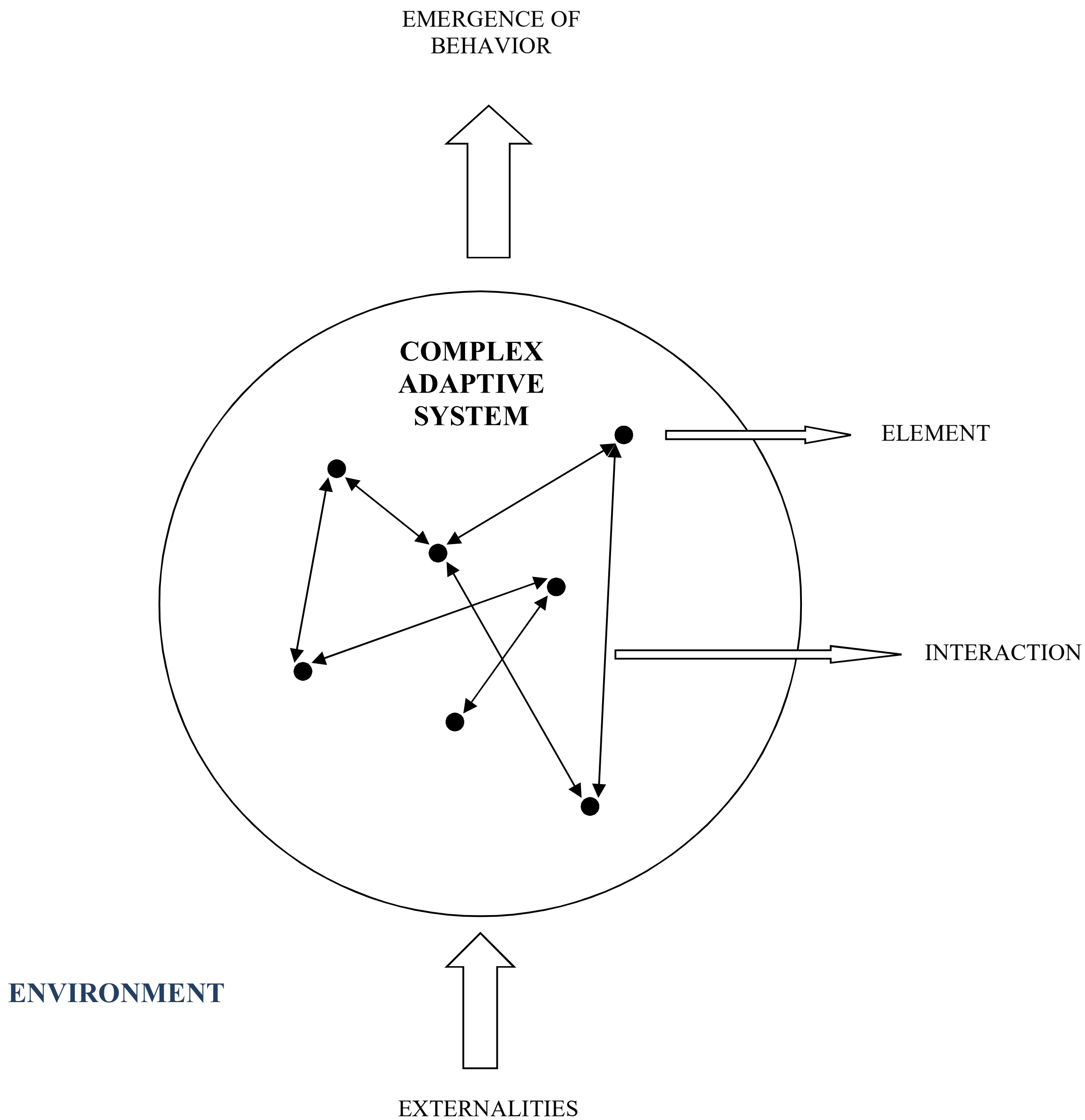

Fig. 7. Gell-Mann's model of a complex adaptive system

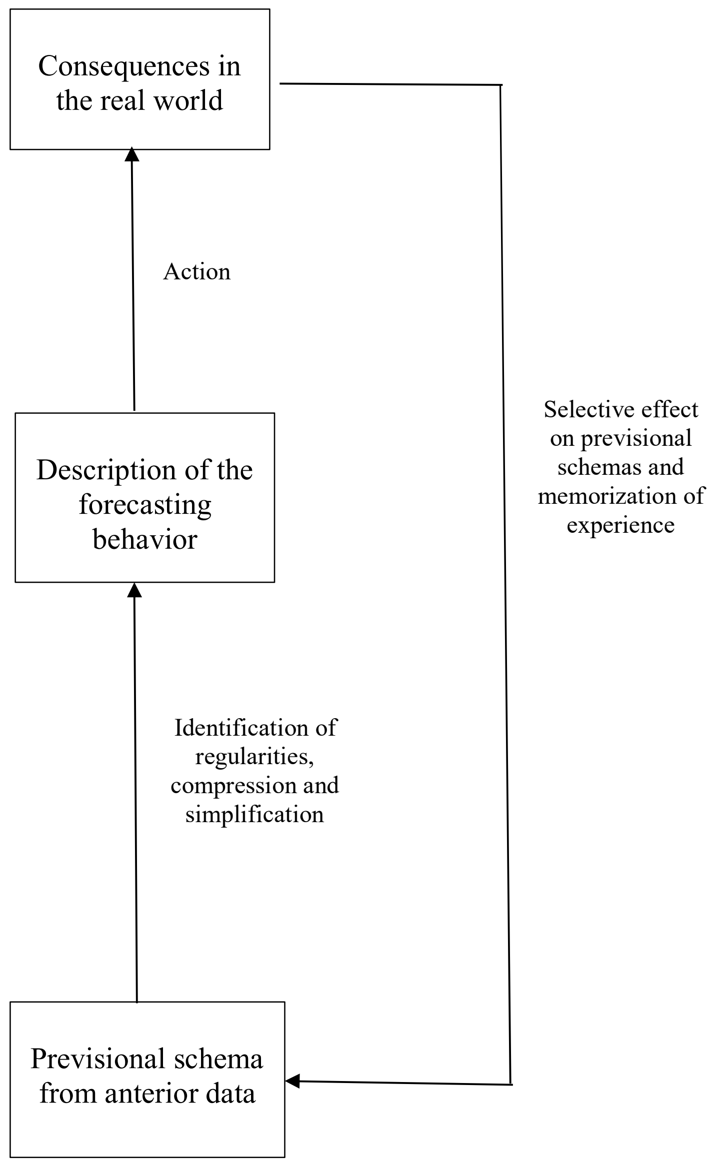

Fig. 8. Knowledge cycle in R&D projects and startups

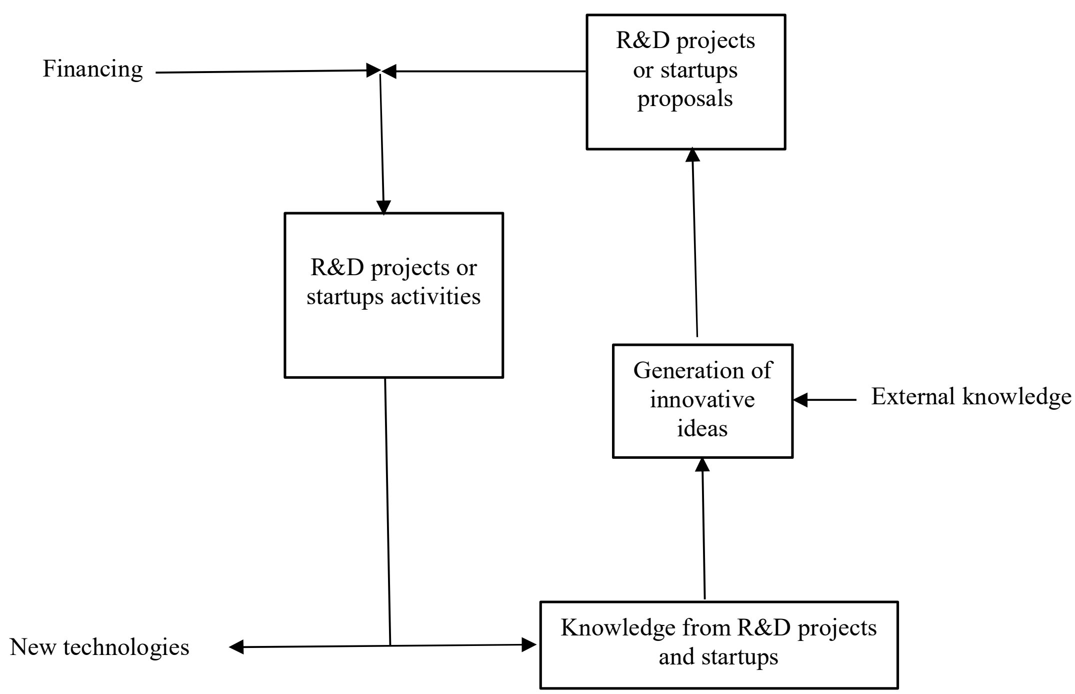

Fig.9. Technology use as complex adaptive system

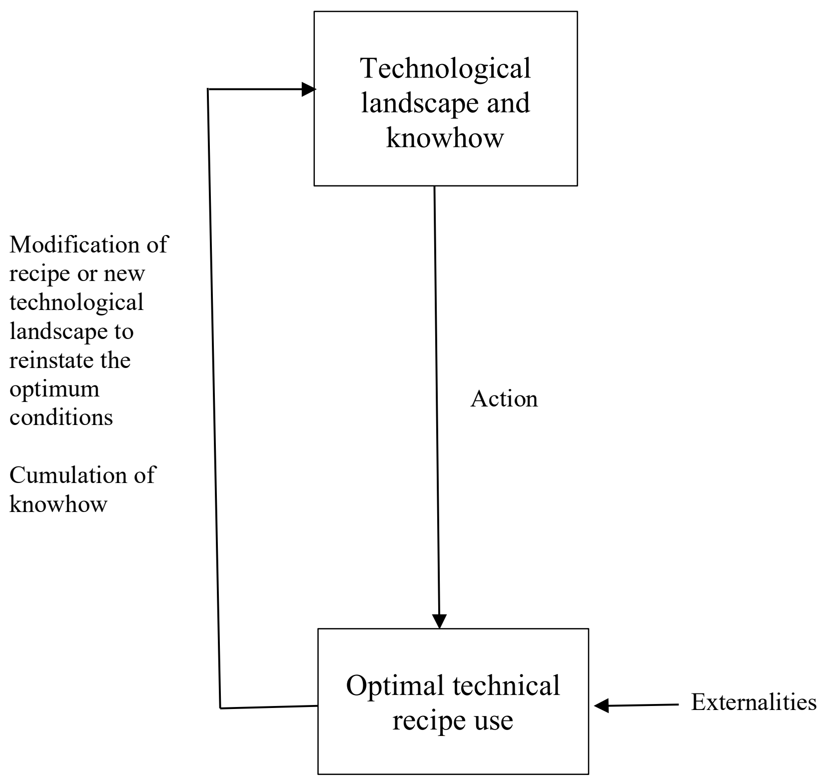

Fig. 10. Science of complexity and the technological innovation process