COMPLEX THEORY AND METHODS IN INTERNATIONAL RELATIONS

TEORIA COMPLEXA E MÉTODOS EM RELAÇÕES INTERNACIONAIS

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Abstract: This article presents the emergence of complexity theory in sciences and in the field of International Relations (IR). The first part shows that the emergence of what is called the IR fifth debate finds its roots in an already old questioning and, hence, makes possible to clarify the notion of complexity. The second part shows how the transdisciplinary methodologies of complex systems are implemented in different issues related to International Relations. Finally, the interest of the approach and the perspectives opened up by the theory and the method of complex systems are discussed.

Key-words: Complexity. Governance. Network. Synergetic Models. Non-linearity.

Resumo: Esse artigo apresenta o surgimento da teoria da complexidade nas Ciências e no campo das Relações Internacionais (RI). A primeira parte consiste em mostrar que o surgimento do quinto debate das RI está enraizado em um questionamento antigo, portanto permite esclarecer a noção de complexidade. A segunda parte mostra como as metodologias transdisciplinares de sistemas complexos são implementadas em diferentes questões relacionadas às relações internacionais. No final, são discutidos os argumentos em favor das perspectivas abertas pela teoria e pelo método de sistemas complexos.

Palavras-Chave: Complexidade. Governança. Rede. Modelos sinergéticos. Não-linearidade.

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Introduction: Race toward complexity

The theory of complexity, and the nonlinear dynamic models it develops, is gaining a growing success in many sciences. Its advent marks a new period in scientific research (Weaver, 1948). Its success can be explained by various properties, which echo the needs of scientists, in particular academics in International Relations (IR). First, it allows the researcher to capture an infinity of behaviours of a system by the mean of parsimonious models in the sense that they do not necessarily need numerous variables. Second, the system in itself is not reified; it presents self-organisation properties. That is to say that its structure is plastic, the boundary of the system can move, and accompanies the emergence of its behaviour. Thirdly, this self-organisation is the result of simple rules, which link and aggregate the sub-elements together to form collective entities of a higher order, on a more macroscopic scale. Fourth, these moving sets of sub-elements are open to information flows, force fields, which are also systems of constraints, causing the system to produce a transformation of both the environment and itself. These four characteristics are found in IR when researchers ask themselves: Who are the agents and the rules that structure their relationships? What are the external forces that constrain their decisions and, finally, what are the possible governance scenarios that are only the behaviour observable at the macroscopic scale of the international system?

This article presents (i) the context in which the Theory of Complexity appears in International Relation. The term being polysemous, (ii) how does a concept appear in the sciences and form an ontological and methodological whole, and (iii) it aims to present two methods by which complex thinking can be implemented. Finally, the differences between the two methods are discussed in the light of IR.

1. **A long theoretical course**

Walt's famous paper titled "One World many Theories" (1998) stressed the diverse reasons why a theory in IR is necessary. By asking "How to respond to China", using different theories, he evoked several scenarios, a possible change in the balance of power or integration into the world markets. He then commented that "[n]o single approach can capture all the complexity of contemporary world politics" (Walt, 1998, p.30)

This example of reflection on what IR theories are, or should be, shows the necessary articulation between ontological, epistemological, and methodological reflections. Why IR? How to capture complexity with models that only manipulate a few variables to remain intelligible? What should we highlight: Ideas or method? (Mearsheimer & Walt, 2013). This permanent tension is at the origin of the four debates classically identified by IR scholars since the interwar period and the advent of IR as an academic discipline (Wiener, 2006; Kavalski, 2007; Battistella et al., 2019, Ch. 3).

In fact, during the 20th century, between the wars, in Great Britain, and more exactly at the University College of Wales, in Aberystwyth, the patron David Davies created the first chair of "International Politics" (Carnegie in the US, created in 1910 the first foundation for international peace outside the university system). A debate appeared between idealist and realist. After the Second World War, a second debate arose between a scientific behaviourist, a positivist and a traditional view of the human sciences. It is about approaching IR with a method comparable to life sciences. The third debate looks at the actors and forces that configure the international system, hence emerging approaches such as realism, liberalism, pluralist and Marxist.

The border that draws the limits between the third and the fourth debates are not the same for all. (Battistella et al., 2019, Ch. 3, note 63). This third debate did not seek to explain "the same world", as they focus on "different dimensions of international relations. After the appearance of neo-realists and neoliberals, exacerbated by the Cold War extreme tension, shortly before the fall of the Eastern bloc, a fourth debate arose in IR. It has opposed the proponents of these two approaches qualified as neo-positivist with the proponents of a constructivist, a reflexivist approach. It lead to the opposition of two ideas: the explanation of the first against the interpretation of the second. The fourth debate, which sees the development of constructivist approaches, perpetuated as a period of promising meta-theory (Wiener, 2006).

These debates have shown that the discipline had to adapt both theoretically and methodologically to build an epistemic axiology that could capture the changes in society, which particularly accelerated after the Second World War. What characterises these debates is the perpetual search for the *agents* and forces that structure the IR landscape. These forces are understood through theoretical tension: Firstly, the ontological desire to describe the world as it is or how it should be. Secondly, the epistemological desire to faithfully capture the world around the people, or to remain free to interpret it. The agent-structure problem has shaped the whole from the 1980s until now (Waltz, 1979; Walt, 1998; Wendt, 1999; Donnelly, 2009, 2019). The main criticisms are often reification and reductionism. Indeed, the IR could not or could describe and / or foresee the political transformations caused in cascade by the collapse of the Soviet Union, which marks the end of the bipolarity. The RI field failed to predict the acceleration of the globalisation of trade and the economy through the emergence of new players and technologies (Sullivan, 2001, p. 4).

It would be inappropriate to say that the first four debates did not embrace the complexity of international relations (Peter Haas, apud Orsini et al., 2020). The more or less peaceful co-existence of the three theories of Realism, Liberalism, and Constructivism illustrates the incessant search for the forces that constrain the life of the international community, like the role of states, the economy, institutions, societies, and the standards and values carried by these actors. To this, one can also add the Critical Theories, addressing the contradictions of the current era based on a synthesis of history and sociology.

This approach emphasises that what "is" at a specific point in history is not immutable. Norms and values, perspectives change over time, and constrain systems can no longer be essentialised. In this sense, the most often articles cited in IR are critiques that concern a kind of reductionism drifting towards a loss of complexity. For instance, Donnelly (2009) said about Waltz`s conceptions of structure "[...] this framework excludes (e.g., ideas, identities, norms, institutions, dynamic density, interaction capacity, process variables) [...]". More recently, after having defined very classically from the Oxford English Dictionary, he added that "Waltzian […] structural realism as the exemplar of a systemic theory impeded the development of truly systemic approaches" (Donnelly, 2019, p. 905). Likewise, concerning the critical approach, Schechter (2002) reviewed all the criticisms addressed to Cox. The approach developed by Cox would contain some omissions, residues of stato-centrism, and would not implement the three forces production, ideas and institutions (Jessop & Sum, 2001, p. 94-95).

Reducing the constitutive dimensions of the theories, the social groups and the values attached to them also leads to a loss of complexity. After these remarks on ontological constructions, what shapes the current epistemic debates? Some IR researchers have chosen to avoid theoretical quarrels and focus on the issues that matter. Mearsheimer and Waltz (2013) strongly condemn the "abandonment" of theories in favour of quantitative methods justified by empirical hypothesis testing. According to them (2013), hypothesis testing is just a too simple way to understand causal relationships. It is in the existence of numerous theories, called "*isms*", that the expected complexity should appear in international policy analyses. Therefore, they opposed, even if they deny it, ontological and epistemological debate. Once again, the complexity is lost in the "translation". The claimed diversity of theoretical approaches has its corollary: the nascent ambiguity of the use of words common to the different approaches making them polysemous.

The term “complexity” is polysemous and may constitute an epistemological obstacle in theory (Bachelard, 1967, Ch. IV). Complexity is a word often used to say that things described by a study are complicated meaning that many variables are involved without highlighting how they are articulated, how they enter in relation. In epistemological and ontological analysis of what is science, many scientists have stressed the need to build theories with moving boundaries between methods and/or classic academic disciplines (Piaget, 2019; McClelland, 1960).

Almost 40 year earlier, McClelland (1960) was already questioning the seeds of IR theories. At that time, he was the president of Society for General Systems Research. This scientific association, made up of researchers from different academic disciplines, already stressed the need of a general framework based on a general system theory. These researchers advocated for a kind of unity of science. Currently, this association is the *“*International Society for the Science Systems” (ISSS).

There are “Special Integration Groups” (SIGs) specific to the social and political sciences as well as to groups specific to information science or life sciences, such as systems biology. These different sub-groups can interact on specific issues, such as the management of epidemic risks such as SARS – COVID-19. Indeed, the management of a pandemic requires understanding the preparedness capacities, which translate into organisational forms of political affairs, but also information systems to implement epidemiological monitoring and, finally, to produce a response by repositioning small molecules thanks to systems biology approaches with "*omics*". An epistemological and methodological axiology capable of capturing this complexity must accompany these shifting limits.

2. The different types of complexity

In classic dictionary definition, since the 16th century, the term “complexity” refers to a “composed of elements that maintain many relationships, diverse, difficult to grasp by the mind and often presenting different aspects”, according to the French dictionary Trésor de la Langue Française Informatisé (2021). The term is borrowed from Latin *complexus*, past participle of classical Latin *complecti,* "to embrace, to understand". Hence, the notion of "made of different, interlocking elements".

The genesis of the term has gradually slipped to a wrong meaning of “complicated”. The 1950s were a turning point in the sciences, as information-processing machines appeared. Weaver (1948), one of the pioneers of computer science, proposed an analysis of the complexity to situate these new sciences with regard to the problem of facts organisation, data with dispositions, modes of treatment of these last ones to arrive to describe the real, to reach at an intelligible result. He proposed three types of complexity. He pinpointed to the problem of simplicity and the difficulty faced early in the twentieth century by biology researchers studying organisms in living conditions in which "dozens" of factors co-vary together.

In fact, the first model of complexity is not a complex approach, but the opposite and takes another terminology "the paradigm of simplicity" (Morin, 1977), during a critique of the Cartesian approach. "In this paradigm, complex problems are tackled by their reduction into more simple issues, explained or solved independently and successively" (Alhadeff-Jones, 2008, p. 68). The second paradigm of "disorganized complexity", proposed by Weaver, poses the prior identification of disorder as a fundamental component of natural phenomena. Weaver presents the example of a billiard table on which the researcher should predict the trajectory according to the initial conditions. The difficulty becomes very important since the task would be to calculate the trajectory of an infinite number of balls colliding. However, theoretically, the model would be the same. On can see that, in this example, the complexity would be linked to the word "complicated".

In physics, models consist in determining variables that could summarise disorganised complexity. This type of complexity is characterised by a mechanistic approach to statistics. The relationships between variables are limited to their simplest expressions. Therefore, models establish the so-called linear causal relationships. The transformation patterns remain invariable. If the described transformations do not fit the reality, the observed social fact, the model is rejected or complicated.

The corollary of this approach is to multiply the models. These are the "*isms*" in IR, called "boxology" in experimental psychology and/or in neurosciences. The awakening of the "Newtonian Slumber" expression of Ruggie, taken up by Kavalski (2012), was observable with a considerable acceleration in the early 1980s, after a slow epistemic maturation. As in IR, or in the example of Weaver's billiards, the problem encountered in neuroscience is to describe the infinity of relationships that exist between sub-elements, neurons, cortical areas, muscles, etc., constituting a biological system.

The paradigm of simplicity consisted in summarising the neurological system as a "black" box in which stimuli were transformed into information. The number of stages of transformation of the stimuli to arrive at the information sent to the muscles increased from the Stimulus-Response leading to the concept of Motor Programme. Critics of these motor programming models have called boxology the excessive increase in the number of information processing steps, based on the use of representations, while the models still did not satisfactorily explain the skilful adaptability to a situation never encountered before. What is a representation, since representation is experience-based?

This is the same questioning as Cox and Schechter (2002, p. xxii), who made the distinction between data and facts that are “made” not “given”. The problem with ideas (representations) is that they constitute a system for analysing a reality that has never been encountered before. Reality imposes a plastic conception of “what is information?” and the reading of time on the scale of the motor actions to be produced. Space and time are therefore intimately linked. This example illustrates theoretical questioning in Cox and Schechter’s work (2002). For these authors, time is a most complex idea and, instead of common sense of time, they referred to the Bergsonian concept of "*durée*" (2002, p 171). So, they stated that "[...] ultimately, time and space are not separate and opposed categories" (2002, p. 28).

The example that illustrates better the problem encountered by researchers when they manipulate ideas and norms that are otherwise fragmented (Homer-Dixon et al., 2013) is the social sciences work that Schelling (1971, 1978, Ch. 4.) did on segregation. The seminal Schelling's work showed that dynamical models are organised in a loop allowing the use of feedback from the environment like other agents acting with the same interests and goals.

An excellent pedagogical simplified example is proposed in the simulation library of NetLogo, which is an open access software (Wilenski, 1997). It is an agent-based model (ABM). As a dynamical system, the ABM receives feedback: the successive decisions of the agents (contingent behaviour) who settle or not in a neighbourhood. Schelling called the resulting segregation “macrobehaviour”. It appeared without verifying that any explicit rule was behind it. The ABM has all the properties of a dynamic system, it is unpredictable, it shows bifurcations (sudden changes in spatial distributions) and self-organisation, that is, the final state of the system is not prescribed at the start.

Hence, the set of “purposive” criteria (micromotives) at the base of the choices enter into interactions with those of the other agents and modify the behaviour by feedback loops. This is what Schelling calls “contingent” behaviour (1978, p. 17). Even with simple purposive rules, the contingency of individual actions resulting from the multitude of interactions, made the system unstable, unpredictable, dynamic. The whole is not equal to the sum of the parts.

This king of model has two implications. Firstly, it could challenge the models that start from ideological postulates to explain segregation (whatever it is; colour, social class, gender, etc.), for instance the implementation Schelling-type model over time tends to show segregation, although each agent prefers to live in a mixed-race neighbourhood, complete segregation is almost all the time (Zhang, 2011). Secondly, the feedback loop mechanisms make "*Newtonian*" time disappear. This is a perception and action cycle and the time is framed by the dynamic of the system, i.e. the action. Here, space and time are intimately linked as Cox and Schechter advocated, but in a real different way. This example makes the transition to the third type of complexity.

The third approach is the "Organised complexity". Weaver (1948) introduced the notion of complexity by taking an example of viruses. Do they know how to reproduce? Are the probabilistic models of disorganised complexity adequate to describe such a phenomenon? With this example, Weaver indicated the difficulty of taking into account a large number of variables without isolating them, going beyond the probabilistic stage. He introduced, without naming it, the emergence property of solutions in complex nonlinear systems that will be described later in this article. Before going further in our approach to complexity, let us quote again the work of Weaver, a visionary of the evolution of science in the second half of the twentieth century.

> These problems -- and a wide range of similar problems in the biological, medical, psychological, economic, and political sciences -- are just too complicated to yield to the old nineteenth century techniques which were so dramatically successful on two-, three-, or four-variable problems of simplicity... These new problems and the future of the world depends on many of them, requires science to make a third great advance, an advance that must be even greater than the nineteenth century conquest of problems of simplicity or the twentieth century victory over problems of disorganized complexity. Science must, over the next 50 years, learn to deal with these problems of organized complexity (Weaver, 1948, Ch. 3).

Since then, many researchers have endeavoured to develop the scientific approach by inscribing it in the complexity that results in the dynamic systems concept. In turn, the word system is polysemic and requires a definition (for a didactic review of the inclusion of complexity in science, De Rosnay, 1975).

2.1. Non-linear dynamic complex systems

The emergence of complexity appeared in the history of many sciences in the sense of academic discipline. It attempts to surpass the "simplicity paradigm" by proposing interdisciplinary or transdisciplinary approaches, always emphasising the notion of project instead of object (Piaget, 2019; Morin, 1977; Weaver, 1948; McClelland, 1960) and promote epistemic models, like cybernetics and mathematics, to cope with complexity in other theoretical fields. Key terms need to be conceptualised to describe the governance of political systems and organised complexity,

Governance and cybernetics share the same Greek root (*kubernetes*), pilot, or rudder. Plato used it to describe the "art of piloting" or the art of governing people (De Rosnay, 1975). The engineering sciences reappropriated the term and it became the term used to describe the way systems were piloted.

This aspect is important for understanding the philosophy of cybernetics and by extension that of governance. The aim of science is to "describe" the world by integrating information into a framework of thought, whereas cybernetics consists of "acting" on the world (Couffignal, 1961, p. 160). His definition of cybernetics is "the art of ensuring the effectiveness of action".

The dynamic models emerged in the context of engineering, which was facing the control of increasingly complex systems. They were used to understand and manage undesirable events that occurred without being predicted by linear models of system control. Hence, cybernetics gradually became a method (Couffignal, 1961), which others would describe as a systemic approach. However, cybernetics introduced a central notion from the will to control, beyond the goal it conceptualises (which can be the "*raison d'être*" of a system, which is true for a machine and a political instinct), it inscribes time and feedback as fundamental principles. The systems described in this approach are open systems whose structure can change through feedback loops. "An open system is in permanent relation with its environment, or, in general terms, with its ecosystem" (De Rosnay, 1975, p. 92).

From the 1950s to the 1970s many back and forth trips between social sciences, biology and engineering took place in the context of the systemic approach, giving rise to *isomorphisms*. Biology, in particular, offers many examples of internal regulation (dynamic equilibrium) and self-organisation (adaptation to change). Gradually, the systemic approach was distinguished from cybernetics by going beyond it. It is not limited to one mathematical description and goes beyond systematic analysis. The systematic approach emphasises the description of the sub-elements that make up the system, as well as the most elementary relationships. The complexity and non-linearity of the modes of operation is lost (De Rosnay, 1975).

At the same time, in social science, Schelling (1978) made the same observation. Even with simple purposive rules, the contingency of individual actions resulting from the multitude of interactions, make the system unstable, unpredictable, and dynamic. The whole is not equal to the sum of the parts. Schelling emphasised that what is observable and must be understood is the aggregate formed by the multitude of individual behaviours. The risk is to consider the aggregate (i.e. the segregative spatial distribution) as the result of a prescribed goal. In this case, it would be a systematic linear cause and effect result. To the notion of systematic, he opposed the notion of systemic, which has for essential property the emergence of self-organised macroscopic behaviours. Regarding work on segregation, Schelling refers to self-organising processes as self-forming neighbourhood (Schelling, 1978).

Schelling cautions the reader by stating that "sometimes [...] we metaphorically ascribe motives to behaviour because something behaves as if it were oriented toward a goal" (1978, p.17). Donnelly (2019) was critical of Waltz's conception of systems in this sense. To this, the conception of linear cause and effect evoked in the work of Mearsheimer and Walt (2013) should be added, which leaves no margin for complexity by the nature, neither of the (descriptive) variables collected nor for the feedback loop. The study of democratisation during the 20th century seems appropriate to explain the effect of a lack of feedback on complex systems.

Events, such as the collapse of the Union of Soviet Socialist Republics (USSR) and the democratisation of the eastern countries, that completed the wave that began in the 1970s with the revolution of eyelets, validated Huntington's model (1993) of three successive waves of democratisation. The certainty of a mechanism of democratisation led scholars to call "transitology" this theoretical approach (Diamond, 1999; Diamond et al. 1989; Fukuyama, 2006). History has shown that democracy has not consolidated, and the model does not fit to areas such as the Middle East (Carothers, 2002). The weakness of this model is to consider the evolution of a national and/or international system (because the propagation of democracy can occur by factors exogenous to the state) would be linear. This approach is epistemologically biased because democratisation is the only "state" in the sense of the system's behaviour, as Fukuyama thought (Carothers, 2002).

3. Complex models in IR

3.1. A model of complexity: Haken's model

Haken (2005) is one of the pioneers of the dynamic approach in social-economic studies. His models are used in a new approach, for instance in ecological economics (Ramos-Martin, 2003) and urban development studies (Haken & Portugali, 1995). In most of these studies, Haken and his collaborators have proposed a stable two-attractor model (Haken, 1976), explained later on figure 1.

The following analysis is proposed to understand Haken's model: study democratisation by drawing parallels with the complex non-linear (dynamical) models proposed to cope with the human motor coordination problems. When a human being tries to control a muskulo-skeletic to grasp an object, for example, the upper limbs can take an infinite angular combination and can be driven by a very different set of muscles and group of motor units.

This problem of abundance and redundancy (in this sense, a comparison can be made between the notion of agent existing in social sciences and all the elements of the musculo-skeletal system, that can act in isolation, enter into interactions, and, sometimes, have identical operating rules) of means is what Bernstein (1967) called the control of degrees of freedom (DoF). It should be noted that Bernstein was a Russian physiologist of Jewish faith, who began his work in the 1930s but the geopolitical context did not allow him to divulge it. Many of his works were translated and published, in English, in 1967, causing an epistemological break with the PM models previously described and criticised under the term boxology.

The control of motor skills is such that despite abundance of degrees of freedom, one may find ordered spatio-temporal patterns. Control would be made possible because there would be a set of rules that tie the sub-elements to each other. This is a coupling called a “coordinative structure”*,* which has dynamic properties, for instance, in order to drive a car the most complex solution would be to control all four wheels independently. There is first a freeze of the degrees of freedom achieved by coupling the rear wheels to the frame.

Then, there is a specific coupling created between the two front wheels: the movement of one is the same as that of the other. There is, therefore, only one collective parameter, that of the relative position of the front wheels, and a single control parameter, that of the single steering wheel. Control is easier, but eliminates certain possibilities, such as parking the vehicle by crabbing. However, this system has no dynamic properties (non-linearity, self-organisation). In the case of a dynamic system, the collective variable can take several values (stable or not), this variable is called an order parameter. It describes the state of the system, the order referring to stability or chaos.

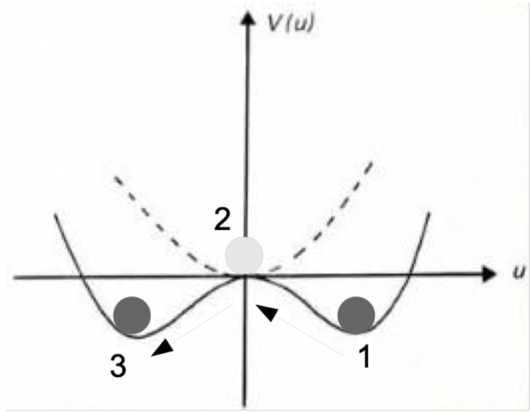
The links between the sub-elements can be described through collective variables also called coordinative variables. In the case of the social sciences, a parallel can be drawn between a coordinative structure and the micromotives already mentioned. These two concepts tell the relationship “to each other”. As in any dynamic theory, the whole system is in interaction with its environment and the set of intrinsic (coordinative structures) and extrinsic properties causes the emergence of a coordination mode, i.e. a specific, ordered, or chaotic behaviour. The existence of coordination though as ordered motor patterns constitutes, what will be called later, “attractors”. This means that there are different stable states that the system can take which are identified by the collective variable, which takes on a specific value.

In this sense, it is an “order” parameter indicating how the system behaves. Figure 1 shows a landscape of which represents the possible states of the system represented by a ball (Haken, 1976). The interaction between the variables changes the state of the system by creating an attractor to which the ball will go. There is a bifurcation caused by the appearance of an attractor, the system changes state: this is a state of self-organisation that the system takes.

In motor control studies, one can evoke the case of locomotion. The neuro-musculoskeletal system is thought of as a dynamic system described by a limited number of variables. Energy expenditure depends on the speed of locomotion. The increase in speed can cause bifurcations towards other mode of coordination (states of the system) in order to decrease energy cost while maintaining the speed of locomotion. One can predict the bifurcations between walking, trotting, and galloping. The structure of locomotion changed and the agency of muscles too, even if they are the same in the three locomotion modes.

Figure 1may be explained as such: The potential function summarises up all the forces that can be exerted on the system, which is represented here by a ball. Depending on the initial conditions and the parameters, an emerging behaviour appears, for example position 1, which corresponds to a regime, i.e. a behaviour which results in a specific coordination between sub-elements. If the control parameter changes, i.e. the information, the landscape representing the potential function changes too. When the attractor constraining the behaviour disappears, the ball is free to move towards another attractor, for example position 3. This new stable regime is the result of a bifurcation (adaptation from Haken, 1976 fig. 2). The shape of the potential function depends on the intrinsic dynamic of each sub-element and the synergy, the coupling, between them.

Figure 1: Stable Two-Attractor Model



Source: Haken (1976).

In IR, international organisations linking different agents could be considered as "coordinative variables" and the "control parameter" could be the international laws. In a dynamic system, the word control does not indicate the "force" with which the system will be controlled. The system structure imposes its own dynamic sensitivity to non-specific changes in the value of the control parameter.

Control parameter is a set of information that feed the whole system and helps it to behave in the desired direction. Sometimes, misconception of the intrinsic system dynamic (interaction between sub-elements) or the chosen parameter of control are inadequate and the subsequent control inefficient. The system is attracted to an inadequate coordination mode, i.e. inadequate results of the policy implemented and embedded into the control parameter.

The analogy with neurosciences is useful because it allows the understanding of complexity in IR. The nervous system sets up coordinative structures phylogenetically and ontogenetically through learning. Here, the parallel is already made with societies making the laws. Pushing further the analogy, phylogenetic and ontogenetic system characteristics could respectively be found in soft or hard law, or customary laws which pre-exists to written laws.

In addition to it, beyond the coordinative structures governing part of the behaviour, the skeletal system also undergoes gravitational forces. It means that active and passive forces drive the system. Passive forces are part of the actor/environment system. It means that the control is not only due to what the system does voluntarily. At least, that means that it must take into account a set of variables and its behaviour will depend on the initial situation. The voluntary acts of the system will be different for each situation for the same results.

The challenge for IR researchers will be to identify what they should consider external and internal system dynamics. That is, what is voluntarily put in place by the system so that it can respond to constraints (coordinative structures), and what is ultimately constitutive, intrinsic, that modifies the behaviour without the system having control. The dichotomy is simple in our analogy with a musculo-skeletal system, it is less so in IR.

Complexity is to consider a set of sub-elements that must be controlled by a set of rules (i.e. system of constraint or interrelations) that must, in the case of a theory, be relatively simple. To do this, the number of control parameters must be restricted. If international law is an example of this control parameter, IR scholars still face a major difficulty in defining sub-elements and defining their intrinsic properties. In the international law example, if the states are the actors who sign and ratify the instruments, it is necessary to define the intrinsic dynamics of the latter, who have an inner life with information circulating internationally via the states themselves, or NGOs, but also transnationally in economics, for instance, with actors, such as companies, or between smaller players.

Once the obstacles of the complex system conceptualisation and the relations between their sub-elements are overcome, "self-organisation" principles of dynamic systems can be studied. In the analogy of the musculo-skeletal system, movement is due both to the action of active (muscles) and passive/dissipative (gravity) forces. Self-organisation is the expression of the interaction between the two types of forces. The system behaves naturally, despite the absence of active forces: it is self-organised (dissipative).

A musculo-skeletal system is an articulated set of pendulum. A grandmother's clock, for example, is a pendulum that oscillates according to gravity (a force that moves the pendulum, but also dissipates because it creates friction); the wound-up mechanism is designed to inject a force at a particular moment of the oscillation to perpetuate the oscillation. This is the characteristic of intelligent systems to perceive the moment and the nature of the energy to be injected into the system in order to make it work. In IR, laws are the active set of forces injected into the system in order to obtain the desired behaviour.

To go further, Haken-type analysis is possible to understand the effect of two recent crises of a different nature that have recently shaken the world: the subprime crisis in 2008 and the SARS-COV2 pandemic. Despite the intricate interplay of economic and political sub-systems, international and domestic policy analysts can find ways to describe and model the functioning of the system as a whole.

Jancovici (2015) stated that the production shortfall of conventional oil since the 2000s has not allowed the economic productivity targets high enough to prevent the speculation-based economy from collapsing in 2008. The “Arab Spring” would be, in part, the conjunction of climate change and the collapse of oil production on which the economies of Arab countries depend heavily. The US response to this crisis was to speed up the production of shale oil. The occurrence of the pandemic has called this economic policy into question. The fall in oil demand caused a collapse in prices for all conventional and unconventional oil production. Shale oil production had also peaked, and supply difficulties to the global community had already made this market fragile. It is technically possible to stop conventional production but not that of shale gas, which must be sold anyway. Hence, the prices went negative.

Modelling the two markets coupling function would reveal the properties of a complex system, attractors and bifurcations. The dynamical approach would consist in considering the coupling between two sub-systems, i.e. the conventional and non-conventional oil systems. Each sub-system has its own dynamic properties and is at the same time coupled to the other and constrained by a control parameter. Jancovici's analysis of the Arab Spring is possible with a Haken-type of model what is not with the linear models of democratisation. The paradox is there, already evoked by Chalmers, in his book “What is this thing called science” (2013), about the repetition of events and cause and effect relationships in an “inductivist” approach. The question of inductivism relates to the necessity or not of the pre-existence of a theory for analysing data sequence. There was indeed a pre-existing model for democracy studies analysis.

Democracy should not be seen only as a goal, but as one of the possible states of a dynamic system that feeds on feedbacks, i.e. the slow evolution of society, sudden events, such as COVID-19, and its relationship to the environment. When the states of a system are stable, they are called “attractors”. The system can fluctuate around a point of equilibrium (attractor named “limit cycle”), this fluctuation is not a bifurcation, it is the characteristics of the limit cycle. Authoritarian regimes, revolution, democracy regime, can be possible states of a system as Haken conceptualised them from a model with two (or more) attractors. The parallel that one could make with political scientists would be a new time that of the study of the quality of democracy (Nowak et al., 2006).

Nevertheless, the models that are more successful as a source of complexity theorisation are most often inspired by information theory (Shannon & Weaver, 1949), cybernetics, and network theory (Barabási, 2016; Watts & Strogatz, 1998; Newman, 2000).

3.2.Network Theory : A “Classic view" of complexity in IR

These models are more frequently used in the social sciences because the sub-elements that make up the complex system can be confused with the individuals that make up a society. In this case, the term for studies using these models is Social Network Analysis (SNA). Networks in social science are described with graph theory. There is no true mathematical difference between graph theory and network theory. These are two nested theories: the first allows a study of the networking of components of a real system (social system for instance) and the second is often used to test the robustness or to determine what type of networking is similar to the previously studied network. This is of primary importance, depending on the problems and hypothesis. It allows seeing how actors connect to each other regardless of the amount of connections. In this case, the analysis will be qualitative (beyond the centralities analyses). It allows describing the specificity of governance (Glattfelder & Battiston, 2009).

For convenience, this author only uses “network analysis terminology”. In these theories, a network is described by two variables: nodes and links. The nodes (or social agents) are the constituent elements of the network. The links constitute the interrelations that exist between them. The use of these models makes possible the understanding of the governance of complex systems. Indeed, the number of international actors (reference), whatever their types, is very large. The Concepts of the links can also be very different in nature. Depending on the chosen links, the relationships between actors are modified and they draw networks of influence, of governance, which can influence international policies. Theory of networks makes possible to describe bifurcations, i.e. the emergence of a mode of control, of governance specific to the plastic organisation of the network, changing by feedback mechanisms (Morin et al., 2017).

Using both qualitative and quantitative approaches, this mixed approach launches a continuous intellectual process that exists between theory and working hypothesis (Rudestam & Newton, 2014). A naive inductive approach would be to believe that a quantitative approach (as allowed by the network theory) exempts the researcher to have theoretical support, from epistemological presuppositions for selecting the variables and their subsequent analysis (Barabási, 2016). For a broader description of pre-experimental models (in the research wheel), Chalmer offers a didactic historical approach to naive inductivism and falsificationism in theory elaboration.

The network analysis addresses the associations among nodes, rather than the attributes of particular nodes (Hafner-Burton et al., 2009). Therefore, in IR, these links between nodes (states or institutions) could be transmission channels of both material (for example, weapons and money) and nonmaterial products (for example, information, beliefs and norms). The robustness of the network analyses should not hide the finesse of analysis necessary to choose the nature of the links between the agents.

Recent studies, for instance, illustrate this intellectual exercise (Boulet et al., 2016; Lajaunie & Mazzega, 2016). Each type of study starts with the appropriation of more or less clearly identifiable textual elements, in this sense the method is qualitative too. These elements may constitute the nature of the information that the system appropriates and consequently transforms it into a link. This information then circulates in it and modifies the system behaviour durably (governance, i.e extrinsic dynamic) by constantly creating new links between agents (and may be modifies the agents, i.e. intrinsic dynamic). The "power" of mathematics does not exonerate from an axiological (epistemological) reflection. This epistemological aspect leads to further reflection on the method.

Rudestam and Newton (2014) demonstrate that the boundary between qualitative and quantitative variables is tenuous. They used the term fuzzy (p.39) to explain that some disciplines have adopted methods for their own needs. This approach is both quantitative and qualitative. One may collect a large amount of data (nodes and links). In this sense, the network theory is easier to use in order to catch a large number of sub-elements than the physical approach used by Haken. The links are qualitative because their identification is based on a textual analysis (Hafner-Burton et al., 2009). Network analysis constitutes a mixed method (p. 57), that fits with the expression "embedded design". There is one predominant method, and the other method is nested within it to enable the researcher to obtain a richer perspective on the phenomenon being studied (Bazelay, 2009, cited in Rudestam & Newton, 2014).

In governance studies, IR scholars often use indices of centralities. These variables enable the scholars to identify main actors in the network, hence, the way in which the whole system behaves, how actors constitute epistemic communities and who create the links between these epistemic communities which may change qualitatively the negotiations (bifurcation) towards a particular regime of governance (Boulet et al, 2016).

Centrality indexes explain some aspects of the governance, but do not explain how policies could modify it. Networks have non-linear properties too and can exhibit bifurcation, i.e. the way the information flows into the system can change quickly and dramatically. To illustrate governance and network dynamical properties, the analysis of the financial world, made by Glattfelder et al. (2009), is a good example. The authors have shown the relationships between the executive boards of the enterprise. In other word, it allows to understand the holdings of big companies in smaller companies. The reports in works councils depend on shareholdings. Each company, that is each owner, whether it is a state, or an individual, organises a participation policy that allows him a certain control of the entire network. From complicated, the network becomes complex when the method used makes it possible to see the organisational forms embedded in the mass of information global and local strategies are clearly identified and fit into the tests of real networks proposed by the theory of networks.

Glattfelder et al. (2009) have shown that very few shareholders are able to control 80% of the market value. In addition to it, they have shown how the networks are organised, i.e locally dispersed, or concentrated and in these differences of concentration, who are the owners (states, foreign companies into a specific state, and so on). Understanding such control mechanisms is important for building a sustainable society (Glattfelder & Battiston, 2019). Understanding properties of global networks, their evolution over time, allows us to understand how power and inequalities can increase.

The problems of sustainable societies could be described by other network properties. The regulation of marine bioprospecting is an example of the principles for implementing sustainable development and the blue economy. The evolution of science is not taken into account by various instruments of the 1982 United Nations Convention on the Law of the Sea (UNCLOS). Since the Convention on Biological Diversity (CBD), new negotiations have been organised to determine the methods of controlling biodiversity beyond national jurisdiction (BBNJ). Stake-holders in these negotiations must be able to understand who owns biodiversity so that BBNJ instruments are as effective as possible, despite a context of fragmentation of ocean governance (Sachs et al., 2019). It has been shown that more than 800 marine organisms were already fully licensed, and this in pieces of genomes to circumvent the the Nagoya protocol (Blasiak et al., 2018).

In addition to it, some companies have a very large percentage of these patents. BASF alone holds 40% of the patents. With a bit of cynicism, one could imagine a complex relationship of companies such that the shares owned by certain large groups are indirectly higher or at least that the takeover of certain patents could be facilitated by the structure of the network as Glattfelder and Battiston have shown (2019).

IR needs to understand governance, to identify key-players, and to propose ways to implement control policy of such complex systems. With the Barabási's team, Jia et al. (2013) have showed that networks could have the same bifurcation properties as physical models. They developed an analytical framework to identify the category of each node, leading to the discovery of two distinct control modes in complex systems: centralised versus distributed control. It allows predictions of the control mode for an arbitrary network and show that one can alter it through small structural perturbations. The theoretical work begins with a modelling of the interactions between nodes on a random model. It then continues with a test of real observational networks in situations that are not random, such as social networks, communications, citations (epistemic community), the World Wide Web, etc. Barabási's team offered other works identifying the nodes that, if some specific connections were added, could change the nature of the control of the system. In IR this aspect is central.

Technological change takes place along ordered and selective patterns, shaped jointly by technological and scientific principles, and economic and other societal factors (Verspagen, 2007). An invention is often built based on a patent already in force. Hence, one may identify ramifications linking by the mean of patents a set of inventions from the more ancients to the more recent ones. For a company, or a State holding a stake in a company, the decision-making process for the creation or development of a new technology is always partly based on already existing technologies, which have both an economic cost and can modify social representations underlying consumer decisions. Some patents are often used (networks of main path) because they offer a good cost-benefice trade-off depending of numerous factors, number of patents or production methods, and consumer choices.

At the start of the creation process, the number of patents is small. These patents constitute networks, which are linear in the literal sense of the term. The increasing number of patents transforms progressively the network and makes it denser. The growth of the network gives it the characteristics of a complex system. The set of patents to be held, or the licences to be owned, may change abruptly, and be described like the bifurcations observed in dynamic systems. No one controls the development of this network. It is a self-organised system. New actors entering the formed system can, however, take control of it, or have it voluntarily branch off towards another form of organisation if they know the underlying architecture of the network. Procurement or licensing strategies for use of patents are governed by the same principles as those previously described in Jia et al. (2013).

In the last examples discussed above, complex models do not in themselves constitute a theory of complexity in IR, but they are sustained by decision-making processed based on factuality on a world which is analysed in its complexity. Behaviours adopted by politicians, decision-makers in companies, can have brutal and unexpected consequences. Failing to predict the future as the IR field often wishes, this approach sheds light on the field of possibilities affordable to decision-makers.

Final considerations

This article describes the long journey towards complexity that science has made during the second part of the 20th century. The parallel between neuroscience and IR has been made in this sense. Epistemic ruptures are present at the same period. Authors in different scientific field disciplines have shown how the approach to complexity, sometimes without naming it as such, is multidisciplinary and holistic.

Complexity is often associated with numbers of sub-elements as in network theory. However, the most important thing is to bring out a particular relationship to time, which materialises through feedback loops, and a dynamic character, with a multiplicity of solutions that allows human beings to get out of linear relations of cause and effect. Hence, Hakens` dynamic models make it possible to provide three original insights and avoids the obstacles of a positivist approach, such as that proposed by Waltz (1979).

Firstly, in general, regarding system theories, the agent-structure relationship as it is thought does not allow "introduce change and indeterminacy into social life: without space for the possibility of agency, theories must fall into predetermination or teleology" (Bousquet & Curtis, 2011, p.52). Secondly, it also makes it possible to broaden the notions of agents and structure to respond to critiques of reductionism (Wendt, 1999, Ch. 1). Thirdly, Haken-type models aim to describe the links between systems and their environment. Closed loop between systems and environment tend towards entropy. They cannot function sustainably and become increasingly complex if they do not exchange energy, information, and matter with the external environment. This is in line with the complex IR progressively oriented toward for “a ‘complex ecologism’ of ‘posthuman IR’ uncovers that the world is not divided into territories in which bounded societies of humans live under singular political authority and in the context of discrete natural environments” (Cudworth & Hobden, 2011, *apud* Kavalski, 2012, p. 141).

He named the organisation of the complex system "*panarchy* – a framework for the integration of ecological, economic and institutional processes as a result of the expanding influence of human activity that begs the analytical coupling of 'people and systems of nature" (Kavalski, 2007, p. 446). To go further, "Ecological complexity does not merely arise from the interrelationships between human and natural systems […] Within social systems, people and groups learn how to change the social environment to improve their reward" (Earnest, 2015, p. 41). This illustrates the isomorphisms of the systemic approach of the beginnings, which have gradually being transformed into an approach to complexity by non-linear dynamic models.

Finally, since so many sub-elements can be included, but not all of them are likely to be relevant, there remains an open question: what are the essential coordination variables or order parameters and how to characterise their dynamics? In other words, who are the agents and how do they interact with each other and with their environment? In order for the different variables (order and control parameters) to be of low dimension, it is for the researcher to make what is called in social science an aggregate. Then, Haken-type model avoid Mearsheimer and Waltz criticisms (2013). Ontological reflection has a large part in constituting these aggregates, which will be put into interaction in a very specific way in dynamic models. Ontology, epistemology, and method are not separable in this approach to complexity. The approach to complexity constitutes a whole without artificially separating ontological and epistemological reflection.

The notion of aggregate or low-level variables is comparable to the "restricted complexity" (Brosig *apud* Orsini et al., 2020): systems with few sub-elements acting with specific boundaries (semi open systems). Reducing the number of sub-elements and identifying their limits illustrates an ontological work that can satisfy the proponents of mainstream approaches because, according to Brosig (apud Orsini et al., 2019), cause and effect relationships remain identifiable. However, there is a little disagreement with this remark. The Haken-type of model describes auto-organisation and bifurcation. These aspects would deserve further development, which would show how IR makes the use of complexity theories autonomous from other disciplines that use the same vision.

Mainstream criticism has not prevented the realisation of several studies in economics focusing on issues of globalisation of trade that also concerns IR. Moreover, if the models of the type proposed by Haken`s approach can lend their flank to criticism, the network theory allows both identifying systemic organisations. In this respect, Barabási's works are a good illustration of this, when put in perspective with other works such as those of Jia et al. (2013), Verspagen (2007), and Glattfelder et al. (2009). They could inspire the political community to work with IR scholars who would use such tools to guide choices in a complex environment.

The success of graph theory lies in the concept of the notion of agent and system. This theory leaves the researcher free to describe social relations on the most microscopic scale without taking away the possibility of demonstrating forms of self-organisation of social sub-groups, which also interact in such a way as to form moving structures both are continuously co-constituted through dynamic evolution (Bousquet & Curtis, 2011). In this sense, this approach to complexity differs ontologically from the approach based on equations, as in the Haken-type model, or as those of the linear positivist approaches.

Complexity theories can constitute both an ontological and a pragmatic epistemological axiology for this new post-disciplinary phase in which the boundaries between disciplines or issues are no longer rigid. Democratisation, economics, health, and sustainable development can be approached jointly under the prism of global governance, which is naturally linked to the development of systemic analyses and non-linear dynamic models. Kim (2019) reviewed the different levels of analysis offered by network theory corresponding to specific sections of the IR literature studying global governance. He stressed the existence of different tools allowing the capture of the dynamic character of organisations that are only transitory. Indeed, the analysis of networks is often used to study social groups and their possible interactions with actors who would be hubs favouring the diffusion of information.

This complex method avoids the excesses of theoretical orthodoxy, as Schelling's works. It avoids the drift of approaches that have pushed the primacy of the idea to its paroxysm at the expense of a reality that can exist independently and can be captured by meticulous data collections that took form in information with specific relations highlighted by dynamical models. This does not preclude the removal of theoretical contributions from all families of IR theories. On the contrary, they are instruments for identifying all the candidate variables that could be chosen as control and order parameters, or as links in communication networks according to the type of non-linear model chosen to capture the complexity of the systems under study. These approaches need to be more actively developed within the IR community; The wide range of uses of network theory, as well as synergetic models, are all methodological innovations that would in turn allow further theoretical developments to take place. These improvements might allow better understanding of new forms of governance, what governance is better equipped, rethinking critically the assumptions about top-down steering and "orchestrating" governance (Kim, 2019; Orsini et al., 2020).

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