



ENGINEERING SCIENCES

Complexity engineering: New ideas for engineering design and engineering education

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Abstract: This paper presents a theoretical approach to complexity engineering by considering the complex thinking framework proposed by Edgar Morin. The main foundations of this approach are an open system design, emergence, randomness inclusion, and Gödel incompleteness, which are contextualized using real-word instructive problems. Considering these concepts, several conjectures related to engineering activity and engineering education are presented taking several Brazilian catastrophes as counterexamples.

Key words: complexity, education, engineering, incompleteness, non-linearity, open systems.

INTRODUCTION

It is impressive how researchers in humanities easily relate historical facts and philosophical thoughts to everyday life, apart from their rhetorical abilities, linguistic competencies, and their ability to connect ideas. These qualities can be intimidating to an engineer attempting to engage in debate with these trained specialists because of the perceived deficiency in background knowledge. However, the aim of this investigation is to establish complexity thinking in engineering, based on an in-depth understanding of a publication by Edgar Morin (2008). Data used is mainly extracted from a Brazilian context, which the authors know deeply, but the insights and conclusions are not limited by this context.

This paper is an attempt to transport some of the ideas presented by Morin in his wide work about complexity to new engineering practices that have emerged from the richness of information and the transdisciplinary work presented by Von Bertalanffy as a theoretical

framework (Von Bertalanffy 1950). In this sense, the philosophical questions and their relation to scientific knowledge is a subject that has already been considered by Morin and Von Bertalanffy; hence, this manuscript aims to relate the principles of thought to engineering practice, when considering conception or operation from a theoretical perspective without technical details or equations.

Consequently, the teaching of engineering can be deeply affected, in relation to the balance between theory and practice, the design of projects and especially to the sources of knowledge, necessarily broader to account for the paradigm of Complexity.

This is initiated with a discussion on the interpretation of the common meaning of the term complexity within the scope of engineering by presenting various examples where a non-shared vision is required in a project. Subsequently, the conceptualization of an open system is presented by speculating on the emergence of self-organization in the design of systems.

Considering this context, randomness is discussed in depth, and it is examined under the conception of a meta-system and in the analysis and synthesis of dynamic processes. Moreover, fast processes that are related to variables of state are distinguished from slow processes that are related to the variation of constitutive parameters.

Based on the idea of meta-systems, the perception of the involved disciplines is considered by exploiting Gödel's incompleteness theorem. Considering these ideas, engineering activities and their contextualization in a new technological world are discussed. In conclusion, some observations are highlighted in an attempt to provoke complex thought, thereby transforming engineering interventions – and, therefore, engineering education – into transdisciplinary processes that harmonize the numerous possibilities for thinking and designing, considering environmental and human aspects as the main issues.

The engineer and complex thought

As this paper concerns to philosophic questions and designers attitude when an engineering problem is presented, the first point to be touched is how complexity can be summarized and understood in a simple way to be connected to the daily design work.

How can engineering methodology move away from an eminently positivist tradition, based on the search for certainty, to another that corresponds to what is most current in terms of different epistemologies, and to incorporate approaches that consider uncertainties and dynamics of systems?

If the adopted option is based on the Theories of Complexity, especially the reflections proposed by Morin (2008), it brings a series of proposals that enrich and can be useful for

the development of the thinking of the engineer, among which:

- Definition of complexity refers to the idea of tissue, the possibility of relating, trying to understand how different variables can be coupled, how there can be an influence between phenomena, and finally a type of thinking that, instead of separate, seek to join and interrelate.
- Recognition of the importance of uncertainty regarding the evolution of phenomena, since what is predictable corresponds to a vision that comes from the past, but does not allow the understanding of how the future will be. This leads to questioning the certainties that are the basis of positivist thinking, appearing as an alternative the thinking based on uncertainty and diverse possibilities.
- Recognition of dialogical relationship between order and disorder as central, since all systems are entropic. Thus, every system develops in disorder, since the increase in entropy is inexorable. However, this process occurs by means of rearrangements on other levels, which then continue their process of disorder and ordering.
- Incompleteness is another concept to be highlighted, since it is impossible to have an idea that corresponds to the totality of any system, because it is not possible to have an understanding of the whole. The very concept of wholeness is false, since systems are dynamic and in a constant process of disorder and order.
- Hologramatic principle, since any system has its properties impregnating its parts, that is, in any part of a system it is possible to distinguish common general properties, besides the particularities

of each of the parts. Systems are larger and smaller than the sum of the parts, since at the same time they inhibit and potentiate its action.

Such proposals of Morin's Theory of Complexity seem to be operative when it comes to discussing their contributions to the development of science in general, and more specifically engineering.

In the case of engineering, it is believed that one faces significant challenges, such as understanding the phenomena that occur in the most different levels of production systems, what concerns the properties and dynamics of the different materials, the most varied processes of design, production and operation, the performance and living experiences of people through their work and, more broadly, phenomena related to society and different consequences related to industrial, services, agricultural production systems. At all these levels there are possible and necessary engineering actions.

These proposals oppose the methods that are usually applied in engineering, especially in what concerns the constitution of a broader vision for the understanding of problems and the search for different ways of solution. How, instead of separating, isolating and manipulating variables, can one enrich the prevailing methods, in order to relate, understand and expand the horizon of possible?

What is being proposed does not mean disabling the existing approaches in engineering and moving on to something totally new. It is a matter of facing the challenge of incorporating non disruptive modes of thinking to those already practiced by the institutions involved, so that engineering methods can be improved to face the challenges related to the contemporaneity, to see the future in a different way, to build pertinent solutions with the needs of society

and with human curiosity, in the search for the expansion of the frontiers of knowledge.

To conceptualize complexity from an engineering perspective it is necessary to address the widely accepted definition in use throughout the years. Considering the daily role of an engineer, the term "complex" can be defined as any aspect that presents special difficulties regarding conception, project, assembling, and operation (Frei & Serugendo 2011). This traditional view is considered to be related to "complicated" systems or projects.

Nowadays, the word "complex" is reserved to systems presenting self-organization and emergence (Sayama 2015). However, this distinction may not be an intrinsic characteristic of the system to be engineered, but also a characteristic of how to look to it: as a simple superposition of parts (complicated system) or a combination of parts and behaviors presenting emergence (complex system).

This is a fundamental point: a system may be complex, but it is not recognized as such. The look of the engineer can simplify – "analyze" in its most original meaning: "divide to understand" – and lose precisely the comprehension of the complexity of the system he (she) projects.

In epistemological terms, complexity is a point of view and is related to the capacity to put together different things, different approaches, and different perspectives, abstracting the physical object. The perspective proposed by Morin includes a dialogized concept that considers different aspects in the same system even if they are diverse or opposed.

Complex may be both the designer's point of view and/or the object to be designed and maintained. The object itself can be by nature complex, but not the view of the engineer. Hence, the problem appears fundamentally when the simplistic, fragmented, non-systemic view finds a complex object to be projected. Many

examples of civil construction - which, in fact, are interventions in natural environment and at the same time intrinsically complex social, result of people and nature interactions such as housing, sanitation, agriculture, preservation, and interactions between people such as the network of interests (politics).

For example, a bridge or an elevated highway is a project that may present great difficulty. In a sense, it is “complicated”. Conception starts with the need to join two locations separated by a geographical factor that obstructs traffic. In this phase, economic, social, environmental, and financial aspects determine the location and the maximum cost that once defined, initiates the establishment of the first specifications of the project. At this point, the engineer may – or may not – perceive complexity.

At this point, natural wear and tear, theoretical weight that must be supported, and geometric factors are considered as precursors to calculations for determining the characteristics of columns and foundations. Later, we consider the definition of the execution phase in which all materials and labor costs are outlined prior to the start of construction thereby, materializing the conception.

The construction phase is often challenging and requires constant management to solve unexpected but inevitable issues that arise during implementation. Upon completion, a bridge or elevated highway requires regular maintenance similar to all engineering plants or devices. Using position and cargo sensors, constant measurements facilitate the prevention and correction of failures.

Thus, regarding the problem of design, build and maintain a bridge has two visions: a disjunctive approach with all the different phase or aspect of the project seen as an independent part (complicated system) or an integrative

approach, with all aspects and phase treated in an interactive point of view (complex).

Another example is related to the conception, design, construction, and operation of an avenue connecting two neighborhoods in a city, aimed at improving urban mobility. In this case, the starting point is to define a route for the avenue, which may involve complicated economic, social, and environmental aspects.

Mathematical knowledge solely is insufficient to accomplish this task; therefore, urban development planning based on the combination of vehicular traffic and human mobility with the objective of assisting in the relocation of a population is essential in this phase. Once a route is defined, the project advances to the execution phase that involves changes in the use of the land including demolitions, landscaping, definition of flooring, and prediction of labor costs.

From the first sketch of the project to reality, a series of odds must be considered. However, all the odds cannot be predicted; this results in a demand for alternative solutions and implies a complex vision of the work.

The view of exploring the examples can be complicated, i.e., accompanied by a disconnection implicit in the semantics of disjunction, dividing the system into independent parts that can be treated individually in a hierarchical or sequential way. Complexity approach of the same cases considers integration and interaction between parts, creating emergence.

The implication of the disjunctive approach is that the complex systems of constructing a bridge or identifying a new route may be seen as a division of operational sequences performed by different individuals who execute tasks that are apparently sealed and disconnected, i.e., treating complex as complicated, not considering interactions and behavior emergence.

In this sense, the bridge, for example, in the disjunctive approach is investigated and considered as a closed system. The interactions of the project with its surroundings can be understood based on probability. Security factors, i.e., exaggerated loads, are attributable to project interactions, even though these factors do not always work as intended if they are not combined with operational and maintenance actions.

These practices of treating complex as complicated are universal, with the risk concept considered as the accident probability, without considering damage in the case of its occurrence.

Taleb (2014), in his book “Antifragile” addresses this issue: “Artificial, man-made mechanical and engineering contraptions with simple responses are complicated, but not “complex,” as they don’t have interdependencies (...) But with complex systems, interdependencies are severe. You need to think in terms of ecology: if you remove a specific animal you disrupt a food chain: its predators will starve and its prey will grow unchecked, causing complications and series of cascading side effects”.

In other text, Taleb (2018) stresses that “the main idea behind complex systems is that the ensemble behaves in ways not predicted by the components. The interactions matter more than the nature of the units. Studying individual ants will never (one can safely say never for most such situations), never give us an idea on how the ant colony operates. For that, one needs to understand an ant colony as an ant colony, no less, no more, not a collection of ants. This is called an “emergent” property of the whole, by which parts and whole differ because what matters is the interactions between such parts.

On the other hand, about the engineering approach or “look”, Simon (1976) says that ... “Complexity may lie in the structure of a system, but it may also lie in the eye of a beholder of

that system. Even when a system is “inherently” simple i.e., describable, in principle, in simple terms an observer may fail to discover that simple description, and may be able to characterize the system only in a very complex way. Moreover, the simplicity or complexity of a description will depend upon the units that are selected as primitives”.

Several Brazilian cases are known indicating that a change of attitude could avert potential disasters. They, for example, the collapse of the Paulo de Frontin Bridge in Rio de Janeiro and a fire incident under the Santo Amaro Bridge in São Paulo, Brazil are suitable examples of this failed approach – assuming “complicatedness”, but avoiding or, worse, not wanting to see inherent complexity.

As a result of non-authorized action, a small fracture appeared at the center of the structure in the case of the Paulo de Frontin Bridge built in November 1971. This action provoked its collapse, which caused 29 deaths and great material damage (Figure 1).

In February 2015, a tanker truck, transporting combustibles was being driven through a very populated neighborhood (Santo Amaro) in the urban area of São Paulo. Due to the lack of coordination among the urban authorities, there was no sign indicating the maximum allowed height necessary to drive under an important bridge. This fact, combined with the irresponsibility of the truck driver, caused a large explosion under the bridge (Figure 2a), which provoked numerous traffic problems. Twenty-five bus lines were deviated during a two-year period causing significant traffic congestion and mobility problems to workers (Figure 2b).

Unfortunately, these engineering catastrophes that occur almost daily all over the world has not led to a change in the ideas and methodologies used in engineering action and thinking. This fact, combined with endemic



Figure 1. Collapse of Paulo de Frontin bridge.

laziness, resulted in two mining tailings dam ruptures, in Mariana (December 2015) (Figure 3a) and Brumadinho (January 2019) (Figure 3b); real ecological and human crimes resulting in the loss of lives and destruction of the environment.

Less shocking, but equally deleterious, some developments, such as the João Goulart Bridge in São Paulo, trying to improve the traffic produced a big environment damage, polluting the neighborhood.

As Figure 4 suggests, there was no coordination between traffic engineers, planning architects, and structural designers, thereby provoking a real urban disaster. Thus, the construction of an avenue, in which a bridge or elevated highway is included, may entail more losses than gains if treated as a closed system. This case is an example of search of a reduction of complication by blind reduction of complexity – creating a true urban wound in the city.

Complex thoughts are developed within a context complementary to the practice of engineering, in which successes may be numbered in all areas of human activity. Therefore, it is recommended that three novel approaches must be added to projects:

- treat project objects as open systems, i.e., consider all the interactions with the environment with respect to technical and human issues (Taleb 2018, Von Bertalanffy 1972);
- consider emerging phenomena resulting from intrinsic non-linearity, i.e., small perturbations of the state of the system or the constitutive parameters can produce considerable changes in the dynamic behavior of the entire system (Lichtenberg & Lieberman 1992);
- acknowledgment of the Gödel's incompleteness theorem because the combination of possible
- effects contributes to undecidability (Petzold 2008).

The complex engineering role can then be understood as the addition of these approaches in a complementary perspective to the closed and linear simplifications that are traditionally used to tackle engineering problems (Wolfram 1984). Moreover, it relies on well-established successes and knowledge in addition to providing a global and transdisciplinary approach. The method also deals with the system of systems notion (Von Bertalanffy 1968).



Figure 2. (a) Tanker truck after explosion underneath the bridge, (b) Traffic congestion and other difficulties encountered by workers.

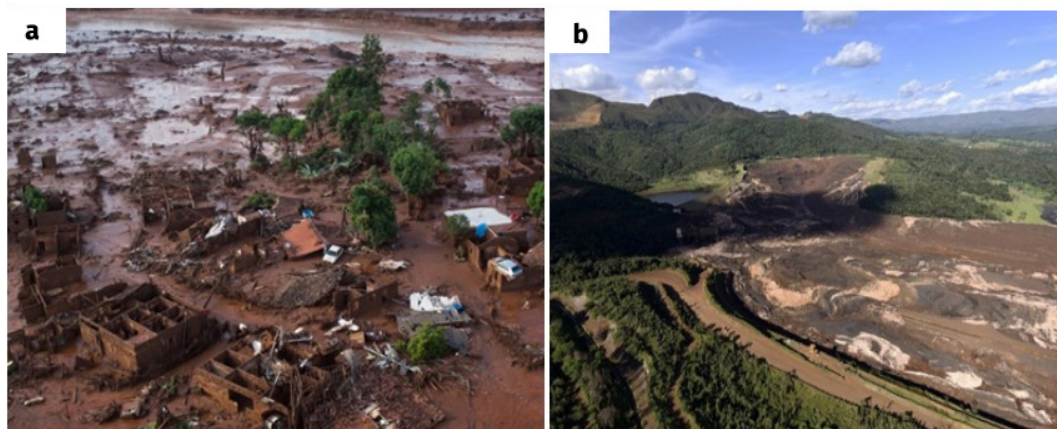


Figure 3. Dam ruptures. (a) Mariana, (b) Brumadinho.



Figure 4. João Goulart Bridge polluting the environment.

Designing and building open systems

The examples presented illustrate the establishment of systems that consider their interaction with the environment as static from the project phase, as reflected by the physical parameters and security coefficients determined from the onset. This approach has been employed with success over the years; however, it operates as if the system under study or construction is closed, disregarding the possible randomness beyond parameter variations.

The number of possibilities facilitated by the development of computational tools allows a large amount of data to be handled relatively easily. Furthermore, it entrusts engineers with powerful analytical tools and syntheses of systems by facilitating unprecedented levels of detail and interaction with worldwide access to data (Hsu & Loh 2019). Consequently, it is possible to consider a large number of interactions and different ways of conceiving entire systems, allowing fast and precise calculations in each case (Wen et al. 2012).

Furthermore, nonlinearities can be modeled, and numerical integration methods allow for the determination of accurate solutions—even for complicated geometric forms (Feng et al. 2018). Moreover, state-of-the-art tools and simulation programs facilitate rapid work for different assembling and execution possibilities with a high degree of predictability (Lee 2008).

The process of conception, design execution, and maintenance constitute an open system, subject to the laws of thermodynamics (Kondepudi & Prigogine 2015) with a large number of variables and parameters that can be tested and simulated to improve behavior predictions. In addition, modern numerical Fourier analysis methods allow for the analysis of the effects from dynamic processes of different temporal scales, permitting several frequency bands of

random effects to be taken into account (Mertins 1999, Piqueira 2009).

Considering dams, bridges, or elevated highways, the new approach is based on the principle that there are no longer real, but rather, new elements that, in reality, reside in the bond between the system and the environment. By using high-speed and high-capacity computational facilities, a large number of possible situations can be modeled and precisely studied beforehand. In addition, the simulations of most interactions allow decisions to be made by considering the uncertainties to be elements of the entire analysis. How does a new plant placed as a new element in the global context of it acts? How does its operation affect human life? How does inclement weather alter construction and operations? How will the surrounding traffic affect the physical parameters? How will the emission of pollution affect the health of neighboring areas? How will the neighboring area organize itself?

There are many questions and scenarios that require simulation and analysis to facilitate better decision-making while adding knowledge to engineering. Consequently, the design results are based on broader and more accurate decisions (Rozum & Albert 2018). Moreover, processing data obtained by different types of sensors during construction and operation will allow for highly efficient preventive and corrective care, thereby avoiding accidents and improving reliability.

Considering the mining industry, the implementation of a dam to collect rejected products should begin with a careful analysis of the pros and cons for the population and the environment. After deciding the location, the problem to be solved considers important environmental, social, and security aspects. The project also involves the infrastructure to be built under suitable conditions of pressure,

humidity, temperature, air circulation, and water.

A project largely depends on the process to be implemented and is subject to great care of production, considering the ergonomic and security care that protects the lives of employees and provides dignity. During the operational phase, other factors should be considered such as where are the waste materials disposed? Are the environmental laws respected? Is the quality of the air and water preserved? All these factors being considered, will the production be economically viable? Once again, different scenarios may be simulated and carefully studied, shaping the physical, chemical, biological, and anthropological properties. These properties guide the multidisciplinary approach to an effective interaction level, approximating possible randomness from the process model (Otto & Eichstaedt 2018).

In this sense, complex engineering presents a multidimensional approach which is neither totalitarian nor dogmatic and facilitates a flexible connection between physical uncertainty and the theoretical indecisiveness. Cultural and human aspects can be considered by using paraconsistent logic principles (Morin 2008, Bremer 2015).

Additionally, the principles of thermodynamics not only play the role of boarding complementary or undesirable conditions, but they also become permanent elements during the conception of projects, representing an important epistemic aperture (Morin 2008). This does not mean that thermodynamics can be directly applied during several phases of design and operation. Rather, the complexity measures originating from statistical physics (Lopez-Ruiz et al. 1995) can be predicted during the design and monitored during operation, thereby improving the decision quality.

Self-organization and non-linearity

Random spurious signals, called noise, create difficulties to typical operation of electronic systems in communication and instrumentation. The project conception in these areas begins by specifying the signal-noise relationship, i.e., the factor that describes the signal intensity relative to noise.

Consequently, a fundamental theorem of information theory arises as follows: if the signal-noise relation of a certain data is greater than or equal to the channel capacity, it is always possible to codify the data and transmit it to a detector with a small margin of error (Shannon & Weaver 1963). In addition to the knowledge acquired from information theory, electronic and communication Engineers have widely exploited the theory of stochastic processes in electromagnetism and circuits. These processes are used to develop modulation and demodulation devices that are responsible for the speed and ubiquity of internet access.

Originally, projects and linear devices were used to achieve these advancements; i.e., by satisfying the superposition principle as follows: the effect of the sum is the sum of the effects. This is a hypothesis that when satisfied, facilitates ease of project and operational precision. However, electronic components present non-linearity and superposition of effects that are not always satisfied, a fact that may result in difficulties, but one that may enhance many projects if well-applied.

In the mid-1980s, there was global attention focused on the fields of physics and mechanical engineering, which was attributable to the computational ease of simulating dynamic systems described by differential non-linear equations (Shannon & Weaver 1983), producing what is referred to as deterministic chaos.

Deterministic chaos is the apparent random behavior of a dynamic system described by

deterministic non-linear equations, associated with the emergence of behaviors that are sensitive to the initial conditions. A dichotomy is then created, characterized by complexity (Morin 2008), i.e., the unpredictable inside the predictable. Electric circuits that demonstrated this phenomenon were developed and modulation techniques and cryptography improved as a result (Sayama 2015, Shannon & Weaver 1963).

Deterministic chaos and synchronization are an integral part of the diverse activities of conception and projects in complex engineering, thereby enhancing the acuity of the interaction models for implementation and operation. These allow for the visualization of a wider variety of scenarios (Carareto et al. 2013).

Another aspect to be considered in the context of complex engineering is the self-organization of a system, constituted by its development and physical, biological, and human surroundings (Hsu & Loh 2019). Given the complexity of physical interactions, there are relatively well-developed methodologies that can be investigated and contextualized to complete the models used as design basis. The biological interactions, for instance, can bring significant and unexpected outcomes.

Alterations to the environment provoked by engineering action may induce landscape degradation and disease propagation. Nonetheless, the most relevant facts to be included are anthropological (Souza & Sanchez 2018). Engineering development is human work that should envision improvement in the quality of life under the most diverse aspects. Humans are gifted with consciousness and discernment, which may directly influence the conception, execution, and operation decisions of a system and primarily contextualize it to the human conditions of a given population.

It is counterproductive to build modern highways in areas where populations do not have the appropriate means to be displaced. Similarly, considering the vital need for water and energy to maintain life, it is incoherent to inhibit the development of alternative sources of energy and spring de-pollution mechanisms. Economic groups may work towards the eradication of hunger, while religious and gun fanatics may instigate the development of weapons of mass destruction. Cultural, social, and economic balance are the main objectives of complex engineering, which should be considered a multi-disciplinary tool of global peace and understanding.

Complexity and incompleteness

There is great excitement and enthusiasm among the state-of-the-art proponents of the latest products concerning intelligent cities and the Internet of Things. Traditional software and hardware developers promote forums, offer freemium solutions as well as financial development and publications, with the objective of capturing an apparently promising market.

Politicians are driven to value applications that integrate the torrent of data that devices can capture. Indeed, there are new possibilities brought about by the enormous capacity of data computing, applying image recognition and eventually acting on devices such as floodgates, traffic lights, etc. There are solutions for street and home security to monitor accidents, floods, crimes and crowds. But what this “brave new world” has to do with engineering and complexity?

First, one thing is to be able to turning on a fruit processor remotely; unfortunately, it might be impossible to consume the resulting juice because teleportation is still science fiction. This is the traditional manner of examining

engineering problems, considering the physical models; each system is unique, closed and aimed at an exclusive mean.

We can imagine that a device can be designed by interconnecting one or more sensors with one or several actuators; between sensors and actuators, a large data processing capacity and the query of data available in a cloud, to define almost instantly how the actuator should behave. This is, for example, the autonomous vehicle principle, but it can also be the basis for designing automatic crime fighting, from face recognition and gun firing, to replacing snipers.

Complex thinking applied to smart cities and the Internet of Things begins with anthropological thinking integrated into biological and the physical fields. A smart city is based on the culture, comfort, and the quality of life of the population.

Again, considering a Brazilian example: a city as São Paulo cannot be considered to be a smart city simply because of the implementation of synchronized traffic lights or the monitoring of flood risk areas. There are many other primary problems that must be addressed such as housing deficiency, poverty, school dropout rate, and criminality. The Internet of Things, together with Artificial Intelligence and Machine Learning can undoubtedly help solve these problems. But without a look that recognizes the complexity of reality, it can not only not help but can make the situation worse, like a well-designed avenue as a civil engineering project, but that rips the city and deepens the violence tearing people apart by destroying flows of people between separate neighborhoods.

Complex engineering proposes the integration of all these aspects, forming a so-called open system of systems (Bremer 2015). This manner of thinking improves the efficiency of solutions; however, any solution is incomplete

because the total knowledge is unreachable. “The totality is the non-truth” (Morin 2008).

The solution is a manner of facing a net of interrelations and feedbacks, uncertainty, and contradiction by employing conceptual tools that are already available as well as new ideas arising from different and innovative lines of thought. The conciliation of units and diversity as well as continuity and ruptures in complex thinking that, similar to logical systems, is incomplete.

To deal with all these questions and with a large mass of data that the integration of the myriad of questions to be treated in a complexity paradigm vision of engineering design, the development of artificial intelligence systems and their wide range of applications is being successfully used (Nguyen et al. 2019). But, even with modern computational techniques and powerful hardware, the Gödel incompleteness theorems for recursive functions and computable number (Turing 2013) must be taken into account, preventing bad interpretations of results.

Complexity, the work of the engineer and engineering education

The work of the engineer involves the integration of different variables presented in the real world; it is related to the pursuit of the task of converting thoughts and ideas into reality.

The old engineering education process has a disjunctive approach, fragmented into different disciplines that are not correlated and a link with the real work is rarely or even never established (Van Rusewuk et al. 2018). Consequently, again the confusion between complex and complicated emerges as a misconception in the engineering community. As previously stated, difficulties are considered to be complex (Bolis et al. 2014).

An old fashion view of complexity is not inextricably related to difficulty; this is related

to something that is complicated or difficult to master, i.e., related to something that is possible to be linked, recalling the weaving process used to build a fabric, an object that has different parts that fit together.

The disjunction between the simplifying and fragmented look and the complex object can “work out”, and following this approach, major civil works were made in Brazil:

- Itaipu hydroelectric dam, one of the largest in the world;
- newly built plant in the Amazon, Belomonte;
- recent discoveries and beginning of exploration of gigantic reserves of gas and oil in the pre-salt layer in the sea along the Brazilian coast;
- the three units of atomic energy production on the coast of the state of Rio de Janeiro, a German project, under construction since the 1970s.

But what does “work out” mean? It only means that no tragic event of great proportions occurred, as described previously in this text in other sites. But the lack of understanding that both were complex projects generates gigantic consequences, not previously modeled or monitored since its implementation: Itaipu (1970s) and Belomonte (2010) caused a displacement of riverine populations, profound disturbance of the ecosystem of the rivers involved and of entire forests (Atlantic and Amazon).

For the engineering involved in the project, what should be built – and it was, indeed – was a concrete wall, which dams the water, a giant lake and the installation of turbines. Thus, it was a civil, hydraulic, electrical engineering project. But the complex look would show the network of determinations that is involved in these cases. Even crimes of death occurred in the fight conducted by the local population and repressed by police, against the lake of Belomonte (and

certainly of Itaipu also, but unknown because of the censorship imposed by the military dictatorship of the time, sponsor of the work).

In the same way, the recent discovery of huge oil reserves in the pre-salt layer off the Brazilian coast could make Brazil one of the largest oil producers in the world. Economists, however, warn of the risk of “Dutch disease” (Bresser-Pereira 2017) of the economy, destroying whole industries because of the appreciation of the exchange rate and the following loss of competitiveness. The choice of a non-renewable and polluting energy source is a key element among a complex system that a complex approach can and must perceive.

The same goes for nuclear power plants, which without being subjected to modeling can present serious problems, at least because they are on land adjacent to the sea, which was, in the original design, considered an advantage, for the cooling of the fission process. After the Fukushima accident, though, it generated enormous opposition to this energy option. The Brazilian government, the builder (during the same period of the military dictatorship) had not modeled the problem of the energy matrix and its risks, advantages and disadvantages at the time and mainly the risks involved. These ventures are on their feet; its effects, and its associated risks, unfortunately, too.

Regarding more specifically the work of engineers, it can be stated that they constantly dealing with problems that could be treated as a complex perspective, mainly in a country with too many natural resources and with uneven income distribution. Real problems are not consolidated; normally, they are poorly formulated and represent an oversimplified point of view.

The first challenge is to determine the questions that should be answered to understand the details of the situation, the different possible correlations, different paths for building solutions, cost, and the benefits over a medium

and long-term view. Another key aspect is that these working processes are iterative; it is not possible to consider or calculate everything that will likely occur in a project building, in project implementation and in use situations related to every possible kind of engineering action.

It is important to maintain the perspective in the engineering profession that preconceived ideas and plans are seldom executed as envisioned. One of the main qualities of this professional work involves determining an approach for managing the different emerging phenomena that will always be encountered.

Therefore, working as an engineer requires certain creative skills that are fundamental when considering uncertainty; additionally, they should also possess the ability to reason in feedback loops.

In this way, engineering work could entail the openness to consider both the advances in the field of science and technology and the new economic, human, environmental, social, and cultural challenges. Using, for example, an economic approach that does not consider the positive and negative externalities related to production systems is not compatible with a complex view.

In the new proposed perspective, cooperative work with different social actors plays a relevant role in the integration of the knowledge from different disciplines related to mathematics, physics, chemistry, engineering sciences and technologies, life sciences, social sciences, and economics for example. Engineering activities, and engineering undergraduate courses too, could be enriched if the following elements proposed by Morin are considered by the already discussed relevant actors: uncertainty, dialogical relationship between order and disorder, incompleteness, the hologramatic principle and the recognition that a system is larger and smaller than the sum of its parts because it

simultaneously inhibits and potentiates human action.

Discussion and conclusion

Considering the aforementioned points, the education of engineers needs to be considered from another perspective. It is not enough to respond to the challenges and demands that are known in the present. The ability to project professional activities into the future is crucial to the success of the education process in order to identify opportunities to work and develop professionally.

Engineers should be able to follow paths that do not currently exist, given that they will likely have a role in the discovery and establishments of these paths. It is not a matter of working with certainties concerning known facts but instead, working with uncertainties and building a future for the development of society.

Among these premises, we must consider the evolution of science, technology, and society in recent years and their understanding, and to use this as a basis for designing a project for a different future. The challenge of incorporating new scientific approaches to the modulation of engineering thinking must be tackled. The transition of engineering education from an eminently positivist tradition, based on the search for certainty, to another that corresponds to what is most current in terms of various epistemologies, and the incorporation of approaches that consider the uncertainty and dynamics of systems is an important part of the modern engineering view.

The option to form engineers based on an approach that considers the theories of complexity, especially the ideas proposed by Edgar Morin, establishes a series of proposals that can both enhance and be very useful to the development of the thinking process of engineers.

The definition of complexity refers to the idea of tissue, the possibility of relating, seeking to understand how different variables can be coupled, how an influence between phenomena can arise, and finally, a kind of thinking that seeks to join and interrelate instead of separate. Such proposals of complexity theories appear to be operative with regard to their contributions to the development of science in general, and engineering in particular.

In the case of engineering, it is believed that significant challenges will be encountered, such as understanding the phenomena that occur in the different levels of performance, concerning properties and dynamics of new materials, design processes, production and operation. This calls into question the methods that are used in engineering, particularly with respect to the constitution of a global view for the understanding of problems and the search for different paths to build sustainable solutions. How can one improve the prevailing methods instead of separating, isolating and manipulating variables, in order to relate, understand and expand the horizon of possible?

However, the proposed concepts do not suggest the dismantling of the existing paradigm and the transition to something completely new. This is a question of addressing the challenge of incorporating new modes of thinking to those already practiced by the institutions involved, so that future engineers can improve their knowledge of history and contemporaneity, to view the future in a different way, to develop pertinent solutions to society's needs based on human curiosity, in the search of the expansion of the frontiers of knowledge.

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MZ supervised the conceptualization, formal analysis, investigation, writing and editing of the study. JP contributed to conceptualization, formal analysis, investigation, resources, writing, review, project administration and funding acquisition. LS also developed the manuscript's conceptualization, formal analysis and investigation.

