Aspects of Modern Systemic Approach (I): Beyond the Dynamic Systems Definition, Structure and Properties

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Authors’ contributions

This work was carried out in collaboration among all authors. Author BC designed the study, performed the statistical analysis and wrote the first draft of the manuscript. Authors AL and MC managed the analyses of the study. Authors BC and AL managed the literature searches related to GST and dynamic systems. All authors read and approved the final manuscript.

ABSTRACT

General Systems Theory, as well as Systems Theory - as integrated part of the first one, are still under the scrutiny of researchers, either through the interest shown for micro-systems or for macro-systems, as derivatives of the system. In accordance with the research undertaken in either of the two ends of the reference range for the system - as a fundamental element of systems theory, our concerns are to familiarize the reader with the diversity of concepts and development stages specific to the two areas of interest - General Systems Theory and Systems Theory. Also, as the objective of the present study, an attempt was made to bring to the fore some definitions and conceptual characterization.

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respective with the structure and properties of different system types. At the same time, are underlined different systemic approaches and representations, along with the position of Systemology in relation to the General Systems Theory and Systems Theory.

Keywords: General systems theory; systemology; systemic approach; systems definition.

1. INTRODUCTION

The General Systems Theory (GST) as a field of research, by itself, follows the study of the properties of various types of systems or systemic approach, as shown in Fig. 1, as well as the enunciation of sets of principles, independent of domain, substance, type or time [1-4].

By the emergence of the GST, which includes Systems Theory (ST) - classical and modern, respectively post-modern, the ways of designing and developing the modelling of the environment, or of the various structures considered, have been opened [5-7]. The GST is also the symbiotic result between applied mathematics and systems science, known in the literature as Systemology. Its origins, as a mathematical theory (as shown in Fig. 2) [8], are especially situated in Theory of Complexity (TC), thus, through the multidisciplinary vision and the use of mathematical language, the TC constitutes the matrix of GST evolution.

As an interdisciplinary epistemological model, the ST represents a set of concepts, methods and principles of independent applications, necessary for the study of the structure, properties and characteristics of systems with variable degree of complexity [5-7,9].

The GST concept used in different scientific environments, such as physics, electrotechnics, pedagogy, chemistry, geography, biology, mathematics, physiology, sociology, psychology, ethnology, ecology, and so on, has undergone a well-defined development, through the scientific approaches of the numerous promoters, some of them being reviewed in Fig. 3.

An extremely important notion, for the following approaches, which subscribes to the GST and ST, is the system concept. As natural, the notion of system appeared and developed over time, as a result of highlighting common features and behaviors for a number of processes and phenomena in different fields of activity and interests [8,9], which allowed their identification, analysis and treatment from a structural-functional point of view, and not only, in a unitary way, from a systemic perspective [10].

In the specialized literature there are various definitions of the concept of system, some reflecting the tendency to define the system in a

![Fig. 1. Different systemic approaches in relation with theories of systems](image-url)
broader generality [11,12], others the tendency to specialize in a certain field of knowledge [13-15]. The system, at least from a strictly conceptual point of view, appeared in an embryonic form, for the first time, in ancient Greek philosophy, stating that the whole is more than the sum of the component parts, Aristotle was the one who gave a first definition of the notion of system, a notion closely related to what emergency means (see Fig. 4).

Both in Fig. 3, but especially in Fig. 4, our concern was to express the complexity of GST and ST, as well as the intensity of study systems; as such, even before our era, the emergence as well as the concept of the system received special attention.
2. MATERIALS AND METHODS

The review of the specialized literature, as well as the application of an artistic approach - through the prism of making images from others much simplified (see as final results the figures from 1 to 5), were the basis in shaping the present case study - which has in the foreground the definition, structure and properties of the systems. Of course, many aspects were probably treated superficially, but our desire and, equally, the focus was on the integration of the concepts, on their (re)thinking in relation to the theoretical exigencies of the current academic community.

Another very interesting aspect was the use of dictionaries, of different nature, which came to emphasize and beautify the purely theoretical side of this approach, moreover, they guided and supported the whole process of defining, respectively characterization of structure and properties of the system. For the latter aspects, a series of mathematical equations were used, and specified where appropriate, precisely to highlight the fact that the study of the system, as well as the GST and ST are based on a solid scientific foundation.

3. RESULTS AND DISCUSSION

3.1 Some Aspects Related to System Definition and Background

The system can be defined as any set organized by resources or procedures in interaction or interdependence, real or abstract, for the realization of a set of specific functions [16,17], respectively as a set of elements that work and interact with each other and with the outside according to certain rules and laws, in order to achieve a meaning or purpose [18]. Consequently, in order to outline this concept, including the notion of a dynamic system, we call for the definition of a border that separates the system from the external environment. Next, we tried to capture a series of definitions found in the dictionary, for the general notion of system, as follows:

- The system is a set of elements (principles, rules, forces, etc.) dependent on each other and forming an organized whole, which places order in a field of theoretical thinking, regulates the classification of the material in a field of natural sciences or makes it a practical activity to work according to the purpose pursued [19].
The system is a set of interacting elements that together form a unitary whole. Any system works to achieve a functionality, to achieve a purpose; these are achieved through a process in which the elements that determine both the content and the processes specific to the system are involved. The systems are organized into hierarchical structures; (...) a system may consist of subsystems, each pursuing a purpose subordinate to the general purpose of the system; systems in turn fall into the supersystems they serve [20].

An assembly of elements (principles, rules, forces, etc.) dependent on each other and forming an organized whole, which places order in a field of theoretical thinking, regulates the classification of material in a field of natural sciences or makes it a practical activity, to work according to the purpose pursued [21].

A complex of elements that influence each other and are coordinated with each other in order to fulfill a common function [22].

An ensemble of elements with certain common features that are in a structural relationship, of interdependence interaction, forming an organized whole [23].

Thus, the system, seen both as an organizational unit of matter, and in relation to the subsystems it integrates (as shown in Fig. 5), respectively with the supersystem into which it can be integrated, is defined as a set of elements, identical or different, connected to each other by connections, which function as a whole.

As a natural continuation, of defining and understanding the concept of system, there followed a series of works that later resumed the subject, among them, of particular importance being the work of the German biologist Ludwig von Berthalanffy (1950), which represents a beginning of the GST, in which the system is defined as a meeting of interdependent elements that work together in order to achieve a common objective through the use of a set of material, information, energy and human resources.

The notion of system therefore has a relative character, in the sense that any system can be decomposed into subsystems and, in turn, can be regarded as a subsystem of a more complex system; for example, an enterprise may be broken down into systems (sections, workshops, jobs, etc.) and in turn, the enterprise may be regarded as a subsystem of a branch or national economy. On this principle, of decomposing the real system (physical, mechanical) into subsystems, the system analysis is based to study the connections between subsystems, in relation to their objectives and according to the existing resources.

In the analysis of any system it must be taken into account that it cannot be separated from the environment to which it belongs as a subsystem, and that one system only functions as a subsystem within another more complex system. The detachment of a system from its environment can only be realized as an abstraction technique, the existence of a system itself takes place through a permanent exchange of substance, energy and information, which takes the form of the inputs and outputs of the system.

![Fig. 5. The system and its relationship with subsystems](image-url)
Knowing a system based on the methodology of system analysis, means and involves, first of all, the study of system inputs and outputs, as well as the concrete ways in which inputs are transformed into outputs, in other words the functionality of the system.

The inputs and outputs of a system, analyzed as causal relationships between subsystems, form the structural-functional connections between them, and the study of these connections is of interest for identifying the behavior that the system presents over time. The notion of system has, as we have seen, a very broad sphere of understanding, being frequently encountered both in science and in technique (in all areas of human thought and action), but almost always in association with a specification attribute. For example, we can mention:

- in mathematics and related fields: "axiomatic system", "equation system", "coordinate system", "numbering system" etc.;
- in physics and related fields: "Physical system", "atomic system", "system of forces", "reference system", "system of material points", "system of measurement", "system of units", "system crystallization" etc.;
- for chemistry and related fields: "Chemical system", "crystallization system", "periodic system" etc.;
- in politics, public administration and related areas: "Social system", "political system", "voting system", "parliamentary system", "presidential system", "monarchic system", "public administration system", "socialist system", "capitalist system" etc.;
- in biology, medicine and related areas: "Biological system", "nervous system", "circulatory system", "bone system", "digestive system" and so on;
- in linguistics and related fields: "Writing system", "grammar system", "philosophical system", "communication system" and so on;
- in computer science, cybernetics and related areas: "Computer system", "file system", "database management system", "operating system", "binary system", "autonomous system", "expert system", "interconnection system", "information system", "data exploitation system" etc.;
- in technique and related fields: "technical system", "digital system", "energy system", "electronic system", "hydraulic drive-system", "navigation system", "heating / cooling system", "transport system", "pneumatic system", "transmission system", "signaling system", "production system" etc.

A system is structured as a connection of elements, each element in turn constituting a system (subsystem). The interaction between the elements of a system can give the system new properties, characteristics and behaviors, different from those of each component element. In the case of real systems, the interaction is performed on the basis of general physico-chemical laws, through mass and energy flows, which are information bearers.

3.2 A Few Remarks on Systems Structure and Elements

In the acceptance of the present work, through the system we will understand a set of elements that interact with each other and with the outside, based on and respecting certain rules, laws and principles, in order to achieve an objective, a functionality. The fundamental characteristic of the physical systems is their materiality; this implies the movement and objective existence in space and time of physical systems.

The study of physical systems and processes is based on the principle of causality: Each state in the objective world is the effect of causes that uniquely determine the respective state. Physical systems have mechanical, thermal, electrical properties, etc., which can be analyzed in successive stages.

In the analysis phase of the system, the model construction is in a sequence of stages, resulting, finally, the mathematical model associated with the physical system:

- Defining the boundaries of the system, given that all physical systems work in interaction with other systems. For this reason it is necessary to define boundaries.
- Defining simplifying hypotheses or defining the allowed approximations - the model must include what is essential in the physical system. If the system is too complicated its utility becomes questionable.
- Establishing the equilibrium or balance equations for the considered system (the dynamic system) or for the component
subsystems, ending with the definition of the additional conditions, taking into account also the specificity of each type of system.

As we have already mentioned, Systems Theory operates with the concept of abstract system, in the form of a mathematical model, which allows the description of the characteristics and behavior of systems. Below we highlight some basic features of the systems, respectively:

- The structural-unitary character reflects the property of a system to be represented as a connection of subsystems whose action is oriented towards a certain meaning (purpose);
- The causal-dynamic character reflects the property of a system to evolve in time under the action of internal and external factors, respecting the principle of causality (according to which, any effect is the result of a cause, the effect is delayed to the cause and, in addition, identical causes generates the same effects under the same conditions);
- The informational character reflects the property of a system to receive, process, store / store and transmit information.

In the sense of systems theory, information means any factor that contributes qualitatively and / or quantitatively to the description of the behavior of a system. In technical systems, the physical quantities used as a support for the transmission and storage of information are called signals.

The variable (state) sizes associated with a system, regardless of its nature, have two essential properties, namely the mediation of the input-output transfer (I→O, which thus becomes an input-state-output transfer (I→S→O), respectively of accumulation in a concentrated (synthetic) form of all the useful information regarding the previous evolution of the system, that is to say of the past history of the system, being of three types:

- Input sizes - independent system sizes (so of type cause), which influence from outside the system status and evolution;
- State quantities - sizes dependent on the input quantities (thus effect type), having the role of characterizing and describing the current state of the system;
- Output sizes - sizes dependent on the state and / or input size (so effect type), having the role of transmitting information (especially to neighboring systems) on the current state of the system; some output sizes may be state sizes at the same time.

A system interacts with neighboring systems only through input and output sizes. Output sizes of a system are input sizes for neighboring systems. Output sizes of technical systems are measurable, while status sizes are not always accessible for measurement.

Systems theory, as mentioned above, operates with two system concepts: I-S-O system (input-state-output) and I-O system (input-output). The I-S-O systems contain input sizes, state sizes, and output sizes, while I-O systems explicitly contain only input sizes and output sizes. Classic systems theory operates with type I-O systems, while modern and post-modern systems theory operate with type I-S-O systems. An abstract system (model) of type I-S-O and an abstract system (model) of type I-O can be associated to a physical system.

In I-S-O systems, the input-output information transfer (I→O) is performed indirectly through the state. The input-state transfer (I→S) takes place with strict delay, following a system-specific dynamic, while the state-transfer (S→O) is instantaneous. In the case of systems that follow the principle of causality, the output size has a component that instantly tracks the changes in the input size. In these systems there is a direct input-output channel (I→O), through which the transfer is made instantly.

The systems theory also operates with trivial systems, where the output size, as a whole, instantly tracks the changes in the input size. Systems of this type (called static systems), do not contain state sizes and the input-output transfer is performed only on the direct channel I→O. Nontrivial systems where the output size is late for changes in the input size are called dynamic systems. For I-O systems, the input-output transfer is performed directly, with strict delay (on dynamic systems) or instantly (on static trivial systems).

When the variables of a system are separated into cause-type variables and, respectively, into effect-type variables, we say that the system is called oriented. In the abstract systems, the
orientation is formal, while in the real systems, the orientation results from the application of the specific physico-chemical laws, with the unconditional observance of the principle of causality. Physical (engineering) systems are based on a series of material components whose properties and interrelationships can change over time, thus the system inputs and outputs can be classified into three categories: matter, energy and information. The three categories of inputs/outputs (matter, energy and information) are subcategorised so that a point situated at the intersection of inputs and outputs represents a certain class of the system and matches a certain domain of interest.

### 3.3 General and Specific System Properties

A system (sometimes called a physical system) can be defined as a set of components interconnected between them (an organized ensemble), so that two gateways exist there: input gateway and output gateway. For example, in the case of an electrical system, the nature of the components is the one mentioned, the gateways are also called input circuits, respectively output circuits.

Physical quantities involved in the operation of a system can be classified into quantities with independent variation (input quantities, excitations) and quantities dependent on those of input (output quantities or responses). It should be noted, however, that the system response is not uniquely determined by excitation. For example, the current charged by a capacitor (condenser) depends both on the value of the voltage applied to the terminals, but also on the electrical charge existing in its dielectric, when the voltage is applied. It turns out that the system also depends on a third size, called its state when the excitation is applied.

The knowledge of the general and specific properties of the systems is particularly useful in the investigation, analysis, modeling, design and control phases of the systems. The following properties characterize the vast majority of systems, both in relation to the external environment (external properties) and in the relation of subsystems (internal properties).

The external properties are generated by the relationships that the system has with (creates with) the environment, considering the non-trivial nature of inputs and outputs. The internal properties depend on structure and the nature of the relationships, practically depending on the interlinked conditions of the subsystems that make up the system.

According to system classification we take into consideration the following properties:

a) System sensitivity refers to the possibility of the state vector to respond or not to certain input/output modifications. This property is extremely important to leadership and control systems, that will have superior performances proportional to how high the sensitivity is, so there is a possibility to influence the states by commands.

Sensitivity can be enhanced in a special way by using design techniques when creating the leadership system. Excitation, response and state are usually marked with the following symbols $x(t), y(t)$ and $q(t)$ in case of analogical systems, respectively $x[n], y[n]$ and $q[n]$ in case of numerical systems. The following figure - Fig. 6 - shows the schematic representation of systems.

![Fig. 6. Schematic representation of analogical and numerical systems](image_url)

b) The open/partially open character of systems - shows us that a system that has links to the environment through at least one input and an output is considered an open system, while the absence of one of the connections (input or output) determines the character partially open. In the absence of both links to the environment, we are talking about an isolated system.
c) Random character of the systems - property determined by the way in which a system chooses from a set of possible states, a certain state. The choice of a state for the evolution of the system depends on its internal structure, its objectives, the nature of internal and external interactions, the turbulence of environmental factors, previous decisions made for its management.

d) System dynamics - general property of systems in which time is a basic parameter, which captures the transformations that take place inside the system, as well as those that take place outside, between the system and its environment. Every system (subsystem) has an internal time, which is system specific, and which is viewed as an invariable time (technological time) in relation to the processes nature, and internal and external connections that characterize it.

e) System complexity - general property that has an objective character that is related to the specificity of the analyzed system and subjective character, generated by the observer's report to the investigated system, by the way that system is investigated. The complexity can be defined according to a set of causes and factors, such as: the number of component elements (subsystems), the non-deterministic behavior of the component subsystems, the possibility of responding to some non-deterministic disturbances and the orientation of the systems towards the realization multitudes of purposes, competing or even contradictory.

f) Observability is the property through which the state successions that the system has can be partly or totally deducted knowing the input and output quantities. Regarding the acknowledgment of the states the system can be in, this can be achieved by using the associated model, knowing the system structure and interconnections or using a tracking system, by knowing all the parameters.

Let there be $S$ a dynamic system. We call the $x_0$ state at time moment $t_0$ observable for a time moment $t_1 \geq t_0$ if this state is uniquely determinable knowing input $u[t_0, t_1]$ and output $y[t_0, t_1]$, determined by the initial state. If this property occurs for $\forall x_0 \in X$, the system is called completely observable; if, in addition, this property occurs for every interval $[t_0, t_1]$ that has margins, the system is called totally observable.

g) Time invariance - a deterministic and causal system is time invariant if the applications $\lambda$ and $\mu$ are independent of time $t$ (in case of analogic systems) and independent of variable $n$ (in case of numeric systems). In many cases linearity and time invariance represent simplifying hypothesis used to obtain ideal systems. From this point of view they should be applied only in signal variation domains for which the system is quasilinear, respectively for limited time intervals that depend on other properties (environment conditions) of the system or its components.

h) Self-regulation - it is the characteristic that expresses the capacity of a system to react by its own means to the internal or environmental disturbances. This property is characteristic to systems that have in their composition an active system and a control block (an regulation block) that can be a subsystem of itself or one from its environment.

i) The antientropic character of the systems is related, in particular, to the possibility of improving the management and reducing the degree of internal disorganization of the open systems, by improving the structural and informational - decision-making properties, as well as by intensifying the information exchange and transactions with the environment.

j) Adaptability is the property through which systems respond with certain outputs to given inputs. Modifying the internal structure of some systems in the context set by this property is called self-adaptability.

k) Causality - a system is causal if it's response for $t \geq t_0$ ($n \geq n_0$) depends exclusively on excitation and initial state of the system, usually $t_0 = 0$ ($n_0 = 0$). If the system is initially in a repose state and
\( x(0) = 0 \quad (x[0] = 0) \), then \( y(0) = 0 \quad (y[0] = 0) \), which is a causal excitation corresponds a causal response. In this case input quantities are called cause quantities and output quantities are effect quantities.

By causality we can understand the trivial fact that an effect can’t occur before the cause that and independent of it (non-anticipative system). A system is strictly causal if the effect occurs strictly after the cause. If effects or components that occur simultaneous with the cause exist, the system is called a borderline causal system. The following can be stated:

- an application \( \lambda \) (state function) exists and allows the determination of the evolution of the system state in time, if the initial excitation - state pair is known:
  \[ \{x(t), q(t)\} \xrightarrow{\lambda(t)} dq/dt = \dot{q}(t), \]
  in case of analogic systems
  \[ \{x[n], q[n]\} \xrightarrow{\lambda[n]} q[n+1], \]
  in case of numeric systems
- an application \( \mu \) (output function) exists and allows the determination of evolution of the system response in time, if the initial excitation - state pair is known:
  \[ \{x(t), q(t)\} \xrightarrow{\mu(t)} y(t), \]
  in case of analogic systems
  \[ \{x[n], q[n]\} \xrightarrow{\mu[n]} y[n], \]
  in case of numeric systems

Stability can also be found under the name BIBO (Bounded Input, Bounded Output). Ensuring stability is a major goal in systems design and control.

m) Accessibility of a state \( x_i \) should occur only if an input \( u_k \) exists in the interval \( (t_0, t_k) \) which leads the system to the output \( x_0 \) when in state \( x_i \). Detectability of an output \( y_j \) in state \( x_k \) it’s the duality of this concept and it needs to generate a significant output.

n) Structurability defines the need for any system to have a lot of intercorrelated component elements, so a specific structure. A system maintains its structure as an expression of maintaining the qualitative nature of the system (structural invariant systems); on the other hand, if the systems respond differently by the values taken by their states in relation to the inputs (commands) and change their structure over time, then we are talking about structurally variable systems.

o) Composability and decomposability refer to the property of a system to compose itself out of a finite number of subsystems and decompose itself in the same way. Decomposability is the base of system analysis and composability is the base of system development, both being important in system analysis and synthesis.

p) Finitude is the property of systems to be finite, in regards to the fact that real systems have finite input, output and state spaces; using these properties in system analysis allows to conceptually define categories of systems and using this base to create structural and functional typologies.

q) Linearity - a dynamic system \( S \) has the linearity property (is linear), if two conditions are met, which are: numerical sets \( U, X, Y, \Omega \) are organized as linear space on the same scalar set \( G \); state
equations have the additive and homogenous property in regards to the pair \((x_0, u_{[t_0,t_1]})\) for the explicit form or with the pair \((x(t), u(t))\).

r) For system equivalence we start considering the following dynamic system

\[ S = S(\Omega, f, g) = S(\Omega, f, g, x) \] (4)

in which the state vector is \(x\). Two states \(x_a, x_b \in S\) of this system are equivalent at the time moment \(t = t_0\) if the outputs deriving from these initial states for the same applied input are equivalent

\[
\begin{align*}
    x^a(t_0) & = (x^a, t_0) \approx x^b(t_0) = (x^b, t_0) \\
    \varphi(t, t_0, x^a, u_{[t_0,t]}) & = \varphi(t, t_0, x^b, u_{[t_0,t]}) \\
    \eta(t, t_0, x^a, u_{[t_0,t]}) & = \eta(t, t_0, x^b, u_{[t_0,t]})
\end{align*}
\] (5)

If two states are equivalent at the time \(t_0\) they remain equivalent \(\forall t \geq t_0\)

\[
    x^a(t_0) \approx x^b(t_0) \Rightarrow x^a(t) \approx x^b(t) \] (6)

If in a system exist equivalent states that means that the system, moreover the state vector \(x\) it's not in a reduced form, meaning that the dimension is greater than necessary to uniquely determine the output when the input is given.

s) Controllability and also state controllability can be achieved if inputs or commands are known or commands and state at a moment is known, only by doing so the state at the next moment can be generated. We can say about the system that is a globally controllable if for every output there is a class of input functions that generate them. When certain outputs can’t be determined applying the input functions, then we say that the system is partially controllable.

Let there be \(S\) a dynamic system. A state \(x_0\) at a moment of time \(t_0\), expressed by the pair \((x_0, t_0)\) is controllable in state \((x_1, t_1)\) if an admissible input exists \(u_{[t_0,t_1]} \subset \Omega\) that transfers the state \((x_0, t_0)\) into state \((x_1, t_1)\). If this property takes place for \(\forall x_0 \in X\), the system is called completely controllable; if in addition this property occurs for every interval \([t_0, t_1]\) that has margins, the system is called totally controllable.

4. CONCLUSION

As it was natural, the notion of system appeared and developed over time, as a result of highlighting common features and behaviors for a number of processes and phenomena in different fields of interests. The knowledge of the general and specific properties of the systems is particularly useful in the investigation, analysis, modeling, design and control phases of the systems. The properties that we mention characterize the majority of systems, in relation to the external environment (external properties) and in the relation with subsystems (internal properties).

Based on the criteria stated above and properties derived from the structural-unitary, causal-dynamic and informational character of the systems, they can be divided - delimited and grouped - into classes. The systems belonging to a class have similar properties and behaviors; so, they can be more easily investigated in this context.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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