From Classical Systems Thinking to Modern Dynamic Systems Theory: Beyond the System Structure and Properties

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Abstract: *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 Ludwig von Berthalanffy (1950), which represents a beginning of the Classical Systems Thinking zone, 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". In the same context, the present paper presents a natural continuation into the gradual transition from Classical Systems Thinking to Modern Dynamic Systems Theory, focusing on structure, properties and classification for different types of systems, mostly found in the specialized literature.*

Keywords: *Dynamic Systems Theory, system structure, system general & specific properties.*

1. Introduction

The Modern Dynamic Systems Theory (MDST) as a field of research, by itself, follows the study of the properties of various types of systems or "systemic approach", as well as the enunciation of sets of principles, independent of domain, substance, type or time [1-4].
By the emergence of the General Systems Theory (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, as part of MDST, have been opened [5-7]. The MDST is the symbiotic result between applied mathematics and "Systemology", its origins, as a mathematical theory [8], are especially situated through the multidisciplinary vision and the use of mathematical language and other specialized disciplines (see Fig. 1).

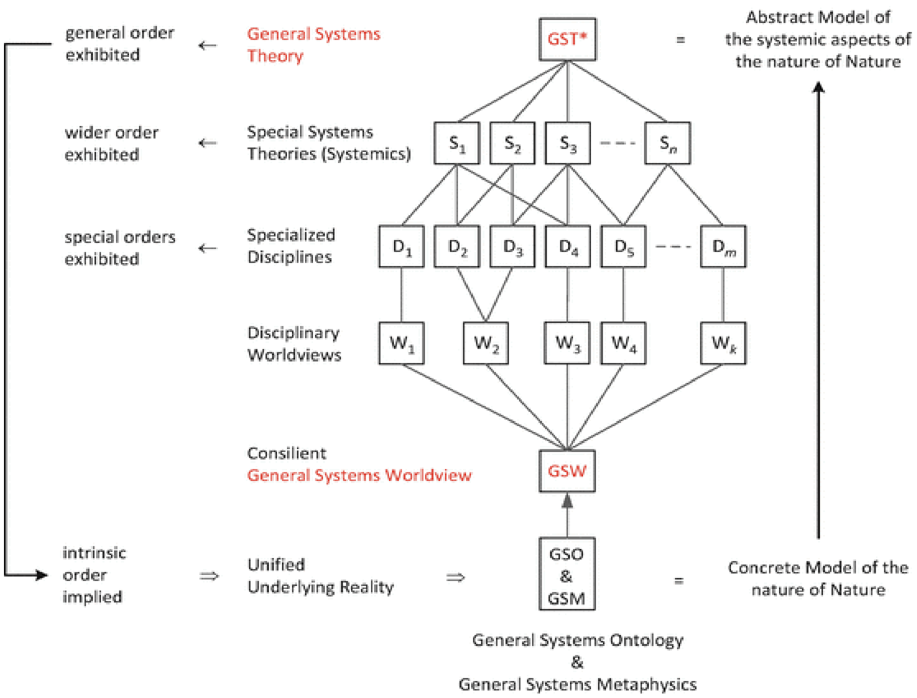

Fig. 1. The Modern Dynamic Systems Theory concept and its relationship with GST, GSO & GSM

As an interdisciplinary epistemological model, the GST represents a "*set of concepts, knowledge, methods and principles of independent applications, necessary and useful for the study of the structure, properties and characteristics of systems with variable degree of complexity*" [5-7, 9].
An extremely important notion, for the following approaches, which subscribes to the GST, is the notion of *system*. 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 [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 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, thus, 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.
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; 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.
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*", "*periodic system*" etc.;
- in politics, public administration and related areas: "*social system*", "*political system*", "*voting system*", "*parliamentary system*", "*presidential system*", "*monarchic 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*" 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*" etc.

2. Systems structure and elements

A system is structured as a connection of elements (see Fig. 2), 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.

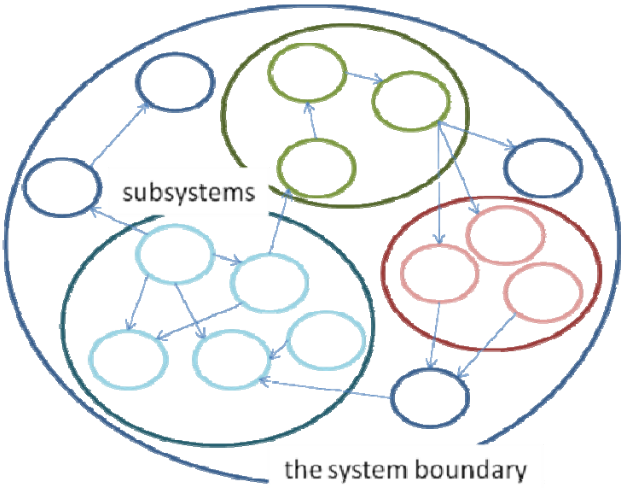

Fig. 2. The system and its relationship with subsystems

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 these 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.

3. General & specific system properties

A 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 (and/or electronic) 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* or *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.
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* (see Fig. 3), while the absence of one connection determines the *partially open* character. In the absence of both links to the environment, we are talking about an *isolated system*.

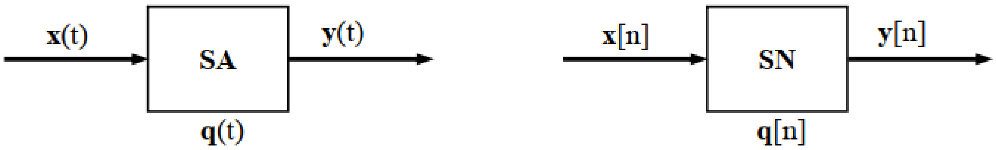

Fig. 3. Schematic representation of analogical and numerical systems

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.
g) *Time invariance* - a deterministic and causal system is time invariant if the applications λ and μ 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 $x(0) = 0$ ($x[0] = 0$), then $y(0) = 0$ ($y[0] = 0$), 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 λ (state function) exists and allows the determination of the evolution of the system state in time, if the initial excitation - state pair is known:

$$\{x(t), q(t)\} \xrightarrow{\lambda(t)} \frac{dq}{dt} = \dot{q}(t)\text{, in case of analogic systems}$$
$$\{x[n], q[n]\} \xrightarrow{\lambda[n]} q[n+1]\text{, in case of numeric systems} \quad (1)$$

- an application μ (*output function*) exists and allows the determination of evolution of the system response in time, if the initial excitation - state pair is known:

$$\{x(t), q(t)\} \xrightarrow{\mu(t)} y(t)\text{, in case of analogic systems}$$
$$\{x[n], q[n]\} \xrightarrow{\mu[n]} y[n]\text{, in case of numeric systems} \quad (2)$$

l) *Stability* represents the property of a system to recover to a state of equilibrium, having the same set of values for the state vector for a period of time, after the internal (external) cause of perturbation was removed. This property makes it so that at big variances in the inputs little variances in the outputs occur. If a system, during his evolution, goes through a perturbation, it exits the equilibrium state for the given moment, going to another state.

A causal and deterministic system is stable if the characteristic signals (the response and the state) are of the boundary mode, in case of an excitation of the bounded mode:

$$|x(t)| < M_x < \infty \Rightarrow \begin{cases} q(t) < M_q < \infty \\ y(t) < M_y < \infty \end{cases}, \forall t \geq t_0 \text{ , in case of analogic systems}$$
$$|x[n]| < M_x < \infty \Rightarrow \begin{cases} q[n] < M_q < \infty \\ y[n] < M_y < \infty \end{cases}, \forall n \geq n_0 \text{ , in case of numeric systems} \quad (3)$$

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

q) For *system equivalence* we start considering the following dynamic system

$$\mathrm{S} = \mathrm{S}(\Omega, \mathrm{f}, \mathrm{g}) = \mathrm{S}(\Omega, \mathrm{f}, \mathrm{g}, \mathrm{x}) \tag{4}$$

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

$$\begin{gathered} x^a(t_0) = (x^a, t_0) \approx x^b(t_0) = (x^b, t_0) \\ \varphi\left(t, t_0, x^a, u_{[t_0,t]}\right) \equiv \varphi\left(t, t_0, x^b, u_{[t_0,t]}\right) \\ \eta\left(t, t_0, x^a, u_{[t_0,t]}\right) \equiv \eta\left(t, t_0, x^b, u_{[t_0,t]}\right) \end{gathered} \tag{5}$$

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

$$x^a(t_0) \approx x^b(t_0) \Rightarrow x^a(t) \approx x^b(t) \tag{6}$$

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.

r) *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.

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 (all outputs or only parts of the outputs). 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 or admissible commands, then we say that the system is *partially controllable*.

4. Conclusions

As it was natural, the notion of system appeared and developed over time, as a result of highlighting common features and behaviours for a number of processes and phenomena in different fields of interest or domains of activity. The knowledge of the structure, even of the general and specific properties of the systems is particularly useful in the investigation, analysis, modelling, 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 behaviours; so, they

can be more easily investigated in this context, from the Classical Systems Thinking (CST) to Modern Dynamic Systems Theory (MDST).

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