A STUDY OF SYSTEM DYNAMICS FROM THE VIEW OF SYSTEM THEORY

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Abstract

Since L.V. Bertalanffy first brought forward the general system theory, people have been paying more attention to research work from the systems point of view, thus bringing about the development of some system scientific fields such as systems engineering, operations research and management science, etc.

Now, in addition to general system theory, there are many new subjects related to studying system dynamic behaviors and self-organization such as synergetics, dissipation structure theory, etc.

In this article, we study system dynamics from a philosophic viewpoint and try to study important points and methods that can be introduced by systems theory. We search into the relationships between system dynamics and other fields.

INTRODUCTION

With the constant development in science and technology, there has occured a developing tendency toward highly diversified and synthesized science and technology. Study methods, once isolated from each other, have entered a new era --- the general and systematical stage. In recent decades, new system disciplines have been emerging one after another. For example, the establishment and development of the general system theory of Bertalanffy, the cybernetics of Wiener, and the information theory of Shannon enable us to study various sorts of systems theoretically and practically in an increasingly extensive manner. The research work ranges from the concrete (e.g. technical, biological, or economical) study methods to the proposal for establishing a system of completed or trans-disciplinary system science. On the other hand, this trend attracts more and more people's attention to the analysis and study of rising disciplines.

System dynamics (S.D.), which studies complicated information feedback systems, was created at the same time as those disciplines above. This systematic discipline, however, has so far remained unfamiliar to scholars in many local areas and countries. This article will, from the angle of system science, study the characteristics of system dynamics and its particular viewpoints and methodology and analyse the connections and distinctions between this discipline and others.

As an new discipline , S.D. was first developed in 1956 by Jay W. Forrester at MIT. In the 50's and 60's, Forrester conducted in depth studies of industrial and economic systems as well as systems combining human, financial, and technical sectors. Through the analysis and study of the properties and characteristics of these systems, he obtained many important insights into systems with information feedbacks into and the essential structure of systems. With the constant expansion of the study range of S.D., its theories and methods are increasingly approaching perfection. For a long time, however, a great number of people have been fascinated by its applications, with little knowledge of its theories and basic ideas. Some of them even have taken S.D. to be merely a method of simulation or a component of certain disciplines. In fact, S.D, since its conception, has developed its own system. Being an independent discipline, S.D. has its own theoretical system and scientific methods. However, it has long been ignored as a result of its close connection with application. Whether in complicated systems study or in the establishment of large-scale, multi-variable, nonlinear system models, the essential assumption and simulations methods used in system dynamics are all based on certain system theories and methologies.

MAIN POINTS

With the help of computer simulation techniques, S.D. is an interdisciplinary science which is based on feedback theory combined with basic views of systems theory and application of computer simulation techniques. S.D. defines a system as a composition of different and interacting elements organically linked together to accomplish a function for a common objective. The prominent characteristic of S.D. is structure-function simulation, which differs from simple function simulation, such as blackbox simulation. It constructs the basic structure of a system based on the micro-structures within the system. The micro-structure of a system is thought to produce the macro-dynamic behavior of that system. Such models are much more suitable to the study of problems varying with time. Beginning with the relationships between the structure and function of systems, we shall research further into the characteristics of structure-function simulation of S.D. in the following paragraphs.

Structures and Functions

A system contains structures and functions. More exactly, a system is an integration of structures and functions. The structure of a system means the order of parts. The structure of a system depends on the characteristics of the parts and the interactions or the relations between them. The function means the order of process or the whole effect formed by the activities of elements themselves or the interactions among elements.

The structure of a system indicates the distinguishing features of the form of a system while the function indicates the features of the behaviors of a system. The difference between structure and function in a system is relative. They are mutually causal and mutually prerequisite. Under certain conditions the structure can be changed into function, and function changed into structure. They cannot be separated from each other.

Therefore, when analyzing and studying a system, we shall take into account not only its functional behaviors, but also its structure. Through the examination of the structure and function of a system alternately, a model will be built which can better reflect the actual system. This requires the collection and study of not only various kinds of data and diagrams that reflect the functions and the behaviors of a system, but also other information about the system structure or about the interrelations and the interactions between elements. This information is not merely a great amount of data, for statistical data represents only a small part of our knowledge of the world. Therefore, it reflects merely a part of the functional phenomena of a system. To construct a model of a system really, we must investigate in detail the causality of a system that the real world contains, and connect visible dynamic variations and invisible causality together.

With the use of logic and our abilities in analyzing and solving problems, the right knowledge or conception of a system can be developed, and then can be combined into the structures of simulations. This process, however, requires knowledge of the dynamic trends of a system and the interrelations between structure and the function, i.e., the relations of the feedback structure and the dynamic behavior of a system. In S.D., a feedback loop can be classified as positive or negative. A system is the composition of those positive and negative feedback loops in a certain way.

Therefore, when a system grows exponentially, there exists a positive feedback loop which plays the leading role in the system. When a system, after being disturbed, returns to its initial state, it indicates that there is at least one strong negative feedback loop in the system. Oscillation shows the existence of one time-delaying negative feedback loop or the existence of more than two negative feedback loops. S shaped growth is produced by connecting positive feedback loops and negative feedback loops with nonlinear links.

The interrelation between structure and function is not only helpful for us in analyzing the system model but also necessary to the process of building a model. When we construct a model of a system, it is helpful often to inspect the reference modes of the system.

Basic Structure of a System

Another prominent characteristic, when we study a system using S.D., is the essential structure of a system. S.D. supposes that the feedback structures are the basic elements constituting a system. A system is made up of elements, activities of elements, and information. Elements are the practical basis of the existence of a system, while information plays a critical part in the system. Depending on information, the elements of a system are constructed to be structure, and the activities of the elements bring into the behaviors and functions of a system.

The concept of the composition of a system was formed gradually with the development of science and technology. Especially information theory, as a sort of fairly strict concept, was not used until early this century. The information theory of Shannon describes the reality and measurements of information quantitatively.

Through studying the common law comparing the self-regulation function in organic systems and the automatic control function in machine systems, Wiener introduced the concept of information feedback from organic systems into machine systems. Thus, cybernetics was founded. In the meantime, Forrester was investigating the dynamic functions existing in industrial and socio-economic systems and introduced the concept of information feedback to the industrial and socio-economic systems. In fact, there is an obvious phenomenon of information feedback in socio-economic system. The problem is how to learn it. A structure (or theory) is essential if we are to effectively interrelate and interpret our observations in any field of knowledge. Without an integrated structure, information remains a hodge-podge of fragments. Without an organized structure, knowledge is a mere collection of observations, practices and conflicting incidents. "But now the concepts of 'feedback" systems seem to be emerging as the long-sought basis for structuring our observations of social systems." (Jay W. Forrester, PRINCIPLES OF SYSTEMS)

In a system, the basic structure is made of feedback loops. A feedback loop is a loop coupling state, decision making (executions) and information, which correspond to the three components of a system, i.e., elements, activities and information respectively. The changes of state variables depend on the results of decision-making or actions, and the decision-making (actions) process can be classified into two kinds. One is to depend on the self-regulation of information feedbacks (such a phenomenon exists universally in the organic world, society and machine systems); the other depends not on the feedback of information but on an intrinsic particular law. This phenomenon exists in the non-organic world, and information in this case, however, is not non-existent at all, but is only at a potential state and hence not utilized yet.

A feedback loop is a fundamental structure which is composed of states, decision-making and information. A complex system, therefore, is the composition of these interacting feedback loops, and the general function is produced due to their mutual connections and interactions with each other.

Wholeness and Level of a System

The wholeness and level of a system are the theoretical basis of S.D. to study and analyze systems by means of synthesis and decomposition principles. "The whole is more than the sum of parts". This point, originating from the thesis of Aristotle, has already become one of the important viewpoints in system theory. The characteristics of wholeness is different from that of elements, because the structure and function of the whole are different from those of the parts. This is known as the principle of wholeness. It represents the fact that as the different parts in a system interconnect and interact with each other to form a particular structure, the characteristics of the system have been changed. It is not merely a piling up of structures and the accumulation of functions by which a new specific structure and function are formed. A national system, for instance, is composed of production systems, finance and trade systems, transportation systems, and so forth. Obviously, the whole nation, as such a big system, should not be considered as the simple summation of these sub-systems. Therefore, when studying a system, we have to consider, with the viewpoint of wholeness, the feedback mechanisms and interrelations between the entire system and its sub-systems, and those among the sub-systems. We should never just simply put some sub-systems together to form the entire system.

Our emphasis on the wholeness of a system does not mean that a system has no level and hierarchy. The relative independence of elements and structures brings about a hierarchy of structure and then the hierarchy in function results because of the relative independance of processes and functions. The hierarchy of a system results because a system is an integration of structures and functions. When a system is being studied, it is of great significance to clarify the level and hierarchy of the system for the reason that a concrete natural law always implies the law of certain systems hierarchy. Laws of elementary systems penetrate naturally into advanced systems. However, the advanced systems have their own specific laws. They can never completely return to the laws of low level systems. Of course, we should not forget that the objective world emerges not only in the form of continuous development from elementary systems to advanced systems, but in the form of the transfer between different levels in a system as well.

Thus, we can lead to three important principles in system study or the establishment of a system model.

1) On the basis of the wholeness and the level of a system, the principle of composition and decomposition can be applied to the study of a system. We emphasize that a system and its whole effect should be studied from the viewp0int of wholeness. On the other hand, the concept of hierarchy and levels in a system implies that a system is composed of sub-systems of different hierarchy and levels. A complex system is composed of (positive or negative) feedback loops of different forms. Thus, by using the decomposition principle, we may dissect a system and analyze the structures and dynamic laws of a system step by step. First we analyze the relations between a system and its environment and determine the boundary of the system. Then we examine the levels of the system, analyze it and search for sectors of a system. Finally we gradually reduce the examination scope, paying particular attention to the feedback mechanisms and the structures of sectors. This process is called gradual focus. Meanwhile, when we analyze and study the mechanisms and the structures of a system, we should rely on the roughness-to-detail principle, i.e., from rough causal-loops to flow-diagrams which reflect the relation among variables, and eventually to the writing of DYNAMO equations. The decomposi-

tion process discussed above is of great importance to analyze and understand the internal structures and the feedback mechanisms of a system.

A process contrary to the decomposition process is the composition process, which is also necessary to system study. Although the decomposition process is important, we should never only stay at this stage. No matter whether it concerns the establishment of a model the study of dynamic behaviors and trends of a system, the final purpose of decomposition is composition. Only if every part and every sector of a system are connected organically into an integrated whole and the functions or behaviors of every part conform to that of wholeness, can the model be made to represent the entire effect and the entire structure of a system. Therefore, in the establishment and the tests of a model, we must gradually pass from the partial tests to the general tests, reform structures and behaviors of the system with the viewpoint of wholeness, and inspect thoroughly and systematically the internal structures and the feedback mechanisms of the system.

2) Various kinds of sectors of a system all have their natural special laws. We should not press the laws of the system upon the sectors. Neither should we mistake the characteristics of sectors to be those of a system, nor based on narrow experiences use characteristics of different sectors indiscriminately. The basic structure of a system is a positive or negative feedback loop. Just because the positive feedback loops and the negative feedback loops connect with each other, the structures of a system are formed and the distinguishing features of the behaviors of a system are produced.

3) To insure the adjustability of the entirety of a system, there must exist one or several dominant parts which show the hierarchical orders. The dominant parts of a system are the core of a system which will dominate the main structures and the functions of the system. They decide the changes and the developing trends of the system. Therefore, among the feedback loops within S.D. systems, there exists one or more dominant loops. The characteristics of these dominant loops and the interactions among them largely determine the characteristics and behaviors of a system. This is known as the principle of dominant parts function. The dominant parts not only exist in stable systems, but also in the evolution and the development of the system. In addition they exist in the course of transition from a previous stable state to a new one. Such a fundamental distinguishing feature, under some conditions, can allow us to capture main factors, and hence simplify the system model. It should be pointed out that the emphasis on the principle of dominant parts does not mean the abandonment of the fnnctions of other parts in a system. The dominant parts of a system can only be formed by the interactions between parts. The behaviors of a system are not completely determined by the dominant parts only; they are the results of the common actions of every part. In addition, under some space-time conditions, the dominant parts and the non-dominant parts can interchange.

Isomorphism of Systems

In the fields of nature, human society, and human ideology, there exist structural and functional similarities. These similarities are the isomorphism of systems. Often several different structures produce the same function, so that we can use one kind of equation or law to describe different fields and different phenomena. This is also the theoretical basis that we use in qualitative or quantitative systems studies.

Isomorphism is based upon the similarities of structures and functions instead of only similarity of functions. Therefore, when we talk about the isomorphism of one system with another system, it strictly means they are similar in structure and function. When creating a model for a system, we can not simply simulate the functions of the system. Rather should we construct its structure which can truly represent the system. Such a model is more objective and can more scientifically describe the real world than the model which does not consider the structure similarity.

For a long time, system dynamics was described in this way. Its purpose was to link the laws and theories of the systems of different fields. It was based only on the isomorphism of systems. S.D. unifies the basic structures of systems by feedback loops and simulates the different features of systems by functions of SMOOTH, DELAY, SWITCH etc.. Thus, we build aS.D. model that can represent the real system in both structure and function. When building S.D. models of different systems, we find that there exist many similarities among different systems in dynamic behavior and internal feedback structures. For instance, birth and death rates of populations and capital investment, discarding rate of industry have the same interrelated positive and negative feedback loops with a delay function in structure. Therefore, from the view of their structures, they are isomorphic. So we can deduce that their dynamic modes may be exponential increase or decrease or oscillation, but not the S shaped mode. As another example, the exponential law is also called "natural increasing law". It can represent the increase of capital or interest in economics. In sociology, it is called the Malthus Law, which represents an unlimited increase in population. In scientiology, it can represent the development of science and technology, and so forth. We find that, in these different systems, their major structures are always positive feedback loops. Through research about the isomorphism in structure of these different systems, it is helpful to raise up the analogous description of systems to their logical homogeneous description. Then we can elevate the special law of any system to a higher degree in order to build a foundation for the general theory about structure and function of systems. At the same time, it also provides a convenient study of the specific structure and laws of a particular system.

System dynamics has been widely used in many fields such as socio-economic systems, population, energy, transportation, etc., ranging from enterprises to professions and from cities to the whole country and the world. Various kinds of S.D. models have appeared continuously. This provides a good base on which to build a "standard model" with standard units. We should never build a model simply for building it, but should study its special behaviors, laws and structures in order to make the research on systems more and more standardized and generalized.

Viewpoint of Interrelation

Interrelation represents the general relationship between the whole and the part; the part and the part; and the system and the environment. We must think in terms of relationships between element motion and information in mutual interaction.

S.D. studies the interrelations between elements within systems, or in other word, the causality. Whether in socio-economic systems or in engineering systems, the phenomenon of mono-cause-multi-effects, and even sometimes the phenomenon of the crossing of causal links exist. With the expansion of our study range, the past single causal relations are becoming more and more unreasonable. Consequently, there arises the need to have a more reasonable causality which can better represent real relationships. S.D., as a discipline that studies general system dynamics behaviors, also requires this.

With the development of knowledge of system structure, the knowledge of causality has undergone several stages ranging from mechanical causality to statistical causality and now to feedback causality. The basic structure of a system dynamics model is the feedback structure; in other words, the system structure that S.D. studies is dependent upon the causality of feedbacks, which is one of the important stages in the study of systems. If we further dissect the feedback loops of systems, we can find that the causality among elements in the feedback loops are all in mechanical and statistical forms. They are in the forms of traditional statistical relations or traditional logical relations. These relations are applicable only in the description of clear-cut or predictable interrelations. With the increasing expansion and depth of the study range of S.D., the phenomena and problems which we are facing are becoming more and more complicated because of the involvement of the human element, the multiplicity of objectives, and the diversity of behaviors. These problems cause the interrelationships among elements to be such more vague and complicated. This makes the methods for describing current systems somewhat outdated.

In an economic system, for instance, the capital allocation among different econimic departments, the determination of the proportion of accumulation and consumption, and the requirements for education and technology development through economic growth all include a process of thinking, selecting, identifying and decision-making. This requires us to have a method which is able to describe this kind of causality. In fact, the process of thinking stated above is set up on the basis of causality of feedback. Therefore, by means of S.D. theory and the combination of other theories (e.g. the disciplines applied in the description of vague causality), a method that can represent the vague causal relations and describe the process of thinking and decision-meking needs to be established. This will be helpful in expanding the study range of S.D. and in increasing the validity of the S.D. model.

CONNECTIONS AND DISPARITIES WITH OTHER DISCIPLINES

In recent years, with the endless increase of study research topics, and the continuous emergence of transversal disciplines and overlapping disciplines, it is necessary for S.D., as a systematical discipline, to study the characteristics and the methods of other disciplines. It is necessary to study the relationship of S.D. with these disciplines, and to draw something worthy for reference from them in order to complete and improve the theories and the methods of S.D.

Synergetics and System Dynamics

At present, there is a new notable discipline in the realm of systems study--synergetics, which is a discipline concerning a systems' self-regulation. A popular example of self-regulation occurs, when the workers in a factory behave in a certain way according to the instructions given by the president. We say that this system has an organization and possesses the functions of an organization. When the workers behave in an actively and coordinated manner in accordance with some mutually tacit regulations, the process is called self-organization. Generally speaking, if a particular structure and functions are actively formed on the basis of some rules without continuous external instructions, it is termed as a phenomenon of self-organization.

According to self-organization theory, a system is able to evolve from the state of disorder to a state of stable order and is also able to move from a structure in good order through a state of disorder to a structure in a new stable order. For a system to change from disorder to order and keep the stable orderly structure, it is necessary that the system exchange energy and material with the external world. This is known as an "open system". It is also required that the "open system" lie far away from the equilibrium state and that non-linear relationships between the elements exist within the system. Disorder means that the independence of elements in a system is in the dominant position. In this case, there is no significant evidence to show the connected structure of the system entirely. When a system is in a disordered state, a stable pattern and an unstable pattern mode must exist. The stable pattern, which corresponds to the fast relaxing variable, restrains against stimulations or disturbances. Synergetics believes that the influence of the stable pattern in the course of changes of a system can be neglected.

The unstable pattern, which corresponds to the slow relaxing variable, however, dominates the process of the change of a system and determines the macro-behaviors of the system. Synergetics calls it the order parameter. The order parameter responds strongly to the external influences and the internal fluctuations of systems. Under certain conditions, it will bring the system into a new stable structure.

At present, most of the systems that S.D. studies are non-linear and open systems which are far away from the equilibrium point.

In these systems, a stable structure is formed due to the interactions between the elements and develops and evolves according to certain laws. Consequently, S.D. models are established on the basis of orderly stable systems; they do not include the evolution of systems from disorder to order.

A stable orderly system, however, can possibly change into an unstable system. Thus, the system becomes more chaotic and disorderly, or even collapes. A nation, for instance, when threstened by an energy crisis, may experience business going bankrupt, increasing unemployment, and skyrocketing prices, which make the economic system change from a stable orderly state to an unstable disorderly state. This may in the end, cause the economy to collapse entirely. Therefore, as a discipline that studies the long-term dynamic behaviors and the phonomena of systems, S.D. should consider structural changes in systems, and causes and factors which bring about great changes, especiall those factors which cause systems to change from orderly states to disorderly and chaotic states.

In a S.D. model, one or more dominant loops or sensitive parameters exist. A negative feedback is always able to resist external disturbances and internal fluctuations to a certain degree, while a positive feedback loop or sensitive parameter is easily affected by such disturbances and may even magnify the effects of disturbances and fluctuations. This may lead a system to disorder. Because of nonlinearity, a stable system, that is, a system in which the negative feedback loops play the dominant role can be changed into a unstable system in which the positive feedback loops play the dominant role in some period.

In synergetics, fluctuations are considered to be the crucial cause of systemic changes. In a system, many parameters which possibly give rise to fluctuations must exist. Once a system is in the critical state, fluctuations may result in great responses that effect the system. These may be only in a small range at the beginning, but in the whole system at the end. The responses will carry the system from order to disorder or from an old structure to a new one. Accordingly, when analyzing and studying a model, we should not only seek good plans and policies but also devote work to those unfavorable factors that may cause changes in a system. In other words, we are required to pay special attention to those positive feedbacks and sensitive parameters, as well as fluctuating points, which may bring about the great changes in a system. It is necessary to study the degrees of their effects, to find out the critical factors that result in the changes in a system, and to try to find a method which is able to control and identify the changes in a system.

In self-organization theory, the slow relaxing variable, playing the dominant role in the activities of a system, is used as the order parameter to describe the activities of the system. Order parameters are applied to describe the kind and degree of order of systems. The Liapunov function is employed to judge whether a stable structure has formed or not, and catastrophe theory is used to determine the forms of a system structure according to the kinds of order parameters. Many S.D. scholars, however, think that the principal factors determining the activities of a system are the dominant loops which represent the dominant structure of a system. The dominant loops are frequently replaced due to the variations of the nonlinear factors and the parameters within the system and the influence of the exogenous variables. Thus, S.D. scholars are now attempting to look for and evoluate the dominant loops by means of eigenvalue analysis and the principles of Liapunov. These are helpful in the study of the structure and the dynamic behaviors of a system, as well as for the simplification of models.

Econometrics, Economic Control Theory and System Dynamics

In the realm of economic systems, several schools of thought have developed which quantitatively study economic laws. Two typical types are econometrics and economic control theory. The former is a field that uses the tools and concepts of the two disciplines--statistics and economics; the latter is a discipline that introduces control theory into the realm of economics. Both of them pay special attention to the accuracy between the model and the statistical observed values of real systems and establish a model on the basis of statistical methods and differential equations. Most of the economic theories are static rather than dynamic, and traditional mathematical tools have great difficulty in analyzing and studying nonlinear relations. Therefore, it is rather difficult for them to represent complex and nonlinear dynamic systems.

At present, control theory is only successfully applied in linear systems. In nonlinear systems, its theory and application meet with difficulties, which limit its applied range and fields. Control Theory mainly studies the characteristics around the equilibrium point or the operating point of a system, so that it is difficult to use for long-term study. Econometrics and Control Theory, however, have many skills with respect to the definition of the precision of a model and the determination of the parameters, and are suitable for short-term and precise predictions.

In contrast to the above fields, S.D. seems to focus more attention on the internal mechanisms and the structure of a system and more emphasizes on the information feedbacks and the interrelations between elements. S.D. supposes that the data reflect only one side of a system. It also supposes that in a socio-economic system there are not only definable and precise relations, but also vague and random factors. These relations and factors are very difficult to solve by traditional mathematical methods.

CONCLUSIONS

Nowadays there is no doubt that system dynamics is a branch of Systems Science.

If the science systems in the past have been classified into two major catagories, social science and natural science, then systems science, a frontier discipline which combines natural science and social science, should be added to the current science systems.

Systems science studies mainly the types, the general patterns, and the laws of activities of systems. It consists of two aspects -- theoretical methods and practical engineering applications. Currently, among those which have been successfully applied in engineering are management engineering, engineering control theory, economic control theory, econometrics, etc.; and in theory are general system theory, cybernetics, information theory, operations research, etc.

Now, as a systematical discipline which studies the dynamic behavior of general system theory, S.D. should become an important branch in systems science. From the aspect of its development and study range, it has gone far beyond mere applications. Its theories and methods can not only be directly applied in simulation and analysis of actual systems but also can provide the study of the structures and the functions of general systems with a theoretical basis. S.D. therefore is not only a method of analyzing systems by means of simulation techniques, but also a systematical discipline which studies dynamic behaviors, internal structure, and the functions of general systems.

S.D. has been developing for 30 years. During much of this time, S.D. has mistakenly been viewed as only a means of stimulation or an equivalent of DYNAMO by people being strangers to the field. And its position in system science has not been fully discussed and studied. With the development and popularization of S.D., it becomes increasingly important field. Nowadays, system dynamics has been developing as a bridge connecting social science and natural science. Moreover, it is expected to be a powerful tool for promoting the creation of a complete hierarchy of system science.

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