System dynamics main concepts

The system dynamics method proposed by J. Forrester follows the development and application of the concept of systems thinking in many areas of research (including engineering, energy, computer science, medicine, management). The idea behind systems thinking is the need to analyze the system as a whole, taking into account the interactions of its elements (cause-effect relationships, feedback loops), as opposed to considering only the individual elements of the system.

It is assumed that the system concept is characterized by:

- construction of the system from elements, subsystems (the system as a composite of interacting, not necessarily synergistic elements);

- Separation of the system from the environment (well-defined boundaries with the environment);

- the function performed by the system (the system performs a set function);

- variability of the system's behavior over time.

The general characteristics of a system are consistent with the definition describing a system as "...a collection of related elements, organized coherently, in such a way as to achieve an established goal." On the other hand, when modeling and numerical simulation using the systems dynamics method, it is important to consider and adopt the assumptions introduced in cybernetics. They define the system as a functional whole separated from its environment and take into account the influence of the environment on the system under consideration through input signals. They also take into account the interaction of the system with the environment via output signals. In addition, systems theory takes into account the separation of systems: causal - concerning the cause and non-causal. The method of systems dynamics is used to conduct research on causal systems, whose operation (output signal, system response) depends solely on the present and previous values of input signals. Systems whose output depends on the predicted values of input signals are referred to as non-causal.

The SD method distinguishes 3 categories of variables: input U(t), output Y(t) and state X(t) (Figure 1).

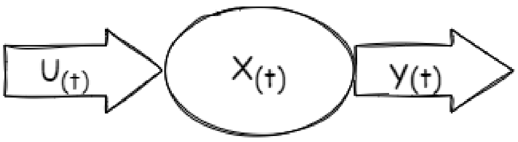

Figure 1: Variables in the SD method.

In a causal system, the value of the vector of output variables Y(t) at time t depends on the current value of the vector of input variables U(t) at time t and the past values of the input variables, e.g. U(t-1), U(t-2),.... If, on the other hand, the system is not causal, then the value of the vector of output variables of the system depends on the predicted values of the vector of input variables, e.g. U(t+1), U(t+2),...,. Thus, such a system cannot be realized in real time. State variables X(t) in systems analyzed using the SD method reflect the history of changes in the values of input variables and output variables. The input and output variables can be identified with the flows of the medium both feeding the system and flowing out of the system. The vector of state variables, also referred to as "system memory," is expressed by an integral equation:

$$X_t = \int_{t_0}^{t_1} (U_t - Y_t) \mathrm{d}t + C \qquad (1),$$

Where: Ut - vector of input variables at time t∈(t0,t1), Yt - vector of output variables at time t, C - vector of state variables at time t0.

J. W. Forrester, the creator of the method of system dynamics, stated that "Integration (accumulation) is the cause of the temporal nature of behavior, causes delays between flows and induces dynamic behavior of the system." Such an approach to the dynamics (time variation) of the system was also adopted by R. Lukaszewicz the pioneer of systems dynamics in Poland and J. Sterman. The introduction of the accumulation issue into the characterization of system dynamics also has an additional practical factor - integration occurs in nature, both in biological and technical systems. Therefore, it is easier to adopt the basic assumptions of the system dynamics method.

Performing the process of numerical simulation requires the development of a model reflecting selected parameters of the behavior of a system or the course of a phenomenon. Numerical simulation of a system has been defined as "the technique of solving a problem by observing the performance over time of a dynamic model of the system." In the SD method, the model takes the form of a structure of related elements defined in a computer simulation environment. The rules of behavior of these elements and their interactions are described by mathematical relationships. According to Sterman, there is no universal modeling procedure that guarantees the development of a correct model and its full utility. Thus, modeling is an inherently creative process, and usually model developers have different goals and make different assumptions and approaches to achieve them. The application of the systems dynamics method, however, requires the completion of certain work steps. The formulation of the problem and determination of the purpose of modeling is stage 1. In stage 2, the main factors characterizing the scope of the research task, cause-effect relationships are determined, and the boundaries of the system (conceptual model) are established. These are the input data for describing the scope of the issue and developing the pattern of cause-effect relationships. The cause-effect diagram contains the main dependencies and feedback loops between the elements of the system under analysis. The established cause-effect dependencies are the basis for the development of a structural diagram containing a formal description of the dependencies in Step 3. The developed version 1. of the formal model is applied to the numerical simulation of the process. Comparative analysis of the simulation results of version 1. of the model and the results of the real system form the basis for its verification and validation. The developed model in stage 4, by correcting the model structure and component characteristics is brought to the correct level of accuracy. Verification and validation of the model enables the implementation of stage 5 - the numerical simulation experiment. Typically, the specified values of the model's decision variables are modified to control the degree to which they affect the behavior of the system, such as the change in performance. Comparative analysis of the results of the simulation process before and after the adjustment of the model's decision variables makes it possible to determine, the degree of their influence on the characteristics of the system. The final stage of the modeling process (6.) is the implementation of changes in the real system, determined during the analysis of the results of the simulation experiment. The system modeling procedure used in the SD method is cyclic - it often requires returning to previous steps and correcting them.

It was determined that the key role in the development of the model concept is played by the established cause-effect relationships, the model structure and the adopted patterns (patterns) of system behavior. These tools are used, among other things, to establish and refine the assumed concept of system dynamics, communication with its stakeholders, also to prepare detailed model specifications.

Causal Loop Diagram (CLD) is the basic and one of the most widely used tools in SD modeling. Analysis of the literature data indicates that CLD diagrams are easy to use primarily at the initial stage of the modeling process for developing an initial hypothesis of system dynamics. Thus, the CLD scheme is an effective tool for both the accumulation of knowledge (including knowledge transferred in a non-formalized manner) and the mapping of the actual characteristics of the system under study. It facilitates concentration on the assumptions that underlie cause-effect relationships. The intuitive notation of the structure of the system makes it possible to consider it, for detailing the assumptions made and correcting the model. It should be supplemented that CLD schemes also have some limitations. The main one is the lack of distinction between flows and resources, and between physical and information flows. They also do not allow to distinguish the nature of dependencies between system elements (e.g. linear and non-linear dependencies). In addition, there is a danger that their introduction, without the adoption of a common conceptual scheme among the system's stakeholders, can lead to the formulation and adoption of an incorrect model, and at the same time to erroneous inferences about the dynamics of the system. CLD diagrams contain the elements of a system, along with the relationships linking them of the type and direction indicated. Causal relationships are positive (+) or negative (-).

The positive relationship (Figure 2) means that an increase in the value of the cause, leads to an increase in the effect above the state, achieved without an increase in the cause. Conversely, decreasing the value of the cause leads to a decrease in the effect below the value achieved without decreasing the value of the cause. A positive cause-effect relationship describes, for example, the effect of service quality on sales value (Figure 2). This relationship indicates that an improvement (increase) in the quality of customer service results in an increase in the value of sales above the level that would have been achieved without an increase in the quality of service (sales are also increased for other reasons, including price reduction, improved product quality, fashion). A positive relationship also means that a decrease in service quality is accompanied by a decrease in sales value below the level that would have been achieved without a decrease in service quality.

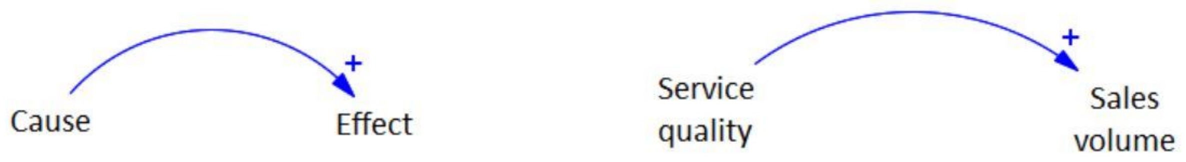

Fig. 2 Positive cause-and-effect relationship

A negative cause-effect relationship, on the other hand, indicates that for an increase in the value of the cause, the value of the effect decreases below the level that would have been achieved without the increase in the value of the cause. For a decrease in the value of the cause, the value of the effect increases above the level that would have been achieved without the decrease in the cause (Figure 3). The negative cause-effect relationship is also used to describe many economic phenomena and processes. For example, it maps the effect of customer service time on the value of sales (Figure 3). Increasing (increasing) service time reduces the value of sales below the level that would be observed without increasing service time. Conversely, a reduction (decrease) in service time results in an increase in sales value above the level achieved without a reduction in service time.

Fig. 3 Negative cause-and-effect relationship

The demonstrated basic types of cause-and-effect relationships are usually combined in complex dependency structures. Especially noteworthy are feedback loops . Feedback plays an important role in cybernetics, automation, mechanics and electronics, among others. According to control theory, feedback loop interaction occurs when the output signal of a system simultaneously interacts with the input of that system. In the systems dynamics method, the occurrence of a feedback loop indicates a certain property of a system component. It means that the component interacts through the succession of a chain of cause and effect relationships. Positive and negative feedback loops are distinguished, as for cause-effect relationships.

A positive feedback loop with respect to a particular element of the system indicates that a change in its characteristics triggers a new change in the same direction after a certain period of time (Figure 4). The inflation model, for example, results from positive causal relationships between the cost of production and the price of the product, the pressure on wages and their amount affecting the cost of production (Figure 4a). Another example is the model of increasing machinery productivity, as a result of positive causal relationships between production volume and sales revenue and investment in machinery development (Figure 4b). Often positive loops are referred to as the "snowball effect" or "vicious circle." To emphasize the importance of the occurrence of two possible directions of change in the state of the system, or its components, one should also point to the statement: "The rich are getting richer and the poor are getting poorer".

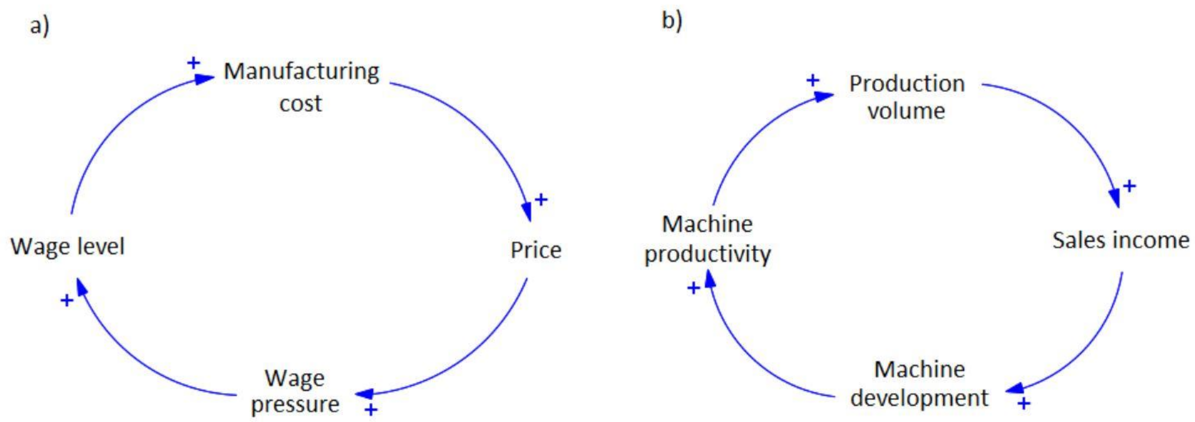

Figure 4: Positive feedback loop diagram: a) inflation, b) increasing machine productivity

A negative feedback loop, on the other hand, is formed when a change in the characteristics of a system component is offset by an action that produces the opposite effect to the change (Figure 5). This type of loop is referred to as "stabilizing (equilibrium) feedback." A stabilizing feedback loop includes an autocorrection mechanism to achieve a certain level (value) of the signal. An example of a stabilizing feedback loop with a fixed level that the system strives for is the process of filling a tank with liquid. The degree of opening of the valve positively affects the flow rate of liquid entering the tank. A positive cause-and-effect relationship also exists between the liquid flow rate and the instantaneous liquid level in the tank. The control of the set liquid level in the tank performs the function of an autocorrection mechanism in this system. The value of the difference between the set liquid level and the actual liquid level has a positive effect on the degree of opening of the valve (a larger volume of liquid to be injected into the tank causes an increase in the degree of opening of the valve). For a complete description of this system, there should be an addendum that a higher actual liquid level leads to a decrease in the value of the difference between the set and actual levels - there is a negative cause-effect relationship here. Another example is an increase in the cost of production development resulting in a decrease in profit. Consequently, it leads to a reduction in investment in production development and a reduction in the rate of production development and, consequently, a reduction in costs.

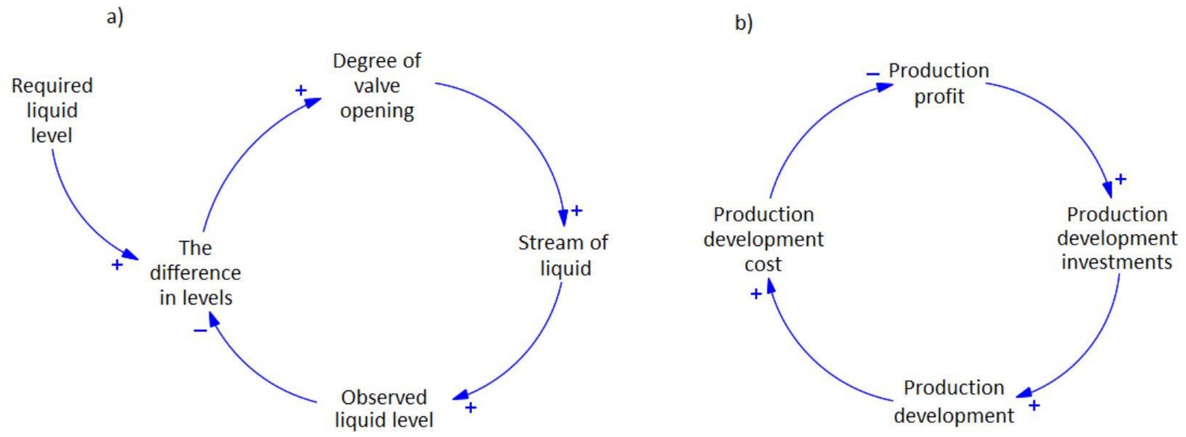

Fig. 5. Negative feedback loop diagram: a) filling the tank, b) investment in production development

It has been established that an important step in the development of CLD schemes is to correctly determine whether the loop under consideration is positive or negative. Used often, the correct way to proceed is to show the degree of development of a change in the state of one of the elements in the loop. When the coupling causes an amplification of the change value (another change in the same direction), then it is a positive loop - otherwise it is a negative loop. An alternative way is to determine the number of negative cause-effect relationships in the loop. When their number is even then the loop under consideration is positive (positive). An odd number of negative cause-effect relationships indicates that the loop is negative. Usually, to facilitate the interpretation of cause-effect diagrams, the designations of the identified positive (reinforcing) and negative (stabilizing) feedback loops are introduced (Figure 6). The direction of the loop designation does not determine its type and should be consistent with the pattern of causal relationships forming the loop. However, it is recommended that the loops be additionally described and labeled.

Fig. 6. Designation of feedback loops: a) positive and b) negative.

R - positive loop (reinforcing loop), B - negative loop (balancing loop).