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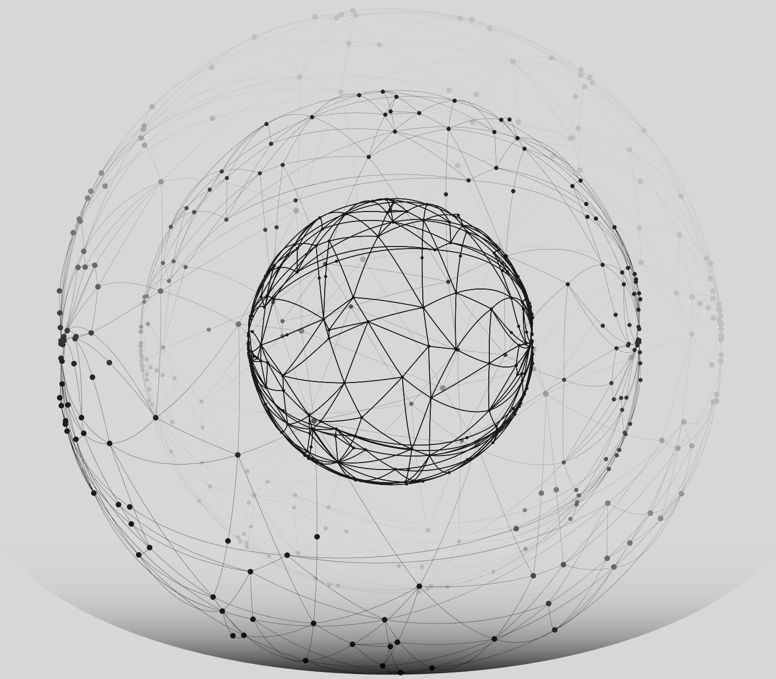
Oleksii Tuhai

DESIGN AND ASSESSMENT OF TECHNOLOGICAL SYSTEMS



Lublin 2021

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Preface

The modern epoch is characterized by fundamental changes both in science and in technological principles of various production, and in the activities of mankind aimed at solving specific problems. This fully applies to the intensification of technological processes that are carried out by machines and equipment of processing production. This is due to the rapid development of fundamentally new approaches and ideas for studying and discovering the potential of new generation machines and their impact on technology. Even referring to the times of the ancient period of making axes and spears, we can attest the appearing of the possibility not only to chop and hunt, but also to represent methods of production, while these processes are considered themselves as forms of human activity. Therefore, a particularly important point is to define a scientific paradigm that encourages the solution of the urgent issue: increasing the productivity of machines and equipment under conditions of high quality of the obtained material or product with minimum values of energy and materials consumption.

An essential methodological technique in solving this issue is the application of a system approach, the epoch of its origin was characterized mostly by the consideration of systems of physical and philosophical origin. In such a case, the Aristotle's postulate: "The importance of the whole is higher than the importance of its components" was later replaced by the postulate of Galileo: "The whole is determined by the properties of its components".

The current state of systems theory and system approach was formed under the influence of achievements of both classical branches of science (mathematics, physics, mechanics, etc.) and non-classical fields (synergetics, computer science, theory of nonlinear dynamics, dynamic chaos, catastrophes). Such a system approach, enriched with new methodsand models is crucial in the study of the constructional design foundations and construction of machines, equipmentand apparatus of processing production.

The idea is to combine different technological processes on the basis of existing branches of material production and to create a generalized idea of interaction processes between the working tools of different machine classes with technological materials.

This material is based on the results of research and scientific literature, the list of which is given at the end of the textbook.

We express particular gratitude to the reviewers for valuable comments and suggestions in preparing the textbook manuscript.

Introduction

The textbook "Design and assessment of technological systems" sets out the basic provisions of the structure and content of technological systems, processes of modeling and constructional design of technological systems.

System analysis was used as the main method. The above information is a prerequisite for the transition of synthesis to a higher system of knowledge in comparison with the analysis. Synthesis is a full picture of the technological system (phenomenon, process, object) and considers the interaction of its parts and their mutual influence and connection. This process requires a deeper knowledge of systems theory, systems techniques, mechanotronics, the theory of optimal decision-making, criteria for estimation constructional design methods and the creation of highly efficient technological systems.

In systems theory, the causal process is called the input, and the consequence is the output. Another fundamental concept of systems theory is the concept of system state. On the basis of these concepts of the systems theory, the issues of the analysis modeling, synthesis and management of technological systems of various physical nature are solved. Especially, it is subject to the processes of creating new and modernizing the existing technological systems with ensuring their efficient operation. These basic provisions of technological systems and their elements are set out in this textbook.

The first chapter is devoted to the basic concepts and definitions of systems theory. The connection of this theory with other system disciplines is shown: system analysis and system approach. The problems of solving the main issues of systems theory are considered. The classification of systems, their functions, formation and structure, as well as the basics of their formal description are given.

The second chapter provides a definition of the technological system. There are given examples of an organizational and production system, a system of interaction "machine-environment", a system of machines for operating a given technological process, as well as a working machine system that consists of separate subsystems. It is shown that in solving the issues of modeling, analysis, synthesis and management any of these systems must be considered from the standpoint of systems theory.

In the third chapter, the question of modeling of technological systems is considered. The classification of models is given. The high attention is paid to the issues of physical and mathematical modeling of systems. Examples of modeling of specific technological systems are given.

The fourth chapter presents the analysis and synthesis of technological systems. The essence of the issues of analysis and synthesis of systems is shown and the structure of their solution is given. The definition of the concepts of optimal and suboptimal synthesis of technological systems is presented. Some problems that are arising in the practical solution of optimal synthesis issues are considered. The method of morphological analysis and synthesis of technological systems is examined. Specific examples are given.

In the fifth chapter the statement of management of technological systems issue is given. The issue of optimal management is set and the solution of this issue by different methods is shown.

The sixth chapter is devoted to the process of constructional design of the technological systems based on its development model. The main tasks of the designer are to create technological systems to meet the customer's needs and to take into account modern requirements in terms of operational indicators of finished products.

The main purpose of writing this textbook was to develop in the reader the ability to systematically consider the issues of technological systems and provide practical methods for their solution. To do this, it is necessary to consider the technological system as a process of interaction of its elements in time and have a clear idea of the theory subject and its main issues.

Chapter 1. Basic concepts of systems theory

Contents of Chapter 1

Keywords: system, system analysis, systems theory, systems classification, abstract systems, hypotheses, theories, scientific knowledge, linguistic systems, logical systems, complex system, system formation, element, element indivisibility, system decomposition, system function, system structure, input and output.

1.1. NOTION AND DETERMINATION IN THE SYSTEMS THEORY

The notion "system" is derived from the Greek word sistema, which means "a whole that is compound of parts, or a connection (combination)". The modern notion of the system is formulated within the framework of the general systems theory. It is known as a set of elements that are in relationships and connections between themselves and form some integrity, unity to achieve the goal. In this case, the goal is a set of results that are determined by the purpose of the system. The availability of purpose forces the elements to be connected into the system, i.e. there is a need for integrity – the most important system property. The element belongs to the system because it is connected with its other elements, so that the set of elements that compound the system can not be divided into some subset. Removing the element or a set of elements from the system causes changes of its property in a direction other than its purpose.

The term "system" has appeared in the scientific literature long ago. This term is most commonly used in mechanics, where it denotes the material system, i.e. the set of material points that are subordinated to certain connections. The main interest for these systems is the dynamics problems, which reveal the causal mechanism of their movement. The laws of dynamics (or the laws of the functioning of mechanical systems in modern terms) have been obtained in a long inductive way. The proposed hypotheses have been tested in numerous experiments. Some of these experiences have become classic. Numerous consequences of the proposed hypotheses were also tested. All this was implemented through the ability existing in mechanics, as well as in most other physics branches, to carry out "pure experiments", i.e. to eliminate harmful factors. Besides, conditions could be reproduced with rather high accuracy at other times and in other places.

Recently, three "system" notions have been widely used in the literature: "system analysis", "system approach" and "systems theory". People quite often put a sign of identity between them, which leads to some confusion. Since we are going to talk about systems theory later, we need to clearly define all these terms.

The word "system" and its related terms have become increasingly popular lately. This is due to the increasing need to study complicated complexes (systems). Such need is determined by the dramatic complication of the created technical structures, devices, technologies and the whole set of business relationships that economists and business managers have to deal with. The need to study biological objects and environmental problems, which are becoming more and more relevant every year, also leads to the study of complex systems.

Due to the need to study complex systems, the discipline of "System analysis" emerged, which is a continuation of the study of operations [1] under uncertainty. There are cases when it is impossible to set goals at all, or the goals we want to set are unrealistic. Examples of such situations are given to us by the economy, when some indicators are planned, but in reality we have completely different ones. In this case, it is necessary to have a models system, to create such a mathematical tool of their analysis, which would be able to realistically predict certain consequences of our decisions, evaluate our capabilities under different alternatives, and formulate goals only on the basis of such system analysis.

The systems complexity, being studied or designed, leads to need to create a special, qualitatively new technique of research, which is called imitation systems – specially organized systems of mathematical models. These models, using computer technology, reflect the complex functioning, being designed or studied.

Investigating the dynamics of a process that allows seeing perspectives and identifying goals is only one aspect of system analysis. Within the framework of system analysis, problems of hierarchical organization designing are studied. Any more or less complex systems are always organized on a hierarchical basis, since centralized information processing and decision making are often impossible due to the large amount of information that must be collected and processed. In the designing of technical systems, the task of system analysis (the task of the designer) is, first of all, in the development of the functional scheme (which can be implemented in many ways) and in the definition of individual goals of the system.

In relation to technical systems, more complex systems are economic complexes, the functional elements of which depend on how they are managed by people. Unlike a machine, people always have their own goals and interests, and it is not enough for a system designer to just formulate goals for the lower links. Additionally, you need to be sure that these goals will be met, i.e. the lower links meet the requirements of the upper links. Moreover, for that, a special system has to be designed.

Hierarchical systems theory, which deals with some aspects of this problem, is one of the most important parts of system analysis.

Thus, "system analysis" is a technical discipline that develops methods of designing complex technical and economic systems, organizational structures, etc. Along with the term "system analysis", the other term – "systems theory" has become widely known.

The emergence of "systems theory" is associated with the name of famous biologist Ludwig von Bertalanffy [2], who organized a center of systems researches in Canada in the 50s and published a large number of works, including books in which he tried to find the common, which is inherent in any rather complex organization of matter, both biological and social.

However, much earlier, the Russian scientist Bogdanov A.A. created the organization theory [3]. In his work, Bogdanov A.A. introduced the organization notion as one of the original concepts. Matter exists in time and in space. It always has the organization. At the same time, the organization can not be imagined without a material carrier.

The basis for theory formation Bogdanov A.A. considered that despite the fantastic variety of material that exists in nature, the number of architectural or organizational forms is relatively small. On this basis, systems theory can be interpreted as a methodology of science, which is a general theory.

In addition, there is a concept of "system approach" that reflects some trends in the systems creation. There are always two lines in the development of science – analysis and synthesis. We always see a desire for analysis – the study of specific facts, insight into the studied phenomenon, disclosure of the phenomenon structure, etc. Additionally, there is always a desire to create synthesizing theories that allow to combine different facts, see the prospects of a particular process, its relationships with other phenomena, etc.

The meanings of the approaches were different at different periods of time. Recently, when "an avalanche" of new facts has come upon humanity, attention to synthesizing constructions has become especially important. The need not just to study the phenomenon or fact, but to establish its connection with other facts, led to the emergence of a special term "system approach".

The researcher has always sought to systematically approach the study of different phenomena. However, he could not always have the needed tool. Nowadays in the age of computer technology, these opportunities have increased abruptly. Hence, the desire to study the phenomenon in its entirety, in connection with other phenomena appeared.

The system approach is constantly driven by the needs of practice, which puts forward increasingly complex projects that require the analysis of cross – sectoral and interdisciplinary problems.

From the analysis of the considered system concepts, it can be concluded that the most common theoretical term is the systems theory, which is the basis for more practical concepts: system analysis and system approach. Therefore, systems theory can be considered as a basic theoretical discipline that implements its basic provisions in more practical disciplines: "System analysis" and "System approach". In this connection, onwards we will only deal with systems theory.

1.2. CLASSIFICATION OF THE SYSTEMS

Various features can influence the classification of systems. Nowadays, it is impossible to give a definitive classification of systems, because the sciences, involved in systems research, are under development. These sciences also include systems theory, which aims at developing general theoretical concepts of systems modeling, researching them to determine properties and possible behaviors, creating systems to perform the necessary functions with specified properties, and controlling them to ensure the necessary behavior of systems.

Based on the general consideration of systems, the last one can be divided into two large classes: material and abstract.

Material systems are divided into systems of inorganic nature (physical, chemical, geological, technical, etc.) and living systems (simple biological systems, organisms, populations, species, ecosystems).

A special class of material living systems is social systems (from the simplest social groups to the socio – economic structure of society).

Abstract systems are concepts, hypotheses, theories, scientific knowledge of systems, linguistic, logical and other systems.

In addition to the classification, systems can be separated by functional and spatial characteristics, types of system complexity, type of modeling, etc.

The system is distinguished from the external world either by spatial or functional features. The system usually has a spatial or functional restraint. This means that you can draw a boundary either in the space of components of this system, or in the space of its functions, on one side of which is the system, and on the other – the external environment. Herewith, the properties of the system differ from those of the external environment.

Here are some examples of systems:

1. the Solar system;
2. a living organism;
3. the Computer centre;
4. an industrial enterprise;
5. a hydraulic circuit;
6. the Criminal Penal of the State;
7. a system of linear equations;
8. a branch of industry;
9. social security system;
10. the operation system of the computer equipment;
11. supervisory control and data acquisition system;
12. national economy planning system;
13. cardiovascular system.

Systems 1-7 consist of material and abstract objects and are formed by spatial features, systems 8-13 by functional features. Some of these systems allow a double description. In such a way, the operating system can be defined both by its functions (management of the process of passing issues and the allocation of resources of this computer hardware) and by a set of programs that implement these functions.

In cases where the system is given by spatial features, the researcher clearly conducts the structuring of the system.

The structuring means the separation of two types of objects in the system – the set of elements and the set of connections – and the correlation of these sets with each other.

So, the main elements of the Solar system are the Sun and the planets, and the links are the gravitational interactions between them. The elements can be separate sections in an industrial enterprise, and connections between them are material, energy and information flows. In a system of linear equations, elements are separate equations, and connections are the collaboration of the constants in different equations.

Within the same system, structuring can be done differently. Thus, a structural unit (element) of an enterprise can be both a section, a precinct or a workplace.

According to the accepted structuring, the types of connections are changing. In addition, what in some cases acts as a form of communication in another can be considered as a type of element. For example, drive couplings of any crane mechanism may not be considered as elements but as links between individual elements (engine and gear – reduction box, gear – reduction box and drum, etc.).

Systems can be divided into complex and simple. By now, there is no exact definition of a complex system. Therefore, depending on the type of research object, one or another concept of a complex system is used, which is true for one object but not always true for another.

The characteristic features of complex systems include [4]:

1. a large number of interconnected elements and subsystems;
2. the complexity of the functions performed by the system to achieve the purpose of its operation;
3. the multidimensionality of the system, which is caused by the presence of a large number of connections between subsystems;
4. the interaction with the external environment and functioning under conditions of random factors;
5. the presence of a large number of criteria for assessing the quality of the system functioning and its subsystems;
6. the diversity of the structure of the complex system, which is conditioned by both the diversity of the structures of its subsystems and the diversity of structures for integrating subsystems into a single system;
7. the existence of management with a hierarchical structure, as well as an extensive information network and intensive information flows;
8. the diversity of the physical nature of the subsystems, which are characterized by their different physical entities;
9. the large dimension and complexity of the system model;
10. the existence of features that are inherent in the system as a whole, but do not inherent in each individual element (for example, a redundant system is reliable and its elements can be unreliable; a closed system consisting of stable elements can be unstable);
11. the absence of the opportunity to obtain reliable information about the features of the system as a whole by studying its individual elements.

As a result, *the complex system* is a set of interconnected and interacting elements and subsystems of different physical nature, which compose an integral whole that provides the system with some complex function (for example, ensuring of the rhythmic production of cars in a large factory).

A system is considered to be *simple* if it consists of a small number of elements of the same physical nature that form an inseparable whole, which ensures that the system performs some simple function (for example, converting rotational motion into progressive or vice versa).

1.3. FORMATION, FUNCTION AND STRUCTURE OF THE SYSTEM

System formation. The dismemberment of the system into elements is one of the first steps in constructing its formal description [8]. In this case, the element acts as an object, which in this examination of the system is not subject to further dismemberment into separate parts. Thus, *the element* is a minimal indivisible object.

The indivisibility of an element is a concept, but not a physical property. Guided by the concept of "element", the researcher reserves the right to go to another level of consideration of issues and explore the elements themselves and their composition, which indicates the physical fragmentation of the elements. Thus, objects are called elements of the arrangement, which is accepted in order to answer specific questions facing the researcher. The research may require the partitioning of elements into incomplete parts or combining several elements into one.

So, when researching the reliability of the lifting crane, the elements of the system are considered to be separate units of mechanisms: engines, brakes, reducers, couplings, drums, etc., and mechanisms for lifting and changing the departure of cargo, rotation and movements of crane, which include individual units can be considered as separate elements for the research of the kinematics of cargo tracking. That is, in the second case, the merging of several units into one mechanism on a functional basis, and the crane system is presented in the form of four elements (mechanisms).

In some cases, such as when investigating the strength characteristics of the crane, the units of the last one are divided into separate parts. As the number of system elements increases, the connections between them become complicated. Such a system can already be referred to as a complex system.

Each element of a system is characterized by such properties that determine its interaction with other elements or affect the properties of the system generally.

In some cases, complex systems are hierarchically divided into subsystems by spatial or functional features. Such subsystems are the set of elements.

In due form, any set of elements of the system with their connections can be considered as a subsystem. However, the use of this concept is most effective if the subsystem is sufficiently independent part of a complex system, but the purpose of its functioning is subordinated to the overall purpose of the system.

The partition of complex systems into subsystems is called *system decomposition*. This process has not been formalized yet and it has heuristic character. The proper allocation of subsystems allows to simplify and ease the processes of modeling, analysis, synthesis and management of systems.

Let us consider an example.

Let the system consist of n = 20 elements, between which there are $n(n-1) = 380$ connections. Divide (if possible) the system into 4 subsystems with 5 elements in each ($n_1 = 5$). Then the number of connections between the elements of one subsystem is $n_1(n_1-1) = 5 \bullet 4 = 20$, and in four subsystems there will be $20 \bullet 4 = 80$ inter-element (internal) connections. The subsystems have $4 \bullet 3 = 12$ connections between themselves. Thus, only $80 + 12 = 92$ connections can be considered in a dismembered system, which is much less than in an undivided system. So creating, researching, predicting behavior, etc. of such systems are greatly simplified.

System function and its structure. Real systems are described by defining their functions and structures.

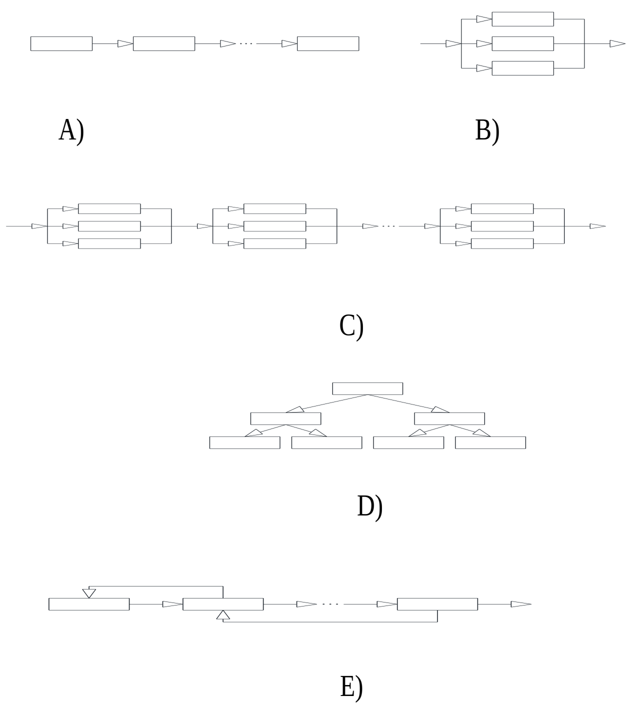
The system function is the rule of getting results predicted by the goal (purpose) of the system. Defining the system function, its behavior is described by the use of some system of concepts: the relation between the variable parameters, vectors, sets. The function determines what the system does to achieve goal regardless of the physical means (elements, connections) that compound the system itself and do not determine how the system is built.

Systems are studied at different levels of abstraction, using different approaches, each of which answers certain questions. In this regard, the system functions can be described with varying detail degree. Theories of sets, algorithms, random processes, and information are used to describe the system functions. If the system is functioning, it means that it receives the results predicted by the system purpose.

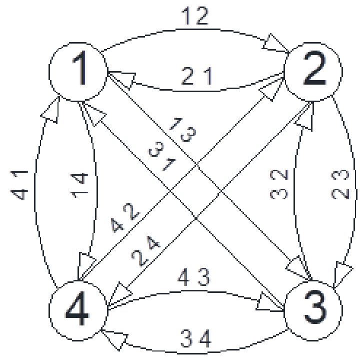
Real complex systems operate under the influence of a large number of random factors, which can be both external and internal (for example, noise, vibration, temperature change, radiation, etc.). These factors complicate the functioning of complex systems, and therefore must be taken into account when they are created and explored in the systems operation.

The system structure is a fixed set of elements and connections between them [7]. In the general systems theory, the structure is considered only as a set of connections between elements. Meaning that the structure is understood as some picture that reflects only the configuration of the system, regardless of its constituent elements. Such an interpretation of its concept is convenient in the structural approach when studying the properties of different systems – systems with parallel, sequential, mixed, hierarchical structures and inverse connections (picture 1.1).

In practice, the concept of "structure" includes not only a plurality of links, but also a plurality of elements between which the connections exist. The structure of the system is often represented in the form of a graph: the elements of the system are represented by vertices of the graph, and the connections by arcs (edges) of the graph (picture 1.2).



Picture 1.1. Systems with sequential (a), parallel (b), mixed (c), hierarchical (d) and inverse (d) connections of elements



Picture 1.2. Picture of a system structure in the form of a graph:
1, 2, 3, 4 – system elements;
12, 21, 13, 31, 14, 41, 23, 32, 24, 42, 34, 43 – connections between system elements

Organization of complex systems is the process of arranging a set of elements in an orderly manner, taking into account their logical connections in order to perform the necessary functions in complex systems [10].

Of course, you can achieve the same goal in different ways based on different principles of systems organization. Each principle of organization provides some way to build a set of systems, similar in purpose, but different in function and structure. A specific system is just an example of implementing some way of organizing.

For example, most modern computer technology is built on the basis of one principle of the organization – the principle of programmatic management of the algorithm implementation based on commands that have an operating address structure.

Thus, organization is a notion of higher rank than function and structure. This is a model on which different specific systems can be built.

Any way to build functions that are sufficient to achieve a goal (a set of results) is called a way of *functional organization.*

The method of constructing the complex system structure from a set of elements that provides the implementation of the necessary class functions, is called the method of *structural organization.*

Determining the method of functional organization, identifying the class of functions inherent in the systems of a specific purpose (regardless of the means necessary for the implementation of these functions), and determining the method of structural organization, identify the rule of constructing structures that implement the identified class of functions corresponding to a specific purpose.

Management is the process of collecting, processing and transmitting of the information.

The system distinguishes control loops along which information flows are circulated. From the control elements to the control tools, primary information is received for processing, and the last one output control information.

There is a sufficiently large class of self – organizing (self – tuning) systems that are able to move through a consistent change of their properties to some stable states due to action of the environment. Such systems include, for example, fixed speed mechanical systems equipped with a Watt's controller.

1.4. SUBJECT OF THE SYSTEMS THEORY

Systems theory is an axiomatic mathematical theory, within which a conceptual apparatus and efficient methods for the study of systems of arbitrary nature have been developed. The systems theory provides a mathematical definition of its subject. This definition is based on the formalization of connections between elements of the system.

If we formally imagine the connection between two elements, the formal description of the system of interconnected (interacting) elements $A_1, ..., A_K$ transformed into a composition of such formal connections between the corresponding pairs of elements (A_i, A_j).

The connection always means the interaction of the elements. As a result, we conclude that the system is a time – interacting processes.

The transformation of the system led to the mathematical definition of its subject, which was introduced by Kalman R. [5]. He highlighted the basic concepts and formulated the main problems from which modern systems theory has grown, intensively develops and finds wide practical use.

Some primary notions are used to formalize the concept of connection. They reflect some aspects of organizing real processes. Any process is a sequence in time of real phenomena. However, it is not a completely arbitrary sequence: the phenomena are somehow objectively organized.

This organization and order are the content of the "*system*" concept. In its most general form, this order is established by two principles of dialectical materialism: determinism and causality.

"All forms of real interconnections of phenomena are ultimately formed on the basis of universal causality, beyond which no phenomenon of reality exists... Causality is common, because there are no phenomenon that wouldn't have their reasons, and there are no phenomenon that wouldn't have other consequences" [6].

The philosophical understanding of determinism is connected with the concept of causality. "The central core of determinism is the provision about the existence of causality, that is, such a connection of phenomena, in which one phenomenon (reason) under certain conditions with necessity causes another phenomenon (consequence)" [6].

In the mathematical formulation of these factors, the concept of causality is reflected in the notion of state and properties of the law of state transition, and the concept of "certain conditions" is reflected in the notion of input.

Causal connection, which satisfies the principles of determinism and causality, means, firstly that none real phenomenon occurs spontaneously, arbitrarily, always another real phenomenon, which preceding it in time also causes it.

Secondly, no phenomenon that is realized at this time depends on what real phenomenon will occur at the times that come after the specified time (in system theory, this property is called causality).

The fact that at the moment a certain phenomenon is being realized, and not another one, indicates that there are certain bases for the realization of this phenomenon. This expresses the principle of determinism of real processes.

The impossibility of the arbitrary occurrence of the phenomenon leads to the formalization of the regularity of the process behavior and to the need to input another process, which belongs to it in the causal connection.

In systems theory, a causal process is called *an input*, and a process – consequence is *an output*.

Another fundamental concept of systems theory is *the concept of state*. In the literature, dedicated to systems theory, the concept of state is given special attention.

On the one hand, any natural – science theory uses this concept and on the other, no one has seen or measured the state of real objects (processes).

It has been experimentally proved that the physical properties of objects vary with the state and these properties can always be identified.

However, the state itself is always hidden. The presence of the state can be proved in various ways. A real system always involves two processes, one of which depends on the other. Therewith, a formal analysis of the nature of the dependence of the output from the input reveals that there is no direct connection between them.

Indeed, a real event at the instant of time t can not depend on what does not really exist at that moment. The events that occured in the process – input of moments t, preceding moment t, at the moment t are not reality. Therefore, an event representing a specific output at moment t does not depend on the input values at the moments $T < t$.

However, the output at moment t also does not depend on the input that realized at the same moment t, since the effect of one phenomenon on another cannot be instantaneous, the propagation of the signal always passes at a finite speed. Cause and consequence cannot occur simultaneously.

On the one hand, the output depends on the input, and on the other – does not. The solution to this contradiction is that the dependency of the output on the input is indirect.

This presents that there are objects that connect the entire previous history of inputs – causes to the moment t and output at that moment. Such objects are called states. Consequently, some condition (determinism) should be considered as the specific cause of the phenomenon in the process – output and the basis for the realization of this phenomenon.

At each moment t, the system is characterized by some state – element of its set of states, which uniquely determines the output value at that moment t, and this is one of the axioms of the systems theory. The influence of the input on the output is reduced to the dependence of the state at each moment t on the output process, which is implemented up to that moment t, i.e. the state accumulates all the reasons that were realized in the past and which determine the current state.

If in the formation of the concept of system the use of input and output processes was predetermined by physical ideas about the functioning of the system, then the concept of state is related to the law of output formation. An object that interacts with the system can only execute this interaction through the input and output of the system, and it is impossible to connect directly with the process in the state's space. The information about the state of the system at some moment of time can only be obtained as a result of solving some theoretical and systemic problem.

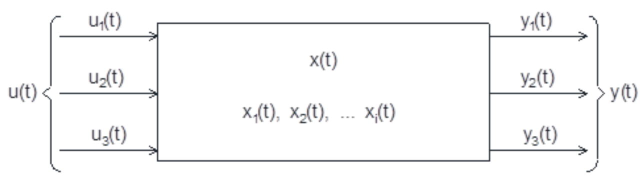
In addition to the input, state and output, there are two other objects that are necessary in the occurance of the concept of the system. The concept of the system also contains limitations on possible processes.

This limitation is expressed by the so – called output display and transient display. Since the output is uniquely determined by the state, there is a connection between them, which is expressed by the display from the set of states to the set of values, which are accepted by the output, which is called the output display.

Similarly, there is a connection between input and state. If at the moment t_0 the system was characterized by the state $x°$ and at the moment $t_1 > to$ – the state X^i, and at the moments of time *1* where $t_0 < T < t_1$, the input took some values of u (т), then the change of state in the state x', but not in any other, was caused by the action of a certain law of system behavior.

In other words, another characteristic is the law that obeys the behavior of the system in the state’s space. In the process of normalization, this law can be described in the form of a display that assigns a state to each state and each input and this display depends on two moments of the time, and on the parameters of the system. It is called a transient display.

Thus, the formation of the system concept includes the primary notions of input *ŭ (t),* state *x (t)* and output *y (t),* as well as the connections between these concepts, which are expressed by the output displays and transitions (Picture 1.3).



Picture 1.3. The system as an input – output converter through its state

The information about multiple states, transient display and output display can answer the following questions:

1. What behavior may the system have?;
2. How to approach the issue of predicting system behavior?;
3. How to solve the issue of providing the necessary behavior?.

The solution of these issues is based on the methodology and basic ideas of systems research, which include the issues of building a model of systems that reflect the inter-connections of real situations, their analysis, synthesis and management.

1.5. FUNDAMENTALS OF FORMALIZATION IN SYSTEMS THEORY

Previously it was noted that the system formalization uses three processes: input, output and process in the state space [9]. For the mathematical problem of a process, it is necessary to distinguish the set of its values and the ordered set that fixes in which sequence these values are realized.

Quite often, the ordered set is interpreted as time, and then deals with processes that take place over time. The ordered set for these three processes is considered to be the same and is called the set of moments of time. It is indicated by T. Indications U, Y and X denote, respectively, the sets of input, output, and sets of states.

The values of the inputs u (t) and outputs *y (t)* processes, as well as the processes of the state *x (t)* of the system at some point in time, are respectively elements of the sets U, Y, and X: u (t) $\in$ U, y (t) $\in$ Y and x (t) $\in$ X.

Each particular system is characterized by its multiple inputs, which are permissible for this system. The set of all system responses, i.e. outputs, is also a characteristic of the system. The specific output *y* (t) $\in$ Y at each moment *t* is completely determined by the state and only the state of the system at this point *x* (t) $\in$ X.

Then there is such display of elements of the set X into elements of the set Y (X $\to$ Y) that the formula can be satisfied.

$$y(t) = \eta\big(t, x(t)\big),\ t \in T \quad (1.1)$$

Here, the dependence of display η from *t* means that the nature of the dependence of the output from the state with time change can vary.

The absence of the dependence of the output *y* at the moment *t* from *u (t)* can also be interpreted as an impossibility for infinitesimal time, changing the input action, causing a change in the system output. At the same time, in the theory of discrete – time systems, display of η is sometimes also determined on the set U, i.e. relation (1.1) has the form

$$y(t_k) = \eta(t_k, x(t_k), u(t_k)),\ k = 1,2,\ldots,n$$

This is because the output response time on input in some situations is infinitely small relative to the discrete interval, and may not be taken into account in the model.

Display n is called output display, or observation function. According to the axioms of the state, at each time system *t* is in a certain state, and the state at moments *t>m* is uniquely determined by the state at the moment *t* and the input segment *u* (т, *t).*

This is the principle of determinism (certainty) in the systems behavior. Formalizing this circumstance establishes the existence of a display set relating elements within the set U into the set X (U$\to$X) for all parameter values т is T, t is T and т <*t.*

The specific display corresponding to fixed *m* and *t* allows for any *x* and any (т, *t)* to determine the state at the moment t, if at the moment т the system was in state *x(*т*)* and the input u *(*т, *t),* was used by dependency

$$x(t) = \mu_\upsilon(x(t)\mu(\tau, t)). \quad (1.2)$$

The axiom of uniquely determined state at moments $t > \tau$ by the state at τ moment and input $u(\tau, t)$ imposes a restriction on the set of display.

According to this axiom, each state of the system uniquely determines the future state (determinism of processes). Based on dependence (1.2), we can construct a display σ through which the system state is determined

$$x(t) = \sigma(t; \tau, x(\tau), u(\tau, t)). \quad (1.3)$$

The transitional display must satisfy the requirement that $x = \sigma(t; t, x, u)$ for all t, x, u, i.e. for a period of zero length, the system cannot be changed into another state (or at the same time can't be in two different states).

In addition, the display must be such that the state at the moment t does not depend on the input values coming in at times greater than the moment t.

Based on the previous dependencies, you can give a mathematical definition of the system.

Some system E is defined, if given ordered sets of the moments of time T, sets of values of inputs U, outputs Y and states of transitional display (7), which satisfies the axioms of coherence, determinism and causality, and display of output η such that for any $y(t)$ is Y there is x (t) is X and $u(t)$ is U for which for any where, the formula is performed

$$y(t) = \eta(t, \sigma(t; \tau, x(\tau), u(\tau, t))). \quad (1.4)$$

and, conversely, any process $y(t)$, $t > \tau$ obtained respectively (1.4) belongs to Y.

In other words, the system that generates the output processes from Y can be defined by three quantities σ, X, η.

These three quantities are an expression of the law of behavior of the system introduced by Kalman R. [5]. It is more traditional to define the system by specifying relations that describe the display σ.

These formulas (equations) are called the system model. However, the last definition is less general.

The system description, for example, in terms of differential equations requires the smoothness of the display σ, which in the general case is optional.

1.6. PROBLEMS OF SYSTEMS THEORY

The problems that arise before a systems researcher are related to the construction of the set X, the displays σ and η, and the study of their properties.

This is a range of systems analysis problems. The analysis begins with the identification of all the factors that influence the studied system behavior. In system analysis, they are called relevant factors.

This issue is related to the study and description of the sets U and Y. Next comes the task of describing the dynamic relationships between input and output, that is, the task of constructing a model of these relationships, which is called *the identification problem.*

The solution to this problem is the set of states X and the σ and η displays.

The identification problem is closely related to the system representation problem, where possible descriptions of patterns of behavior are studied, i.e. the possible form of the σ and η displays. From a synthesis point of view, this problem is to build a system that implements a given input – output behavior.

Let X, σ and η be given or identified. One of the main goals of obtaining X, σ and η is a possibility of *prediction (a prognosis)* of the system behavior.

Of course, the prediction of the output behavior *y (t)* is of interest. However, given the formula (1.1), this problem can be reduced to the prediction of the process in the states space.

It follows from formula (1.1) that the prediction *x (t) of day* $t > t_0$ at the known input $u(t_0,t)$ is possible if x_0 is known at the moment t_0.

In this regard, another issue of systems theory from the analysis point of view is related to the study of problem solvability to find the system states by the input and output observations, which is called the *systems observation issue.*

Let the input u be fixed and the information, obtained by output only in the moment *t1*, is used for finding of state in the moment *t1*. Then the task is reduced to solvability with respect to the *x* output equation of system (1.1) at *y(t1) = y1*.

If the dimension is equal to the dimension *x* and the equations in system (1.1) are independent, then a single solution *x1* can be determined from this system. However, the set of states of the system, of course, is wider than the set Y, which is the manifestation of the system complexity.

For systems in which X and Y are finitely measurable linear spaces, this is expressed in the fact that the dimension X is greater than the dimension Y. Then the solution of equation (1.1) is not unique, i.e. observed *y1* will correspond to different states in which it can be realized.

Therefore, the output information at a fixed moment *t1* is not sufficient to establish the state at this moment, and to distinguish states it is necessary to expand the information of the studies. For this, it is necessary to observe the output more than at one moment *t,* for example, in the whole interval [t0, т1].

If the process *x[T0, t1]* uniquely determines the output y[t0, t1] corresponding to it, then there is a display H_u: $X[_{t0,t1,}] \rightarrow Y[_{t0,t1,}]$. If H_u had inverse display of H_u^{-1}, then any observed output *y[t0, t1]* would be created by a single process *x[t0,t1*], and the problem of state estimation would be solved. It is enough to find H_u^{-1} to solve it.

If H_u reflects different x[t0, t1] in the same output *y[t0, t1]*, then it is impossible to estimate the state of this output uniquely. A system whose display H_u is mutually unambiguous is called *observational.*

Note that the observation property depends on the particular type *u(t).* Therefore, when estimating the state not only the problem of synthesis of the corresponding algorithm arises, but also the problem of finding the input *u(t),* at which the system will be sufficiently observable. From the definition of a sufficiently observational system, it follows that observation is a property of the displays g and n, i.e. the intrinsic property of the system.

In the theory of finite – state machines, the problem of observation, of course, is called a diagnostic issue.

An example of the observation problem is the concern of diagnosing machines, such as excavators. Specific breakage is one of the possible states in which the excavator as a system is currently located.

The issue is to evaluate this state by the observed output, for example, pressure in the hydraulic system and analysis of its working fluid, etc.

From the complete observation t0 of the system at the interval [t0, t1] follows the possibility to estimate any state at the moment y at the output *Y[T0, T1]*. If we consider the issue of state estimation at the moment t0 of the output observed up to the moment t0, for example, for *y[t-1, t0]*, where t_{-1} < t0, then, since the display η depends on *t*, it differs from the problem described above. The task of estimating the state of the output, which was observed in previous moments of time, is called the *reconstruction issue* or *systems evaluation.*

The next problem of systems theory is related to the study of problems concerning the formation of special behavior within systems. If the observation task arises from the need to predict the future behavior of the system, then the formation of special behavior is caused by the need to satisfy certain requirements imposed on the process. The latter are called the goal that is set for the system.

At the same time, it is considered that when an input process begins to form in the system, it does not meet the requirements that are formulated for the purpose of control.

Only the inputs can influence the system behavior. So, the set of inputs is allocated a subset U1, the elements of which are formed by the subject. Therefore, the set of inputs is broken down into two subsets U1 and U2, one of which, independent of the subject, is called drilling – U2, and the other is called *management* – U1.

The system, the goal and the input data, on the basis of which the problem of finding controls that ensure the achievement of the goal should be solved, is called the *problem of control theory.*

System behavior requirements, of course, impose the output process. However, given the formula (1.1), they can always (and this is advisable when solving control problems) be reformatted as conditions imposed on the process in the states space.

One of the most important problems of control theory is the two – point boundary value problem, which is formulated as follows.

Imagine that the purpose of control is that at the moment t1> t0 the system is in state x^1, moreover at the moment t_0 is in state x^0. It is necessary to find such an input *u*(t) is U in order for the congruence to be satisfied

$$x^1 = \sigma(t_1; t_0, x^0, \bar{u}(t)). \quad (1.5)$$

If we fix (t_0, x^0), for some (t_1, x^1) the equation (1.5) can be solved and for others can't be solved. A system (t_0, x^0) is called <u>*globally accessible*</u> if for any x^1 there exist t_1 $(x^1) > t_0$ and $u(t)$ that satisfy the formula (1.5).

A system (t_1, x^1) is called <u>*globally managing*</u> if for any x^0 there are t_0 $(x^0) < t_1$ and $u(t)$ such that satisfy the formula (1.5).

If you can specify the circumference end of the point x^0 such that for x^1 from this circumference the accessibility meet the conditions that means the local accessibility. Local management is similarly defined. You may consider the concept of controllability and attainability at a given finite time interval.

Controllability and attainability are properties of transitional display σ.

The tasks involved in developing effective criteria that allow display σ to determine whether the system is sufficiently controllable or accessible are <u>*the subject of systems control theory*</u>.

An important issue of systems analysis is <u>*the sustainability problem.*</u>

It raises from the question of whether the system will perform its function and purpose in conditions where different perturbations occur, which is often a manifestation of incomplete knowledge of the environment and the system itself.

Imagine that the system purpose is to transform a given input u^0, which generates a process state x^0 and an output y^0. If, as a result of some circumstances, the process x in the states space does not coincide with x^0, i.e. $x(t_0) = x\ (t0) + \Delta\ x(t0)$, which may be due to the fact that at the moment t_0 there is a deviation $\Delta\ x(t_0)$, then the question arises whether by $t > t_0$ and $t > \infty$ the process $y(t) = \eta (t, x(t))$ coincides with the process y^0, or will it be close enough to it or not.

The specified dependence will hold if $\sigma(t; t_0, x^\circ + \Delta x, u^\circ(t_0, t)\backslash$ will coincide with $\sigma(t; t_0, x^\circ, u^\circ(t_0, t)$. The process Δx (t_0) is called <u>*the non-drilling motion of the system*</u>, and the process $x(t)$ – <u>*is the drilling motion.*</u>

The study of display properties σ, which provide the specified convergence or their proximity, is the subject of <u>*systems theory stability.*</u>

Other problems of systems theory are the detailing of the main problems outlined above. These issues arise when synthesizing systems with the required properties. These include the following synthesis tasks:

- functional – structural and parametric in the states space of the system;
- optimal software management;
- optimal control laws, i.e. control that is formed at each moment of time based on information about the state of the system at that moment;
- control laws that ensure the stability of the system;
- inverse connections, i.e. output control; adaptive systems, where the process of identification of the system, which is associated with the estimation of structural parameters, takes place in the control process;
- identification systems or input data classifications, etc.

Some of these problems will be discussed in the following sections.

QUESTIONS FOR SELF-CONTROL:

1. What is a "**system**"? Provide basic definitions and give examples.
2. What does the term "**system analysis**" mean?
3. What systems are known to you? List and classify them.
4. Which systems can be classified as simple and complex? Give examples.
5. Provide basic features of complex systems.
6. Describe a notion of "**element of the system**".
7. Provide a definition of "**system functions**".
8. What is the "**system structure**"? Provide a graphical formation of the system structure in the form of a graph?
9. Define the concept of "**systems theory**".
10. Define the concept of "**input**" in systems theory.
11. Define the concept of "**output**" in systems theory.
12. Define the concept of "**state**" within systems theory.
13. How is it possible to present a system that converts input to output through its state?
14. What is the essence and content of formalization in "**systems theory**"?
15. What problems does "**systems theory**" have?
16. Provide an example of solving the issues of finding the state of the system by observation of input and output.
17. What is the subject of "**systems sustainability theory**" and what can we refer to the sustainability problem?
18. Name the main "**problems of systems theory**" (problems of synthesis).

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Chapter 2. Definition of technological systems

Contents of Chapter 2

Keywords: technical systems, mechanical system, production and organizational systems, machine, machine-environment, machine systems, technological system "environment-machine", modeling of system "environment-machine", classification features of machines, structural scheme of machines, types of working tools, basic indicators and characteristics of machines, quality indicators of machines, energy machine, technological machine, transport machines, test machines, executive (working) tools, energy part, machine formation, stages of constructional design, life – cycle stages of machine.

2.1. BASIC CONCEPTS OF THE TECHNOLOGICAL SYSTEMS

The evolution of living beings has been lasting for over three billion years. Their intellect has been formed for about three million years, and only forty to fifty millennia passed as they subsequently called themselves a homo sapiens.

A human has always been amazed at the harmony of nature and has learned from it, creating ever more complex objects, which now are called *technical systems*.

The technical system comes from the Greek word "techne" – art, mastery [1]. It is a set of tools that are created to carry out the processes of production and maintenance of non – productive needs of society.

The main purpose of technical systems is to completely or partially replace the productive organizational functions of the person in order to facilitate the work and increase his productivity.

There are technical systems – production (machines, mechanisms, tools, control facilities of machines and technological processes, means of transport, communication, individual enterprises, production complexes, etc.) and non – production (household, communal, scientific research, education, cultural, military, medical etc).

Depending on the mode and formation of the basic elements that carry out the transfer and conversion of energy and information, technical systems are divided into mechanical, hydraulic, electrical, electronic, optical. Most technical systems, as a rule, are mixed systems where there is a use of elements of different physical nature, such as electro-mechanical, hydromechanical, opto – mechanical and other technical systems.

Among the viewed systems, mechanical systems occupy a special place. The fact is that virtually all complex technical systems have in their composition either elements of mechanical systems, or entire subsystems of mechanical systems.

A mechanical system is an unrestricted device, mechanism, machine, construction, etc. in which energy is transferred and transformed by mechanical elements (shafts, gear wheels, clutches, etc.). In some cases, separate systems of living beings can be brought together to a mechanical system, for example, the musculoskeletal system of animals and humans can be represented in the form of a link mechanism.

A number of other objects can also be modeled as mechanical systems. These systems are quite simple, clearly evident and the most researched.

2.2. PRODUCTION – ORGANIZATIONAL TECHNICAL SYSTEM

Let us consider the formation and characteristics of production – organizational technical system on the example of the construction system of hydraulic technical structure.

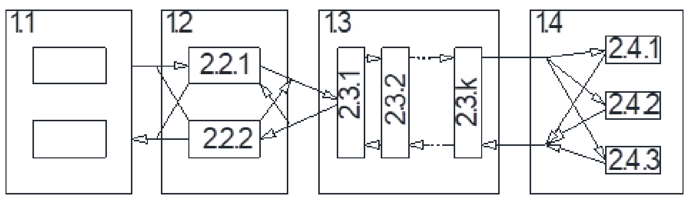
This system is used to provide and manage the construction process and consists of the following facilities (subsystems) (picture 2.1): quarries, reinforced concrete plants, transfer lines, packing system of dams, supplying complex of equipment, complex of assembly and lifting and transport works.

Concrete works are the most time consuming and continuous in the construction of hydraulic technical structure, so when considering this system we will pay the greatest attention to them.

The system generally works in this order. The quarry stone is processed into crushed stone by a specially selected system of machines and sent to concrete plants for concrete mixing. The sand, which is also used for concrete mixing is delivered from other quarries.

There are different types of concrete for different works, and each of the factories has the ability to mix any of the types. In addition, the reinforced concrete plants produce the necessary reinforced concrete and reinforcement constructions. Each of the plant’s concrete mixing units can produce any of the concrete types (concrete types differ in the percentage of cement and additives), but it takes some time to adjust production from one type to another.

Concrete is mixed by each of the concrete mixing units in portions, which are loaded into mobile concrete – mixing machines and taken to the construction place along the route. Unloading, laying and compacting of concrete are carried out in different places by different machines (concrete pavers, concrete pumps, lifting cranes, etc.) and by different technologies, which depend, among other things, on the stage of construction. The composition of machines for laying and compaction of concrete, the conditions of access to them are changing with increasing the height of the dam. Unloaded concrete – mixing machine goes back to the concrete plants.



Picture 2.1. Technical system of construction of hydraulic technical structure:
Level 1 subsystems: 1.1 – quarries; 1.2 – concrete plants; 1.3 – transfer links; 1.4 – complexes for the construction of hydraulic technical structure.
Level 2 subsystems: 2.2.1, 2.2.2 – 1st and 2nd concrete plants; 2.3.1-2.3.K – track sections; 2.4.1-2.4.3 – unloading machines

Reinforcement constructions are produced in the reinforcement shops, which are partly sent by special vehicles for construction of the structure, and the rest of the metal constructions is used for the production of reinforced concrete constructions.

These constructions are produced in special posts, where there reinforcing steel and concrete mix are laying in the form. After compaction and concrete hardening in the steaming chambers, the reinforced concrete constructions are sent in the construction of the dam by special vehicles. Once the reinforced concrete structures have been unloaded and erected using cranes, the vehicles return to the concrete plants and the mixing cycle is repeated.

To have an idea of the tasks sizes that need to be solved, let us imagine that there are several plants working on the construction, which produce about 40 types of concrete and several dozen types of reinforced concrete and reinforcement constructions; the technological lines of the machines system for the manufacturing of the crushed stone (drilling machines, crushers, bolters, conveyors, loaders) are working in the quarries and several hundred cars and several dozen construction machines, machines of various purpose are counted for the extraction of sand (excavators and cars; motor transport enterprises (management of mechanization); more than dozen unloading machines and machines for laying concrete on the dam are working; the length of the motorways is several tens of kilometers with a high traffic load transport, which creates obstacles in the transportation of goods.

Creating such a system requires the following tasks:

1. the choice of the route for the conveyance of concrete and constructions to the building, as well as crushed stone and sand to the concrete plants (in this case, the use of national roads, laying of the new ones, laying special access roads and tunnels, etc. is possible);
2. selection of quantitative and qualitative composition of mechanization management;
3. selection of types of concrete plants, their operating modes, locations;
4. selection of the composition of lifting – and – transport, unloading and laying machines, their operating modes;
5. selection of the machines system for the manufacture of crushed stones etc.

It is clear that in this case full – scale experiments are limited. Considering the uniqueness of such construction, the results of experiments obtained in one conditions will be of little use in others.

The above example gives some insight into the nature of one type of complex production – organizational technical system.

Let us take a closer look at the basic features that are inherent to this system.

Even when superficially considering this complex technical system, we had to introduce the concept of subsystem as some fairly autonomous part of the whole system.

The division of a complex system into subsystems, as a rule, is carried out with a certain element of arbitrariness and depends on the technical decisions that are made, the goals of creating the system, and the researcher's views on the system. This is primarily due to the diversity of the elements that make up a complex system. In this example, the "transfer" subsystem, which reflects the motion of vehicles along the route from the reinforced concrete plants to the place of construction, may, in turn, be divided into smaller subsystems, for example, subsystems of transportation of concrete by concrete – mixing machines and transportation by special vehicles of reinforced and concrete constructions. These subsystems, in turn, can be further subdivided into smaller subsystems – these are subsystems of transportation, technical maintenance and auto repairs.

In this production – organizational system, as well as in other complex technical systems, one of the main features is the interaction of dedicated subsystems. This interaction results from one or another division of the system into subsystems.

As previously noted, this division of the system into subsystems has a certain element of arbitrariness. The results of the interaction of one system with another are taken into account in one way or another in order to ensure the functioning of the entire system as a whole. Of course, such interaction is reduced to the exchange of signals between subsystems, which is carried out through the connection channels that are routed from one subsystem to another.

These connection channels can both correspond to the common channels existing in the system and can be generated by the division of the system into subsystems. In addition, the interaction is carried out between the outside environment and the selected elements of the system. The consideration of this interaction is similar to the consideration of interaction between individual subsystems, i. e. the outside environment is represented as such a subsystem.

Thus, the consideration of the production – organizational system of the construction of a hydraulic technical structure shows that a complex technical system is represented in the form of a multilevel construction of elements that interact with each other and with the outside environment.

Here, the elements of level 1 include subsystems, which are initially divided as systems, the elements of level 2 – subsystems that are formed by the division of level 1 subsystems, and so long as the formed elements – do not become easy to research or manage.

The production – organizational system of the construction of a hydraulic technical structure is presented in the form of a two – level construction of the interconnected moments (picture 2.1). In this picture, the arrows show not the actual connection channels, but the channels that serve for accounting the interaction that exists between the selected subsystems.

In fact, the channel exchange corresponds in this case, for example, to the input or form of a vehicle unit from the subsystem, which is under consideration. At the same time, the subsystems are selected based on the actual features of the construction. For the sake of simplicity, it is accepted that two concrete plants are producing, there are three places of concrete laying with appropriate mechanisms.

In reality, these elements may be much larger. The interaction with the outside environment in this case can be reduced to the failure of plants operation and laying machines, changes in road conditions, based on meteorological conditions or heavy traffic of foreign transport, etc.

In the viewed system, subsystems 1.2.1, 1.2.2, 1.4.1-1.4.3 do not only represent the concrete plants and unloading devices respectively, but actually include vehicles as pending (unloading), and those that are currently being loaded (unloaded).

Similarly, subsystems 1.3.1-1.3.k include not only the parameters of the relevant sections of the track sections, but also the characteristics of the vehicles moving on them. Such a representation of a complex system in the form of a multilevel structure of interacting elements aims at studying the system in individual parts.

2.3. Technological system "environment – machine"

When considering the production and organizational technical system for the construction of a hydraulic technical structure, we have seen that when operating certain works there is a connection between the machine and the environment with which it interacts.

Thus, a number of works are carried out in the production of crushed stone in the quarry: stripping operations, which are operated in order to eliminate the empty rock; separation of the mineral layer from the mountain massif and its preliminary loosening in preparation for loading operations; transportation of the rock mass to the processing place; grinding and sorting of stone material; loading material into vehicles and sending them to concrete plants.

All these processes are operated with the help of special technological and transport machines. This example shows that machines are created for the implementation of certain technological or transport processes that are operated to change the properties, shapes, sizes and location of raw materials in order to obtain the finished product.

In this case, the environment means the operation of processing and transportation of raw materials, which is inseparable with these or those machines. Thus, the interaction of the machine with the environment is a technical system, the subsystems of which are the environment and the machine, and the nature of their interaction is determined by the structure of connections between the environment and the machine.

Comprehensive consideration of machines and environments in the form of a technical system reveals the only patterns of interaction between them. In the process of interaction with the external environment, the operation of the machine, depending on the principle of operation, is continuous, discrete or cyclical.

The operation of the machine in each type of interaction takes place on its own internal cycles. These cycles are characterized by phases of growth of certain characteristics, their stabilization and decline.

The immediate operating environments (work environments) where the basic transformative function of the machine is carried out include the technological, organizational or natural environment. The machines carry out the resistance force influence , which can have both a useful (separation of the material from the array, its crushing, etc.), as well as negative influence (wear – and – tear of the elements of the machine, vibration, noise, etc.).

Static characteristics of force changes of the machine on the environment quite often have the form of an exponent or a parabola. This makes it possible to predict some general pattern of operation of the machine in a particular environment when considering the interaction of the machine with the environment as a system.

In order to ensure interaction between the environment and the machine, all the necessary connections with the environment must be established, purposeful functioning of the machine must be ensured, i.e. *technological system "environment-machine"* must be built.

It requires a model (mathematical or physical) to build such a system, its analysis and optimal management. Mathematical models should be recognized as the most advanced models of such systems.

Mathematical *modeling of the "environment-machine"* system can be operated by different methods [2]. The interaction of the machine with the environment characterized by the output characteristics of the machine y_1 ... y_m, is that these characteristics are continuously compared with the characteristics z_1, ..., z_m, which determine the connections with one or the other elements of the environment.

The purpose of this technical system is the behavior of the system that the divergences Δ_1, ..., Δ_m, between the output characteristics of the machine (working tool) y_1 ... y_m and environment z_1 , ..., z_m were constantly zero, so that new elements of the environment would not come into contact with the machine.

$Y_1 = Z_1$, ..., $y_m = z_m$, then the machine adequately reflects the state of the environment and the goal of the "machine-environment" system is considered to be achieved. However, if there are non–zero divergences, then through the feedback mechanism, action is taken through the drive mechanisms on the machine and through the working tools of the machine on the environment.

The flexibility and mobility of the system is determined by the number of input functions of the machine u_i, that can be acted on the system. The more functions u_i, the more flexible and easier to adapt to environment change.

On the other hand, the number of arbitrary input functions u_i depends on the number of linkages imposed on the system. This dependence first increases and then decreases at *s* increases.

The number of input functions of the machine can be reduced to zero. In this case, we will have a system with a rigid structure, which can not function properly with the slightest change of environment.

What properties should the system have to ensure proper functioning? Firstly, it should have a structure (formation) that enables it to remove part of the overlapped linkages in the operation process.

Secondly, increasing the number of output characteristics (coordinates of the working tool) by the machine increases the level of functioning of the "machine-environment" system.

Thirdly, the system might be able to change the structure based on the redistribution of functions, assignments of levels of control, coordinating and matching elements and self – organization of interactions between the machine and the environment.

Note that the divergences $\Delta 1$, ..., Δ_m can be reduced by acting on both the machine and the environment, for example, with the help of the working tools of the machine.

The maximum efficiency of the "machine-environment" system will be ensured with full consideration of the interaction of working tools with the environment and the choice of the machine formation that would ensure optimal interaction. This can be achieved when the machine and the environment are considered as the only system that is a subsystem of a higher level of the system – the system of machines for manufacturing of certain product.

2.4. MACHINE SYSTEM

One of the main strategic directions of material production in various industries is the creation of integrated production complexes and their automation. The construction of the machine system for ensuring the optimal (the best) functioning of integrated production complexes is one of the most important problems of modern production.

The problem of creating the machine system covers a significant area of modern man's activity and includes problems associated with the creation of machines, the study of their functioning in different environments and management in the operating of various kinds of technological processes.

Problems of creating and using machine system include the primary issues of new machine development and correct systematic use of them under rational loads, coordinated functioning and efficient operation.

On the way of creating the machine system, it is necessary to solve a number of scientific issues, where the central problem is the interactions that arise between the environment, the machine and human in the world of modern technologies. The interaction between machine and environment has been discussed before, and the role of human in these processes is paramount, because all systems and processes are created for the sake of humans.

At the same time, humans are directly involved, so their interaction with machines must be rational. All processes that are operated more productively and efficiently by the machine must be transmitted to the machine, and what is better operated by the human or cannot be operated by the machine must remain operated by the human.

The world of modern technology reaches such a level that only a few elements of technological processes remain behind the person, and everything else is operated by the machines.

An example is electronic engineering, where virtually all technological and transportation processes are mechanized and automated. There are only a few management functions left behind the human, and only those that are better operated by the human.

Unfortunately, we cannot say the same about the construction industry yet, where much of the technological processes, especially finishing, are operated by humans or mechanisms and machinery with the direct involvement of humans.

The creation of the machine system constitutes the development of the "environment-machine" system [10] on the basis of a purposeful organization of a multilevel structure, which includes machines, a set of technologies and management systems.

In such structure, a level of self – organization can be achieved, i.e. the formation in which a given state of the system is established without permanent external organizational influence. The principles of organization and self – organization in the machine system can be carried out at the expense of optimal completing of machines, introduction of automation products, improvement of mechanisms of management coordination, organization of production, innovations and many other factors of the progressive development of modern technologies.

The machine system is a complex technological system that requires considerable resources to streamline and organize it. The transformation of the "environment-machine" system into the machine system must be carried out using the laws of system differentiation and integration [3].

System differentiation is the use of divergences and inconsistencies between the system components. If the constituent systems become quite different in their organization and react differently to external actions, then this can cause the system to collapse and disappear. The system collapse is counteracted by system integration (unification), i.e the growth of the system integrity, the strengthening of connections and the interdependence of its components.

The machine system creation can be based on the following basic concepts.

Firstly, machine systems are the means of intensifying production and other areas of human activity.

Therefore, the functioning of the machine system should be considered as a process of coordinated interaction of technology and personnel in the environment of modern technologies.

Secondly, the machine system creation implies an increase in the integral efficiency of production, so the specific use of machines must be consistent with their life cycle stages (period of service), and also take into account the functioning phases of the environment. The economic efficiency of modern production can be ensured only with the high technical efficiency of the machine system.

Thirdly, the machine system must form a harmonious unity of energy, information and constructive properties of modern technical systems.

Fourthly, the machine system must be designed in such a way that it can function while maintaining a certain interrelation between the level of organization of the environment and the constructive – functional opportunities (complexity) of the machines. This leads to the possibility of developing a fundamentally new principle in creating machines and predicting the process of their development.

This principle is that the progress of mechanical engineering should be determined by the quantitative interrelations between the output parameters of the machine and their interaction with the environment.

An example of the machine system is a set of machines used for crushing and sorting stone material to produce crushed stone and gravel [3].

For the production of crushed stone by crushing solid rocks and for the separation of gravel from the gravel – sand mixture, special complexes are created: crushing and sorting plants, where the main processing operations (crushing, sorting, separation of foreign impurities) are fully mechanized and interconnected in a certain sequence and form a continuous technological process (Picture 2.2).

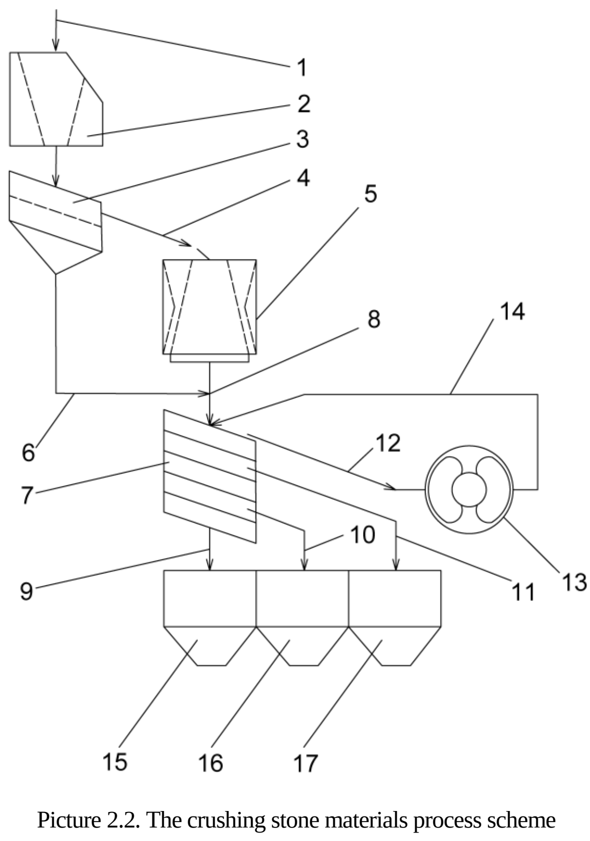
According to the technology, the stone delivered to the plant in the form of large pieces is directed for crushing by means of the conveyor 1 into the crusher 2. The resulting crushed material is transferred from the crusher 2 to the bolter 3, where it is divided into fractions by size. The crushed material almost always has excessive pieces that need additional crushing. When sorting the crushed material on the bolter 3 such excessive pieces are delayed on the top of its sieve, from where with the help of the conveyor 4 they are moved to a specially placed crusher 5 of re – crushing.

The sorting process operated on the bolter 3 is operated in order to separate from the pre – crushing product only its excess pieces to transfer them to the crusher 5 of re – crushing. The rest of the material passed through the holes of the bolter sieve 3, is sent 5a through the conveyor 6 for its final sorting by size on the bolter 7, where the product of crushing from the crusher 5 falls at the same time on the conveyor 8.

On the bolter 7, the material is divided into three fractions and with the help of conveyors 9 – 11 is directed to the intake bins of finished product.

In addition, pieces of material left on the top bolter sieve 7 are directed for one more crushing cycle through the conveyor 12 into the crusher 13.

The raw product of this crushing is directed through the conveyor 14 to the bolter 7 of the final sorting.



Picture 2.2. The crushing stone materials process scheme

From batch bins 15-17 crushed stone of different fractions in certain portions is directed to the reinforced concrete plants or for other needs with the help of dispensing mechanisms.

Picture 2.2 shows a scheme of one of the processes of crushing stone materials. At the same time, other schemes of such technological processes are used in practice.

As we can observe from the above example, the machine system is required to implement such a technological process. Depending on the production needs, these machines must be agreed in terms of functionality, productivity, reliability and so on.

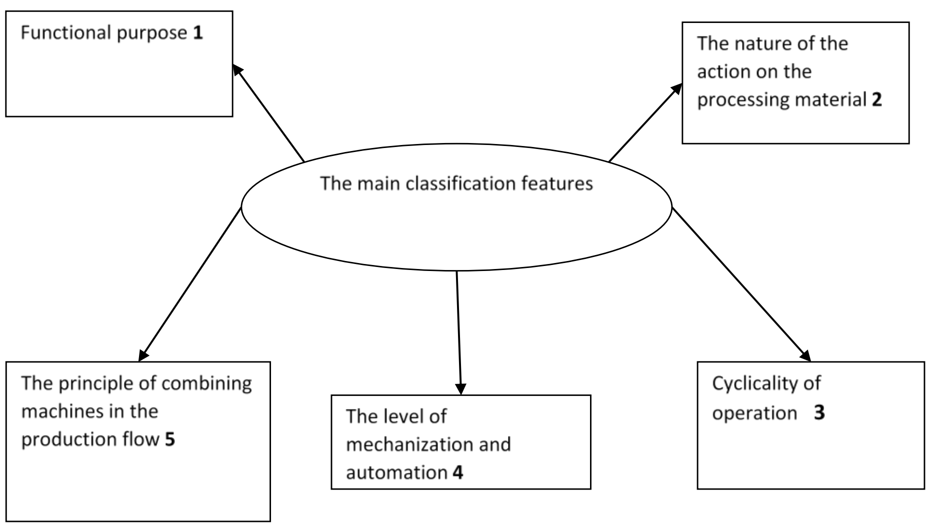
In addition, machines of different types can be used at each stage of the crushing process. Thus, crushers 2, 5 and 13 can be jaw crushers, conetype crushers, roll crushers and impact crushers.

Similarly, there are different types of bolters and conveyors. Each of these machine types has its advantages and disadvantages. However, the highest efficiency from the operation of these machines can only be obtained if they are considered as the machine system for operation of the complete technological process, not as separate machines.

At the same time, each of these machines is a subsystem of the machine system, so the consideration of the individual machine as a system in terms of their rational formation, strength of elements, modes of motion, reliability, metal content is also a very pressing issue.

2.5. FUNCTIONAL-STRUCTURAL FORMATION OF MACHINES AND BASICS OF THEIR CONSTRUCTIONAL DESIGN

Classification features of machines. Machines and equipment of processing industries can be classified according to a number of features, the main ones of which are shown in picture 2.3.



Picture 2.3. Classification features of machines and equipment

By functional use, the machines are divided into machines for operating a certain technological process: crushing, cutting, sorting, mixing, transporting, compaction, dispensing, depuration. The characteristic machines of this classification feature are crushers, separators, bolters, mixers, dispensing mechanisms, filters, centrifuges, compresses, vibrating equipment. As an example, the classification features of machine and equipment, which are used in food production are as follows:

- machines for distribution of bulk and liquid products;
- machines for the preparation and homogenization of nutritive emulsions;
- machines for individual division of plastic nutritive products;
- machines for crushing, mixing, excorticating and milling of bulk products;
- machines for cutting of nutritive products;
- machines for dispensing of the components of nutritive products;
- machines for washing containers of liquid nutritive products;
- machines for mixing plastic and liquid nutritive products;
- machines with rotating shells for mechanical, thermal or chemical conditioning of nutritive products;
- machines for compressing of nutritive and feed products;
- ultrasonic equipment for intensification of nutritive production processes;
- automatic mechanisms for measuring nutritive products mass;
- automatic machines for nutritive products packaging;
- heat exchange, diffusion and evaporation apparatus for nutritive production;
- conveyors and reloading machines for complex mechanization of nutritive production. *With regard to the nature of the effect on the processing material, the following can be distinguished:*
- machines in which the product is exposed to static or dynamic mechanical action and when processing the material does not change its properties, but can change only the shape, sizes or other similar parameters;
- machines in which the material changes its physical, chemical properties or aggregate state due to physical – mechanical, biochemical, thermal or electrical actions.

In the first case, an example can be crushing equipment: in nutritive production – crushing of bones, in construction industry – crushing of the crushed stone.

An example of a second feature in nutritive production is the diffusion apparatus in which the target components are extracted; in the construction industry – the formation of concrete mortar.

In some cases, technological equipment is a combination of machine and apparatus that combines mechanical physical – chemical, thermal and other actions.

On cycling of operating of technological process:

- machines can be batch and continuous action. In batch machines, the processed product is affected for a certain period of time and the finished product is removed from the machine after this period. That is, the process of obtaining a certain product is cyclical and usually consists of the time of loading, preparation of the product and unloading.

- in machines of continuous action the process of loading, preparation and unloading of finished product are carried out without interruption in time.

An example of machines of this classification are mixers both cyclical and continuous action.

Machines of non – automatic, semi – automatic and automatic processes are distinguished by the level of mechanization and automation of operations.

In non – automatic machines, auxiliary processes (loading, unloading, control) and some other technological processes are operated by human action on the object of labour. In such machines, mechanisms and tools only facilitate the work of human, but do not eliminate it.

In semi – automatic machines the basic technological operations and processes are operated by the machine, while some transport, control and other auxiliary processes are manual.

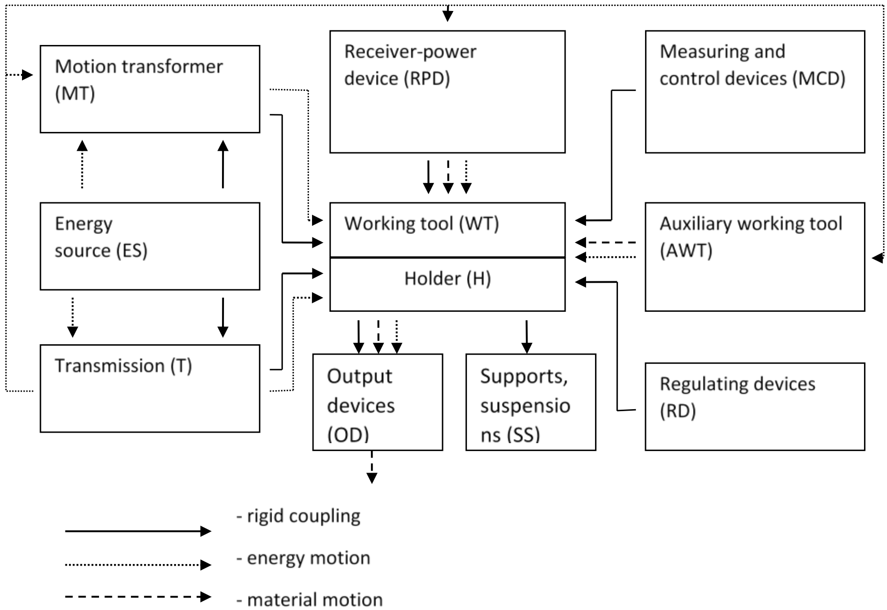
In automatic machines, technological operations and processes, as well as all auxiliary operations and processes, including transportation and control, are operated by the machine.

The peculiarity of semi – automatic and automatic machines is the presence, in addition to the usual mechanisms and devices, of special mechanisms and devices that provide automatic operation of the machines.

According to the concept of combination in the production flow, the following can be distinguished: separate machines; devices or complexes of machines, combined machines and automatic machines systems. If the working tools of the machine operate different processes and operations associated with a certain sequence, then such a machine is integrated or complex. Such machines provide accelerated processes, saving labor and production area, reducing energy consumption and reducing operating costs. Combined machines that operate a certain complete cycle of operations and processes are more proper than integrated ones.

The consistent development of production leads to the development and application of an automatic system of machines (robots and manipulator mechanisms) that ensure a high level and efficiency of the workflow.

Structural scheme of machines and their elements. Machine (equipment) used in treatment facility includes a number of elements, devices designed for operating certain technological processes and functions [4] (picture 2.4).



Picture 2.4. Structural diagram of the machine

Elements of the structural scheme of machines (picture 2.2) have the following purposes.

An energy source (ES) is the machine drive that converts one type of energy into another (usually electrical to mechanical) and supplies it to the working tool (WT). The machine drive includes *an energy converter (EC), a transmission (T) and a motion transformer (MT)*. As the EC, the vast majority uses the electric motor, sometimes electromagnets, hydraulic pneumatic actuators. Transmission mechanisms can be divided into 3 types: which do not change, which change and which regulate the speed. The first type includes all kinds of clutch. Belt, chain, gear, friction transmissions are used to change the speed of the movement, and the variators are used to regulate the speed. MT is used to change the type of movement, most often rotational motion will be transformed into other types, such as reciprocating.

Holder (H) – is the element of the machine, which serves directly for the attachment and connection of individual elements of the machine; can be made in the form of a cast frame holder, metal construction or frame (welded or collapsible).

Working tool (WT) is an element of the machine that directly affects the product in this WT, the element operating the main technological function is called the main WT, and elements operating additional operations are called auxiliary working tool (AWT).

Receiver power device (RPD) are elements of the machine that serve to receive (provision) the primary product.

Output devices (OD) are elements of a machine that are used to output one or more resulting products of the technological processing.

Supports and Suspensions (SS) are machine elements that are used to connect the elements of moving machines with the fixed machines by means of springs and other spring elements.

Many modern machines and equipment include *control devices (CD), regulator devices (RD), measuring and control devices (MCD) and sensors (S).*

Working tools of the machine. Machines can have one or more working tools, they can be all movable, or some movable and the others fixed, or all stationary. In the latest case, the technological effect is achieved in most cases by the material motion.

Types of working tools. The following working tools are used in machinery and equipment.

Sieve working tools. They are used in bolters and separators for the distribution of bulk materials. For example, it is a set of sieve surfaces for splitting crushed stone into fractions for the preparation of building mixtures in the construction industry.

Rotary working tools. They are widespread in the construction and cereal – processing industries. Such tools operate high – speed rotational motion and are used for grinding and sorting, excorticating and hydrothermal processing, as well as in other machines and devices. This is, for example, the impeller of the rotary crusher or the excorticating and milling machine, various knives, rotors of air blowers and so on.

Roller working tools. Rotors for grinding, pressing and dispensing of products are also used. For example, milled, excorticating and grinding equipment is used.

Vibrating working tools. The oscillators for the intensification of most processes in processing machines: grinding, sorting, mixing, compaction, pressing are used.

Drum working tools. Drum tools are mainly used for mixing various mixtures and solutions (e.g. gravity mixers).

Air and hydraulic flows. They are used in air separators, pneumatic conveying equipment, heaters, washing machines, cereal humidifying machines, hydrodynamic classifiers and so on. They are also used in auxiliary working tools for the intensification of the main process, as well as the agitators for bulk materials.

Electromagnetic fields. These are the working tools of magnetic separators and so on. Auxiliary qualities of the working tools are used, as a rule, for the intensification of the technological process.

Screw working tools. These are working tools of presses of different construction (one-, two-, and multi- screw presses), machines for spinning of liquid fraction and so on. Usually screws are used in conjunction with matrices of different configuration, which is also considered as working tool;

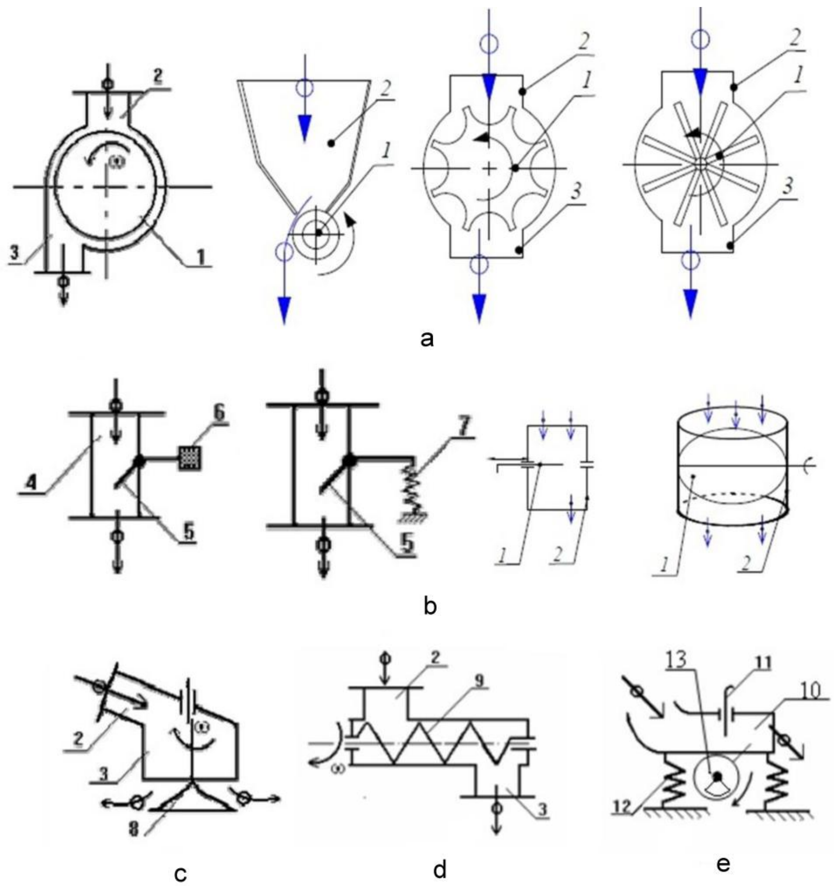
Chambers. These are working tools – vacuum, with high pressure, low and high temperature, nitrogen, argon and other gases, with ionization, etc.

In addition to the mentioned working tools, hammers, disks, beaters, abrasive and friction surfaces, pins, tapes, ladles, etc. are also used.

Receiver power devices. Receiver power devices in one form or another are part of any technological machine. Receiver power devices are not only a structural component of technological machines, but also form a whole class – dispensing mechanisms (gateway, rotary table dispensers and so on), operating independent functions that can be aggregated with the main technological machine. The functions operated by them differ depending on the specific machine and the type of product being processed. Most receiver power devices have the following requirements:

- continuously (uniformly in time) and evenly (in length, width or area of the working tool) submit the product to the work area;
- are able to change (regulate) the amount of product directed into the machine;
- ensure the hermetization of the internal (working) cavities of the machine.

Drum, valve (throttle), rotary table, screw and vibration receiver power devices are the most widespread (picture 2.5)



Picture 2.5. Receiver power devices schemes:
a) drum; b) valve – loading; c) screw; d) rotary table; e) vibration.
1 – a drum; 2 – an intake branch pipe ; 3 – an output branch pipe ; 4 – a branch pipe; 5 – valve; 6 – cargo; 7 – spring; 8 – rotary table; 9 – screw; 10 – tray; 11 – throttle; 12 – suspension; 13 – vibrator

Output devices. The most commonly output devices are used of the following types: valve, drum (usually gateway) screw, vibrating.

The following requirements are required for the output devices:

- to ensure the continuous and unimpeded removal of the product from the machine;
- prevent dust and product loss;
- to be simple and reliable in operation, easy to maintain;
- the output devices must ensure hermetization of the machine, as it is under discharge or excessive pressure, so they must not allow excessive suction or leakage of air, steam or other gas.

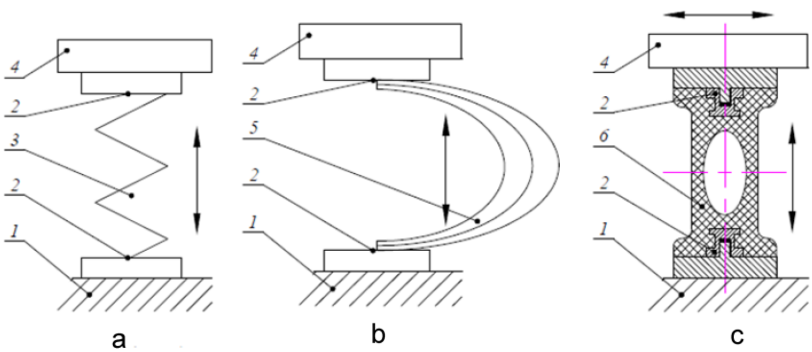
Supports and suspensions. Supports and suspensions are used to connect the moving and stationary elements of machines.

The shafts and axles are connected to the holder parts by means of bearing joints of various types.

The working tools of the oscillating machines are connected to the fixed joints by means of supports and suspensions. The type of support is selected depending on the type and amplitude of the oscillations.

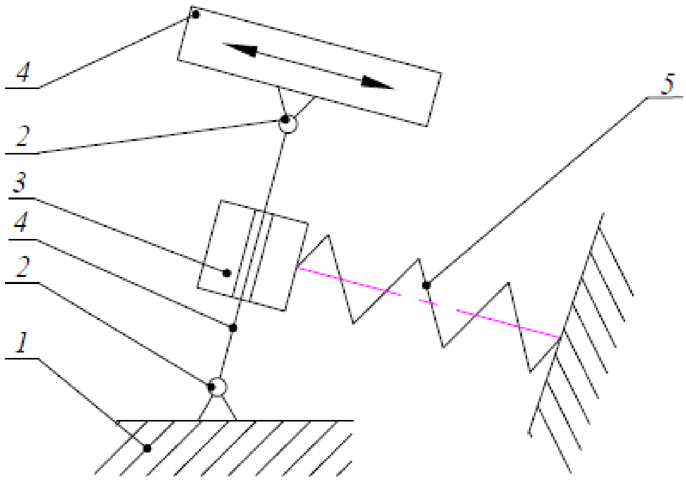
The articulating links are used for elements with *straight oscillations*.

Steel springs (picture 2.6, a) are used to provide *circular oscillations* in the vertical plane, and bent in the form of a semicircle or an oval (picture 2.6, b), or rubber-metal supports (picture 2.6, b) are used to provide elliptical oscillations, moreover rubber-metal supports are used for small amplitudes (for example, in a vibration dispenser (picture 2.6, c), or vibration sites, bolters.



Picture 2.6. Connection of moving and fixed elements of machines scheme.
Symbolic notation of a – helical spring, b – leaf spring, c – rubber support.
1 – holder (frame); 2 – metal support; 3 – helical spring; 4 – moving part of the machine;
5 – leaf spring; 6 – rubber support

If the element carry out *oscillates applied at an angle to the horizon*, the combined supports (picture 2.7) are used, consisting of articulating links and screw cylindrical springs, whose axes coincide with the directions of oscillations (for example, in the separator).



Picture 2.7. Scheme of connection of movable and fixed elements of machines with the use of combined support. Combined support symbolic notation.
1 – holder (frame); 2 – articulating link; 3 – support moving element (joint bearing); 4 – machine moving element; 5 – spring;

Machines with working tools that operate *circular translational motion* in the horizontal plane use flexible suspension brackets made of steel – wire rope, synthetic materials. Combined supports are used to provide *complex spatial variations*.

The main indicators and characteristics of machines that make it possible to estimate the workflow are effectiveness and capability, the determination of which is one of the main tasks of design of any machine. There are many methods and approaches for determining these indicators [5].

However, there is an opportunity from one standpoint to consider the method of determination. The idea of the method is to consider the energy balance of the machine – environment system at the stage of direct contact between the working tool and the environment being analyzed. This approach allows you to identify indicators that have a significant impact on the workflow, as well as opens the way to estimate the effectiveness of a particular process.

Common to any workflow is that the useful external energy of the machine can be defined as the production of useful power at the time of its use , i.e. in the general form can be written

$$A_{p.o.} = kPdt, \quad J \qquad (2.1)$$

where – index efficiency of the machine, which is determined by its constructive features.

As to the energy consumption of the technological process (crushing, sorting, mixing, etc.), its total expression can be obtained based on the idea of the physics of the process, which can be formulated as: the product of the energy density required to obtain a unit of environment, E_c (J / kg) the total amount of environment *m(kg)* processed:

$$A_c = E_m dm, \quad J \quad (2.2)$$

Equation (2.2) is an indicator of the energy expended in processing a unit of material mass. Similarly, you can determine the energy level per unit of volume recycling (for example, in a crusher's work chamber). Then we have the formula for the iinternal work:

$$A = W_V dV, \quad J \quad (2.3)$$

Now, you can write the energy balance of the machine-environment system:

$$kPdt = E_m dm \quad \text{or} \quad kPdt = W_v dV. \quad (2.4)$$

The physics of the parameter is that it determines the energy level that is absorbed by a particular environment according to the summed external energy level (2.4). This parameter is a qualitative indicator of the process. The indicator changes with the change of the state of the environment, as well as with a possible change of the operating parameters of the machine. Mass indicator *dm*, as well as volume, is a quality indicator of the process.

The energy balance equation (2.4) makes it possible to write in standard form and process production:

$$\overline{m} = \frac{k\overline{P}}{E}, \quad кг/с, \text{ or } \overline{V} = \frac{k\overline{P}}{W_v}, \quad м^3/с. \quad (2.5)$$

where $\overline{m} = \frac{dm}{dt}$, a $\overline{V} = \frac{dV}{dt}$.

It follows from (2.5) that productivity is the formula of the useful energy and the energy consumed per unit of process, i.e this formula determines the speed of transmission of the material being processed. The ratio $\frac{k}{E}$, as in $\frac{k}{W}$, formula (2.5) determines the level of efficiency of the machine.

Thus, equations (2.4)-(2.5) make it possible to find out a methodology for determining process parameters and to estimate the efficiency of machine parameters generally.

The quality of machines and equipment, in the broad sense of the word, is a universal philosophical category that encompasses both the phenomena of the outside world and human consciousness (tab. 2.1) [6].

Table 2.1. The concept of quality (based on examples of historical development)

Authors, sources	Formulation of definitions of concept quality
1	2
Aristotle (IV century BC)	Differences between subjects; differentiation on the basis of "good-bad"
Hegel (XIX century)	Quality is first of all identical with the existence of identity, so something ceases to be what it actually is, when it loses its quality
Chinese version	Hieroglyph denoting quality consists of two elements: "balance" and "money", therefore, the concept of "quality" is identical with the concept of "high-grade", "expensive"
Shewhart (1931)	Quality has two aspects: objective physical characteristics; subjective aspect: the thing "goodness"
Ishikawa K. (1950)	Quality is a property that really satisfies consumers
Juran J. (1979)	Suitability for use (fitness for purpose); subjective side: quality is the degree of consumer satisfaction (in order to realize quality, the manufacturer must learn about the consumer's requirements and make his product meet these requirements)
International Standard 180 8402-94	Quality is a set of properties and characteristics of a product or service that give them the ability to meet specified or foreseeable needs.
DSTU180 9000-2001	"Quality is the degree to which a set of characteristics meets the requirements"

Aristotle in the IV century BC was the first one, who analyzed the category of quality and defined it as a "species difference" of one entity from another, belonging to the same species. He pointed to the variability of quality as a change in the state of things, their ability to turn into their opposite (proper-damaged, useful-harmful, sweet-bitter, warm-cold, white-black).

Hegel believed that "quality is in general identical with existence identity... something, because of its quality, is what it actually is and, by losing its quality, ceases to be what it actually is".

In addition to the philosophical interpretation of quality, there is a narrower concept of the word "quality": product quality, quality of work, business qualities, quality of executive mastery, quality of life, etc. The quality of product and services will be the subject of our examination.

The product quality category is one of the most difficult to deal with by professionals.

The product quality category is used in the selection of items to meet both production and individual needs, production planning and estimation of its results, determination of its complexity and efficiency, organization of work, creation of new products.

The quality category is also applied when there is a need to consider the composition and nature of product properties. There are two characteristic methods of quality change. The first one is simply regrouping those characteristics that product has. In this case, the new quality is formed by changing the number and nature of the connections between the characteristics, the composition of which remains the previous, and only the structure changes. However, if the mechanism of quality development consisted only in such a simple redistribution of characteristics, then the quality of product would not develop progressively and some characteristics would benefit at the expense of others.

The second method is more difficult – changing the composition of product characteristics.

The first involves in the jumps with a smooth transition of qualitative changes to the new quality and the second involves in the jumps with a sharp change of quality, and a fundamental increasing technical level.

There are many definitions of the "product quality" concept, among which the most precise formulation is that of the European Organization for Quality Control: "Product – is considered to be of good quality if at the lowest cost throughout its life cycle, it maximally contributes to the health and happiness of people who are involved in its constructional design and restoration (reuse), with minimum energy and other resources and with acceptable environmental and social impacts". This statement clearly defines the connection of the product quality problem with other vital problems for human, i.e. the preservation of the environment, the rational use of natural resources, the impact of economic activity on the living conditions of our descendants.

In order to streamline quality terminology, the International Standards Organization has completed a considerable amount of work, which has resulted in the development and publication of standard 180 8402:1994. Later this standard was revised, added to the standard 180 9000:2000, adopted in Ukraine as DSTU 180 9000-2001. This standard defines the following.

Quality is the degree to which a set of characteristics satisfies certain requirements. A requirement is a formulated need or expectation that is generally understood or obligatory.

The requirements can be related to any aspect such as performance, efficiency or trace-ability. Performance is the degree of realization of the planned activity and achievement of the planned results. Efficiency means the relationship between the achieved result and the used resources. Traceability is called the ability to trace the backstory, application, or whereabouts of topic under consideration.

Quality management is a coordinated activity that aims at directing and controlling the organization for quality. An organization is considered to be an aggregate of people and means of production with a division of responsibility, authority and relationships. Quality directing and management typically cover the development of quality policies and objectives, quality planning, quality control, quality assurance and quality improvement.

Quality policy – the overall intentions and focus of a quality – related organization, legally formulated by senior management, to which a person or group of individuals relate, who direct and control organization activity on the highest level.

Quality goals are what they want or aim for in quality industry. Goals are generally based on the organization’s quality policy and are defined for the appropriate functions and levels within the organization.

Quality planning is a component of quality management focused on setting quality goals and identifying the operational processes and appropriate resources needed to achieve those goals. An integral part of quality planning can be a quality program – a document that defines what techniques and resources are appropriate, who and when to apply to a specific project, product, process, or contract.

Quality control is a component of quality management focused on meeting quality requirements.

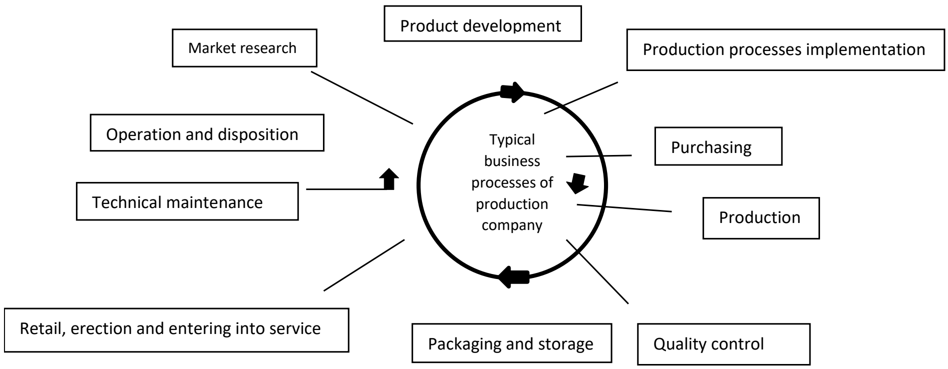
Quality assurance is a component of quality management that focuses on ensuring that quality requirements will be met.

Quality improvement is a component of quality management that focuses on increasing the ability to meet quality requirements.

A quality management system is a management system that guides and controls the organization's quality activities.

Quality circle is a conceptual model of interdependent activities that affect quality at different stages of manufacturing of product or services.

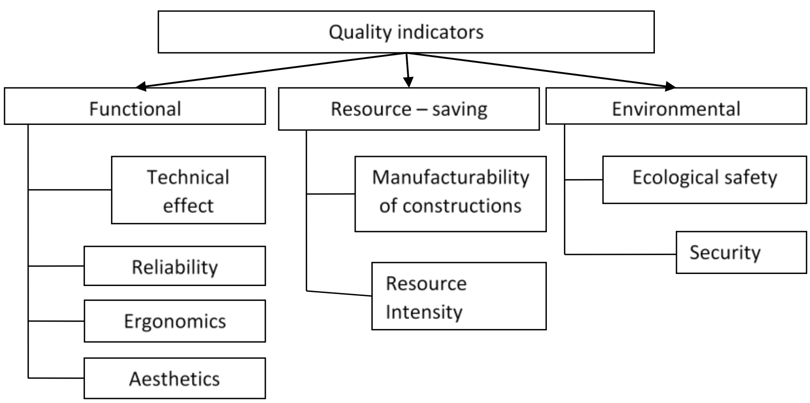
The quality circle is shown in the picture 2.8.



Picture 2.8. The quality circle

At the end of the basic terms review, it should be noted that in both foreign and native practice, instead of the terms "quality control" and "quality management systems", the following terms are most often used, respectively: "quality management" and "quality systems".

Machine quality indicators. The production quality can be expressed by measuring indicators (picture 2.9).



Picture 2.9. Quality indicators

Functional quality indicators of machines express their consumer properties. Indicators of technical effect characterize the ability of the machine to operate its functions under the specified conditions of use for the intended purpose: productivity, power, operating characteristics, defining useful work, etc.

Reliability is estimated by dependability, durability, maintainability and storage.

Ergonomics is estimated by hygienic indicators – compliance with sanitary standards, anthropometric compliance of the product with the physiological properties of human and features of the functioning of human senses (speed of movement and power capabilities of human, hearing thresholds, vision, etc.). The ergonomics include psychological indicators, reflected in engineering and psychological requirements (requirements of psychology of labor and general psychology), which are imposed to the products (work at depths, at height, etc.).

In estimating ergonomic indicators, the elements of construction that influnce the human efficiency are distinguished – the cabin and its equipment (hatches, windows, communications, ventilation and lighting). The cabin equipment also includes indicator and signaling devices, hand operated control levers, treadle and working furniture.

The aesthetics indicators include:

1. appearance indicators (selection by color, processing, symmetry or asymmetry, design harmony, expressiveness, originality, etc.);
2. indicators of forms modernity (originality of forms and silhouette, conformity of form and functions, harmony of proportions, decorativeness of separate elements, etc.).

Resource saving quality indicators of machines:

1. manufacturability indicators – constructive material intensity, energy intensity, complexity, transportability and a measure of standardization. These indicators characterize the costs incurred in the construction of material, energy and labor resources, which are required for the execution of production, preparation for transportation, functioning, operation, technical maintenance and repair;
2. Resource intensity indicators of workflow reflect the perfection of a product as they consume material, fuel, and energy resources in the functioning process in its intended use, i.e. the ability of the product to operate its functions when using resources in volumes that meet established standards.

Environmental indicators include the following ecological indicators:

1. the content of harmful impurities emitted by the machine into the environment;
2. the probability of emissions by the machine of harmful particles, gases, radiation during its storage, transportation, maintenance and repair.

These indicators are estimated by comparing the actual values with the standards for nature protection, set in those that meet GOST, with the permissible content of impurities in the air, soil and reservoirs. These standards are established on the basis of the analysis of possible harmful actions: chemical, biological, light, sound, radioactive, etc.

Safety indicators reflect the level of human security in the system "Human-machine" when using the established measures and means of protection in the event of emergencies caused by accidental violations of rules, changes in conditions and modes of operation of the product. Safety indicators are the probability of a human safe work when manufacturing or operating a machine for a fixed time, the time of activation of protective devices, etc.

Quality assurance and competitiveness of machines. The main types of quality assurance and competitiveness of machines:

1. technical – constructive, technological and metrological;
2. economic – financial, regulatory and material;
3. social – organizational, legal and regular.

All these types are used in complex. The experience of complex approach to them is generalized in the international standards of the ISO series 9000 and the standards developed on their basis:

1. GOST 40.9001. Quality system. Model for quality assurance in design and development, production, installation and maintenance of products;
2. GOST 40.9002. Quality system. A model for quality assurance in final control and testing.

Competitiveness is a set of properties and characteristics that provide a superior (in comparison with other products) possibility of realization of this product in a specific domestic or external market in the given period.

The main criteria for competitiveness:

1. technical level of the machine reflects the relative perfection of this machine in comparison with others of similar purpose, which are supplied (or with prospective delivery) in the same market;
2. economic level of the machine determines the relative amount of consumer costs for the purchase and use of this machine in comparison with other similar products, including payment of customs duties, taxes, transportation costs, erection and adjustment of the purchased machine, payment for spare parts, materials and fuel, maintenance costs and repair;
3. patent – legal security of the machine is determined in terms of specific market conditions.

In providing and estimating the technical and economic levels in the stages of development of the machine construction takes into account the totality of functional, resource – saving and environmental properties and quality indicators that characterize them.

The economic level is estimated at the full cost of the purchase and use of machinery, including one – off and operating (current) costs. One – time costs include the price of the machine, additional costs are possible; customs duties and costs, costs for packaging, transportation and erection, adjustment, etc. These also include the costs for constructions, the need for which is caused by consumer’s installation conditions and technical maintenance.

Operating (current) costs include staff remuneration, fuel costs, electricity, basic and auxiliary materials, repairs, the purchase of additional technical and operational information and documentation for personnel training and product operation.

The patent – legal security of a product is expressed by:

- patent purity – it is a measure of the implementation in the product of technical solutions that do not fall within the scope of patents exclusive rights issued in Ukraine (for the domestic market), as well as issued in the countries of deemed export;
- patent protection of a product – it is a measure of protection of a product by patents in Ukraine and in the countries of deemed export or selling of a license (product embodiment of domestic technical decisions recognized as the invention in the country and abroad).

In order to keep up product competitiveness, a constant study of market conjuncture is required. Therefore, the development of product, the execution of design operations and the formation of requirements for the product is preceded by a stage of marketing, search and market study. Marketing functions are a constant provision of feedback from developers and manufacturers with the consumer, control of receiving reliable information from him and forming a technically and economically valid design strategy.

The primary information for quality requirements; current international, national and regional standards and standards of firms governing product quality:

- government enactments, current legislations, regulations and technical orders of product imported into the country;
- the results of market conjuncture research and demand for similar product;
- results of comparative tests of research and exhibition samples, and certification of similar product that produced in the country and abroad.

Quality level is a relative quality characteristic based on the comparison of a set of indicators (using indicators of prospective samples, analogues and standards).

Prospective sample is a sample whose set of indicators correspond to the predictable, economically optimal level of quality of product of this type for a certain period. The economically optimal level of quality of the prospective sample is determined so that it is not chronic "morally" until the product is absorbed into service. A promising sample should take full account of scientific and technological achievements and the consumer's requirements for a long – term perspective.

Analog is an example of a product of domestic and foreign production of the same type, constructive device, of functional purpose, principle of operation, scale or conditions of use, as the product which is under development.

The estimation of the quality level of product is as follows:

Preceding (enlarged) estimation of the quality level of equipment, reflecting this level in the future and produced at the stage of the technical specification by determining the coefficient:

$$K_y^{(1)} = \frac{K_{тз}}{K_{сз}} \quad (2.6)$$

Interim estimation of the quality level of product or the level of conclusions developing by the coefficient:

$$K_y^{(2)} = \frac{K'_{ту}}{K_{сз}} \quad (2.7)$$

Final estimation of the quality level of the product generally, or the level of new equipment mastered in production by the coefficient:

$$K_y^{(3)} = \frac{K''_{ту}}{K_{сз}} \quad (2.8)$$

The final estimation of the quality level of operating product generally by the coefficient:

$$K_y^{(4)} = \frac{K_{эд}}{K_{сз}} \quad (2.9)$$

where $K_{зд}$ – quality level coefficients;

$K_{ту}$ – quality coefficients of the specifications at the appropriate development stages;

$K_{сз}$ – aggregate quality indicators, reflected in accordance with social mandate (initial requirements of the customer or consumer), technical requirements, specifications and operational documentation.

Standards with prospective requirements, research reports, technical requirement, design documentation, working, operational and repair documentation are used as initial documents.

Differential, complex and mixed methods are used to assess the quality level (technical level).

Differential method is a estimation of individually taken indicators for the purpose of further action on these indicators. The complex method is a comparison of certain set of single indicators with a similar set of basic indicators by their numerical values. The mixed method is used when there is no possibility to obtain summarized conclusions and conclusions of single indicators simultaneously.

2.6. CONSTRUCTIONAL DESIGN OF TECHNOLOGICAL SYSTEMS BASED ON MACHINES

An individual machine can be considered as a core element of a machine system, which is used to perform a particular workflow.

The concept of *machine* covers a large variety of objects that are used by human to meet his needs.

By definition of Artobolevski I. I. the term *machine* means a device created by human, as a result of the study and use of the laws of nature to facilitate or completely replace his physical and mental work, to increase productivity and accuracy in the execution of technological, transport and other processes [7].

In a shorter form, the term "machine" can be defined as follows: *a machine* is a technological system that operate mechanical movements to transform energy, materials, and information. Since mechanical movements are carried out in machines at the expense of individual elements, which are interconnected and united in some entirety for a specific purpose, they have all the characteristics of systems.

Each machine as a technological system has a specific purpose and formation (structure). The purpose of the machine is determined by the functions it can operate in different conditions of use.

To implement these functions, a machine structure is created that defines its properties. Structurally, a machine as a system may consist of subsystems of different levels and of the individual elements that form these subsystems.

By the functional feature, machines can be divided into energy, working and informative.

An energy machine is a machine used for transformation of any type of energy into mechanical energy or vice versa.

In the first case, it is called the engine – machine and in the other it is a generator – machine.

Engine – machines include: electric motors, steam and hydraulic turbines, internal combustion engines, etc.

Generator – machines include electric power generators, compressors, hydraulic pumps.

A working machine is a machine which is used to transform position changes and to research properties of materials. Working machines are divided into technological, transport and testing.

Technological machines are working machines in which the transformation of the material is occuring by changing the properties, shape, sizes and position. Technological machines include metal – working machinery, construction machinery, agricultural machinery and other machines.

Transport machines are designed to move various objects in the space. These machines include: locomotives, electric locomotives, cars, lifting and transporting machines, elevators, etc.

Testing machines are used to investigate, for example, the effect of mechanical action under specified conditions on the properties of a material or product (pull test machine friction machine, hardness gage, etc.).

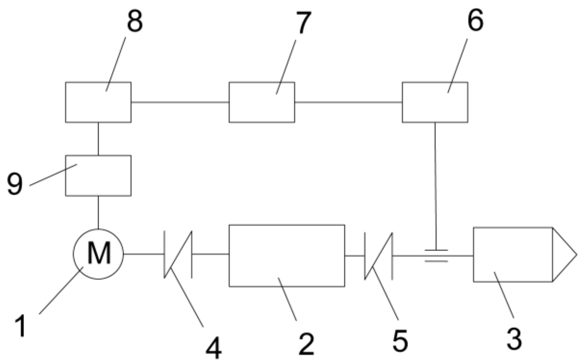
An information machine is a machine for converting information. The basis of these machines are computing machines (computer equipment), which are used to operate calculations, logic and mathematical operations, process modeling, solving optimization problems, etc.

Automatic machines hold a prominent place in the modern technology. They are mainly used when it is necessary to operate the same operation many times.

Metal – working automatic machines are examples of automatic machines. In addition, machines with computer –based hardware that automatically operate complex processes on a pre – created program in optimal mode are used.

Automated control systems that operate with human participation and automatic control systems, such as robot movement that operate without any human participation are used to perform the functions of control and to manage the technological processes and enterprises.

Robots are manipulator mechanisms with control means based on computer equipment, which are used to operate movements and control functions that replace similar human functions.



Picture 2.10. Functional and structural scheme of the machine structure: 1 – engine; 2 – the transmission mechanism; 3 – working tool; 4, 5 – connection elements between the machine elements; 6, 7, 8, 9 – respectively measuring, controlling, managing and regulating devices

According to the functional feature construction machines can be divided into classes there: horizontal railless transport; lifting and mounting; continuous transport; loading and unloading; earthmoving; drilling; piles; mechanical processing (crushing and sorting) of stone materials; preparation, transportation and laying of concrete mixtures and mortars; production of reinforced concrete products; road; finishing and mechanized tools.

Each of these machine classes is divided into groups that differ in the nature of the workflow (interaction with material) or mode of operation. Thus, earthmoving machines are divided into earthmoving and earthmoving equipment.

In turn, earthmoving machines can be cyclic (single bucket excavators) and continuous operations (multi bucket or rotary excavators).

In addition, groups can be divided into types that differ in the constructional design of individual elements. All types of machines have a number of sizes, which differ from each other in terms of basic technological parameters (load capacity, take – off and lifting height for the crane, bucket capacity for the excavator), but have basically similar formation.

In functional and structural terms, modern working machines consist of a number of interacting parts (elements): energy part, transmission mechanisms, executive (working) tools and a complex of measuring devices and devices of control, regulation, management (picture 2.10).

The executive (working) tools are the main part of the machine. They operate a set of technological processes for the transformation of material (object of labor) into a product of manufacture.

As the working tools transform various natural materials, processes and raw materials into a product of manufacture, so the principle of action, constructive forms and other characteristics of the working tool are determined by the properties of the material for processing, the parameters and features of the process implemented by the working tool.

For example, the working tool of the excavator (bucket) is adapted for digging and excavation, crushing plates of the jaw crusher are adapted for grinding of input construction materials.

The energy part (engine) provides the mechanisms with energy and the working orientation by converting different types of energy into mechanical energy. Depending on the required effort on the working tool and its mode of motion, the engine has certain mechanical characteristics (dependencies of the movement speed on the effort).

Engines have undergone a number of historic stages in their development, from the invention of the steam engine to the widespread use of electric engines. Moreover, electric engines are used for each functional mechanism.

Today, internal combustion engines are widely used in transport, construction and other machines, which in the future are likely to be of limited use because they have significant toxicity and cause undesirable environmental impacts, and also due to the limited hydrocarbon fuel.

The transmission mechanism is an intermediate link between the engine and the working tool, the task of which is to transfer the motion energy from the engine to the working or executive mechanism.

The energy and motion of the engine are transformed by various transmission mechanisms (gears, chain, belt transmissions, shafts, clutches, hydraulic transmissions) into the necessary motions of the working tool.

Since the engine shaft has a higher speed of rotation than the main shaft of the working tool, the task of the transmission mechanism is to reduce the speed of rotation of the engine shaft to the speed level of the main shaft of the working tool.

The transmission mechanism on the one hand is determined by the principle of action, the nature of the motion and other parameters of the working tool, and on the other is determined by the type and construction of the engine. The transmission mechanism of the machine connects into a single unit – *a technical device* that performs the specified technological functions in the production process.

The managing and control part of the machine ensures the autonomous functioning of a technical device that operates a particular work process through self – adjustment, self – regulation and self – control.

In this process, a human becomes part of the manufacturing process, instead of being its main participant and to switch to creative activities.

Analysis of the _functional and structural formation of the machine_ shows that the machine consists of elements (subsystems) that are interconnected.

In addition, each of the considered subsystems is divided into lower – level subsystems. Thus, the internal combustion engine includes subsystems: cylinder – piston group, transformation of the progressive motion of the piston into rotational motion of the crankshaft, power supply, gas distribution, inflammation, lubrication, cooling. Moreover, there is some relationship between these engine subsystems.

Similar lower – level subsystems can be removed in transmission and executive mechanism, measuring, controlling and regulating devices. All this shows that the machine is a complex technical system with a hierarchical structural formation.

In addition, the life cycle of the machine is a complex system. The structure of the life cycle of the machine includes the processes of its development, manufacture, operation and repair, which cover the time from the idea appearing of the machine creation to its removal from service.

The life cycle usually includes the following major stages or forms (picture 2.4):

1. Formation of requirements for the machine and development of a technical requirement (TR).
2. Machine constructional design.
3. Manufacturing, testing and finishing of a prototype machine.
4. Serial machine production.
5. Operation and purposeful use of the machine.
6. Machine repair.

The first stage of the machine life cycle is external constructional design.

This stage is directed to the issues involved in figuring out the goals for achievement of which the machine is being created. The range of tasks that are planned to be solved with the help of the machine is specified, as well as the properties of the external environment and the characteristics of its influence on the machine are studied.

The result of external constructional design is a technical specification for the project design, which contains the basic requirements for the machine and its interaction with the external environment, which makes it possible to solve the set tasks for the creation of the machine.

The second stage, to emphasize its difference from the first, is often called interior constructional design. This is the stage of direct development of the machine constructional design. It is directed to the issues related to the definition of the internal structure of the machine, with the technical solutions of its subsystems and constructions of their elements, as well as the parameters and modes of operation of the machine.

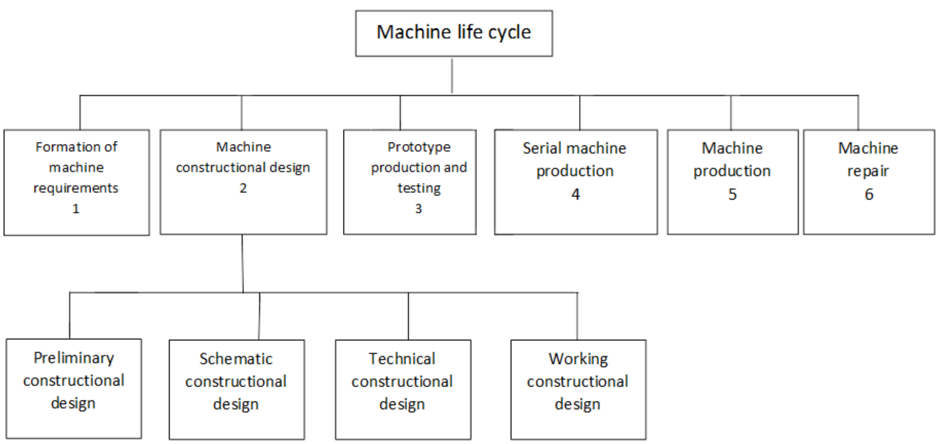
The purpose of constructional internal design is to develop all the necessary constructional – design documentation, which is a working design of the machine that meets the requirements of the technical specification, i.e. the requirements of external constructional design.

From an informational point of view, constructional internal design is the process of converting input information about a design object, the state of knowledge in this field, about the experience of designing objects of similar purpose into the output information in the form of constructional – design and technological documentation, which is made in a certain form and contains a description of the object for its material realization, i.e. production.

From the point of view of the theory of decision making, constructional design is the process of making constructional design decisions, which aims to obtain a description of the machine with a given degree of detailing, which satisfies the requirements of the technical specification.

The second stage (of the constructional design) links the scientific research with the practical implementation and is the process of developing a description sufficient for creating a still non existing machine. This stage is without a doubt one of the most important stages in the life cycle of the machine. It has four main phases:

1. preliminary constructional design or phase of technical proposals;
2. schematic constructional design;
3. technical constructional design;
4. working constructional design.



Picture 2.11. Machine life cycle stages

In the first stage, the formation of the technical concept and the basic (accounting) parameters of the machine, ensuring the fulfillment of the requirements of the technical specification, is carried out [8].

At this stage, the inaccuracies in the requirements of the technical specification are eliminated and external constructional design requirements are harmonized with internal constructional design capabilities.

Characteristic of this preliminary constructional design is the lack of detailed structuring. Here, decisions are made on issues relating to the machine as a whole. The output of this stage is the technical proposals for the development of the constructional design of the machine.

The main purpose of schematic constructional design is to clarify the characteristics and parameters of the machine associated with the constructional design development of its main subsystems and devices and the formation of their accounting. The latest is carried out on the basis of hierarchical (level) structuring of the machine and is accompanied by a wide range of calculations and experimental studies.

The elaboration must be of such depth that a comparative analysis of the quality indicators of the constructional design solutions of the various machine variants can be made, taking into account the constructional and operational characteristics. The output of this stage is a schematic constructional design of the machine.

The technical constructional design phase involves the development of a set of constructional documents containing the final technical solutions of the machine. The technical constructional design evaluates the final conformity of the constructional design solutions to the requirements of the technical specification and the degree of complexity of the machine production, as well as suggest the rules for its operation and repair. The output of this phase is a technical constructional design, which is the basis for the development of working constructional documentation.

Finally, at the *working constructional design phase (designing)*, the depth of the constructional design elaboration reaches the level of details. The result of the work at this phase is a working constructional design, which is a set of constructional documentation for the machine, instructions for the manufacture and assembly of its elements in joints and devices, and the machine as a whole, as well as instructions for testing, operation and repair of the machine.

The processes of setting and solving constructional design problems that satisfy the given conditions are carried out in the constructional design stages. The following stages of the life cycle of the machine largely depend on these stages.

In the third stage of the life cycle of the machine is the production and testing of a prototype machine.

The machine prototype may be created by the developer, i.e. by the organization that develop constructional documentation, or by the manufacturer – organization that develop constructional documentation, or by the manufacturer – organization that will carry out serial machine production.

At this phase, a separate sample or experimental batch of machines may be produced. The technology of manufacturing individual parts and assembling them into separate joints, devices and machines as a whole is being worked out during the production of the prototype.

After production of the prototype, the machines carry out preliminary factory tests, during which rational operational modes are worked out, they reveal the need for any changes in the constructional design of the machine or its components.

According to the results of preliminary tests, which are carried out jointly by the developer and the manufacturer, they solve the question of the possibility of acceptance tests implementation, adjust the constructional documentation, make changes in the construction of the prototype.

After successful preliminary tests, the issue of acceptance tests implementation is solved, which, depending on the nature of connection between the co – executors, may be departmental, inter – departmental and national.

Acceptance tests certify the conformity of the machine to the developed technical documentation and the possibility of starting the machine in serial production.

The fourth stage is the stage of serial production of the machine. The implementation of this stage begins with the technological preparation of production, which is aimed at developing technological lines for the manufacture of parts and assembling them into joints, devices and the machine as a whole. It also selects equipment, materials, tools, etc.

At this stage, the technological requirements for the manufacturing process of the machine, which are aimed at reducing the cost of production, reducing energy and material costs, as well as providing functional indicators, social, operational and economic requirements, must be satisfied. This can be done by selecting the most effective methods of manufacturing parts and strengthening their surface layer, as well as improving the purity and accuracy of the parts cutting. The result of this phase is the serial production of machines of one or another quality that go into service.

At the fifth stage (operational stage) the use of the machine is occuring. At this stage, the constructive, technological and other properties of the machine are manifested. The basic requirement for machines in the process of operation is to perform their functions for the purpose with minimal operating costs. The latest largely depends on the level of reliability of the machine, which, in turn, depends on how well the solution issues of strength, rigidity, durability and accuracy are made when designing.

In addition, the operational reliability of the machine is highly dependent *on* the operating conditions and driving modes of the drive mechanisms, which are determined by the quality of the machine management.

Ensuring the necessary operational reliability of the machine depends on its technical state, which must be maintained at the required level through timely technical maintenance and repairs.

The quality of the carrying out of the latest one depends largely on the level of repairability of the machine, which is ensured when the construction of the machine provides a system of controllability, accessibility, replaceability, interchangeability, standardization and unification. The level of technical state of the machine is determined by diagnosing individual elements, subsystems and the machine generally as a system.

All viewed *stages of the life cycle of the machine* are accompanied by scientific researches, i.e. at each stage there are problems that can not be solved in the traditional ways, but require the development of special methods. The final goal of these researches is to develop machines that would have high economic effectiveness.

In the design process, a significant number of factors that determine the efficiency of production and use of machines should be taken into account. Sometimes the simplification of the machine construction and its manufacturing technology results in considerable maintenance and repair costs during operation.

Deep economic researches show that the main criteria for effectiveness of the machine is often not its cost, which is determined by the materials costs, research, design work and manufacture of the machine, but its productivity, reliability, energy costs, maintenance cost, repairs, etc.

From the analysis of the stages of the life cycle of the machine we can conclude that they are closely interconnected. External design determines the purpose of the machine and its requirements. On the basis of external design, internal design is carried out, which determines the structure of the machine, construction and packaging (placement) of its components. The decisions made determine the technology of manufacturing machine parts and machine assembling. The construction and the level of technology of the machine make a significant impact on its operational reliability. Operational conditions determine the level of technical state of the machine.

Upon reaching a certain technical state of the machine, certain types of repair are carried out with some frequency.

Thus, all the above shows that *the life cycle of a machine* can be considered as a complex technical system, the subsystems of which are separate stages of creating machines, which, in turn, are divided into subsystems of lower levels.

So, the constructional design process is divided into the stages of external and internal design, at the same time the latest one is divided into preliminary, sketchy, technical and working. Therefore, the process of creating a machine must be approached as a complex technical system, taking into account the connections between the individual elements. Failure to take account of this can lead to the perverse outcome in the machine creation process.

2.7. THE MAIN TASKS IN THE DESIGN OF TECHNOLOGICAL SYSTEMS

As was shown earlier, first of all, parts of a complex system are subsystems of different levels, into which the initial system is divided. Since the subsystems of the upper levels are often quite complex and divided further, in reality the smallest, indivisible systems, which are conditionally called elements, are subject of study.

An independent part is the so – called interface circuit of elements, i.e. a circuit that implements addressing signals that reflect element interaction. It is determined that systems are not called complex if they are studied as a whole without the specified structuring.

This is the main difference between simple and complex systems. The difference between them is generated not so much by the research itself, but mainly by the tasks facing the researchers.

Let us take a detailed look at the components of complex technological systems in order to study the problems that arise in their research. Firstly, let us turn to the elements of technological systems. Each element is a dynamic system that functions in time, changes its state over time due to internal and external causes, receives inputs and produces outputs signals in the process of interaction with other elements of the system.

The indicated properties are common to different elements, but each element has its own characteristics.

In the technological system of construction of hydraulic structures it is possible to distinguish heterogeneous elements – reinforced concrete plants, unloading devices, machines system for the production of crushed stone, etc.

The operation of each element and system generally is significantly influenced by random factors (failures of technological machines and transport vehicles, random flows of transport on different sections of the road from factories to the place of construction, random durations of various operations).

All of the above leads to the conclusion that to describe the elements of complex technological systems it is necessary to have a set of formal mathematical models that satisfy, on the one hand, the general properties of all dynamic elements, and on the other – take into account the different individual features of the functioning of each particular element.

Thus, one of the most important tasks of the technical systems theory is the search for mathematical models that adequately reflect the specifics of the elements of complex systems. At the same time, such mathematical models should allow the research of systems by analytical or machine (computer) methods.

A number of such models that are widely used in the complex technical systems theory will be viewed next.

The basis of the operation of complex technological systems is the interaction of elements, which is represented as a mechanism of signal exchange. This mechanism involves the processes of forming the output signals and responding on the input signals by various elements, addressing the signals and passing them through the connection channels.

The accounting of processes of forming the output signals and responding on the input signals belongs to the problem of constructing elements as dynamic technical systems. It is further convenient to consider that the signal is not subject to distortion when passing through the connection channel and the transmission process itself is instantaneous. Such channels are called ideal. They occur when the system is divided in case the real system does not have any connection channels and they are input only for the existing interaction of system elements.

Such connection channels exist in the technological system of construction of hydraulic structures. In a real system, there are real connection channels (for example, a software control system for the movement of a welding manipulator mechanism in a reinforcement shop of the reinforced concrete plant), which, of course, are not ideal.

In this case, it is convenient to formalize them as separate elements of the system that realize delays and deviations of signals. Such elements are connected with other elements of already perfect connection channels.

So, to study the process of interaction of elements of the technological system, it is enough to consider a interface circuit that implements the addressing of signals in the system with ideal connection channels.

When considering the interface circuit, the elements are represented as multiport networks that have a certain number of input and output contacts – the number of these contacts is different for various elements.

If all the input contacts of the elements of the system and its output contacts are numbered, the task of the interface circuit means the comparison in each pair (i, j) (where i, j are sequence numbers respectively of the input and output contacts) of the fact of the presence or absence of an ideal connection channel. Such construction also takes into account the interaction of the system with the outside environment, it is enough to imagine the outside environment as a phantom element, which has a large number of input contacts.

The certain problems arise with the interface circuit of elements of the technological system. First of all, it is the task of structural analysis of complex technical systems that reveal different connections between system elements.

There is an arising interest in the question of the existence of a chain of connection channels that connect different elements. A deeper study involves taking into account the direction of signal transmission, as well as their types. Under the term "type" a meaningful interpretation of the purpose of the transmitted signals is understood.

For example, some signals correspond to material flows in the system, others to informational, the third one serve to the management purposes. Such division of signals, of course, is manifested in the fact of their occurrence at certain output terminals, which makes it possible to use structural methods for studying the specified tasks, which allow finding the so – called typical structural configurations (circles, cycles, loops, etc.).

These configurations play an important role in determining the capabilities of the signals of transmission and processing system. Moreover, such properties of structures as connectivity, hierarchy, etc. are also revealed.

Formal structural transformations play a special role when the initial structure of the system is transformed into another. So, some subsystems can be divided into a number of smaller subsystems or, conversely, a number of elements are combined into one subsystem.

Such transformations play an important role at the synthesis phase, when the issue of the possibility of creating a system that has the set properties and has some standard set of elements is being solved.

However, it should be noted that the methods of structural analysis and synthesis of complex technical systems are developed much less than the methods of synthesis and analysis of the dynamics of individual elements [9, 10].

Based on the foregoing, it can be concluded that the main task of the theory of complex technical systems should be considered the development of methods that allow, on the basis of studying the features of functioning, obtaining the characteristics of individual elements and analysis of the mechanism of interaction between elements, to obtain the characteristics of the system as a whole.

The system modeling method is the only method that exists today and allows to find the characteristics of the system as a whole. The methods of machine modeling using computer technology need to be recognized as the most effective and productive.

However, the modeling method can be successfully applied only if its implementation fully takes into account the features of objects modeling, i.e. the modeling should be purposeful (in the direction of harmonization of model experiments with the properties of the modeled system).

On the basis of models of technological systems, their properties and characteristics can be determined, analysis of their functioning and structures can be carried out, the systems structure and the parameters of their elements can be optimized, the systems management, including the optimal, etc. can be managed.

QUESTIONS FOR SELF-CONTROL:

1. What is a "**mechanical system**"? Provide some basic definitions and give examples.
2. What is meant by the term "**technical system**"? Give examples.
3. What production and organizational systems are known to you?
4. What is "an environment-machine" **technological system**?
5. How is a "**machine system**" created and what is it based on?
6. What is meant by the term "**machine**"?
7. Provide classificational features of the machine.
8. Outline the structural scheme of the machines and their elements.
9. List main tools of the machine.
10. Which devices in one form or another are included in any technological machine?
11. Provide basic indicators and characteristics of the machines.
12. Explain the concept of "**quality**" in the examples of historical development.
13. What is the "**quality circle**"and what elements do you know?
14. What quality indicators of the machine do you know?
15. How to ensure the quality and competitiveness of machines? How can machines be divided according to their functional features?
16. What is "**the machine life cycle**"?
17. What stages of "**the machine life cycle**" do you know?
18. What is the main issue when designing technological systems?

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Chapter 3. The modeling process of constructional design of technological systems

Contents of Chapter 3

Keywords: model, model description, modeling, models formulation, modeling issue, similarity, modeling methods, analytical methods, numerical methods, simulation modeling methods, statistical modeling, full-scale modeling, semi-scale modeling, physical modeling, mechanical similarity, similarity criteria, similarity theorems, dimensional analysis method.

3.1. PRINCIPLES OF TECHNOLOGICAL SYSTEMS MODELING

Theory methods of technical systems are based on the description of certain facts, phenomena, and processes. Our knowledge is always relative, so any description in one language or another also reflects only some aspects of the phenomena and can never be complete.

If you use the language of philosophy, you can say that description, reflecting our knowledge, is always relative.

Recently, the word "model" has become quite widespread. The concept of *model* suggest many different explanations. There is even a classification of models.

In the systems theory, the term *model*, *model description* means some description that reflects the particular features of the process being studied, which interest the researcher. The accuracy and quality of such a description are determined first of all by the model's correspondence with the requirements of the research, the correspondence of the results obtained with the model results to the actual running of the process.

Models formulation is always an informal procedure and usually depends on the researcher, his experience, his talent. It always relies on some research material and it is often said that the modeling process has a phenomenological principle.

The model should reflect the phenomena correctly enough, but this is not enough. It should be easy to use. Therefore, the degree of particularization of the model, the form of its representation, etc. are determined by the purpose of the research and are directly dependent on the researcher.

Working with the same research material, different researchers may represent it completely differently. But for all that difference, there are general principles of modeling that are unacceptable to neglect. Let us dwell on this more in detail.

The main *issue of the analysis of technological systems* is to distinguish real motions from the set of seemingly acceptable ones, to formulate the principles of their selection. Hereinafter, the word "motion" we understand as a broader concept – the change of the system in general, every interaction of its material objects.

The modeling issue is to describe these principles of selection in terms and variables, which most fully characterize the system under study according to the views of the researcher. Selection principles are narrow many of the acceptable motions, rejecting those that cannot be implemented. The more perfect the model is, the set of real motions becomes narrower, the more accurate the prediction becomes. In different areas of knowledge the principles of motions selection are different.

Modern science considers three levels of systems: systems of non-living matter (these include technical systems); systems of living matter (biological systems); systems that research themselves (social systems).

Technical systems and technological systems belong to the lower level of systems, on which the basic principles of selection are conservation laws: matter, momentum, energy, etc. Any modeling should begin with the researcher's choice of the major (or, as stated, phase) variables with the help of which the conservation laws are written.

But conservation laws do not distinguish a single motion from the plurality of the seemingly possible ones and do not conclude all selection principles. The second law of thermodynamics (process irreversibility), the principles of minimum energy dissipation, stability of motion, and so on must be taken into account. Various kinds of conditions (restrictions) are very important: boundary, initial, etc.

At the level of biological and social systems, all the principles of motion selection that are valid for non-living matter systems are hold valid. The fact that laws that are valid for non-living matter systems are hold valid for living matter systems has been a subject of discussions for a long time. Particularly the second law of thermodynamics poses many difficulties.

This question was resolved by Ludwig von Bertalanffy, who was the first to demonstrate that living beings are open systems. This means that they cannot exist without the exchange of matter and energy with the outside environment (this explains the entropy decreasing observed in them).

In living systems, as in non-living systems, the modeling process begins with the recording of conservation laws. However, the main variables are different in appearance here than in non-living systems.

In the general case, modeling can be defined as a special form of a formalized approach to the research of complex systems. The theoretical framework of modeling is the theory of similarity [1].

Similarity is a one-to-one dependence between two objects (systems), in which the functions of transition from the parameters of one object to another are known, and the mathematical descriptions of these objects can be transformed into identities. Theory of similarity makes it possible to establish the existence of similarity or to develop a way to obtain it.

Modeling is the process of representing an object (technological system) to an adequate (similar) model and experimentations with the model to obtain information about the object of research.

In modeling, the model acts both as a mean and as an object of research, which is in relation with the similarity of the real information for managing the system, to evaluate the functioning indicators and thereby to find the most effective variant of construction and optimal mode of functioning of the real system.

According to the systematic approach in the processes of creation and research of complex technological systems the modeling of their elements and functional subsystems is operated in several stages and at different levels depending on the degree of particularization of the system.

Modeling methodology depends directly on the level of modeling. Each level of modeling corresponds to a certain concept of the system, the element of the system, the laws of functioning of the system elements generally and the operation of external loads.

Modeling is a method of practical or theoretical indirect research of an object on an intermediate system which [2]:

1. is located in some objective according to the recognizable object;
2. is capable to replace the studied object in a number of relations in the process of its research;
3. ultimately gives information about what we are interested in and what object is being constructionally designed;
4. can be natural or artificial (material or sign).

An intermediate system that satisfies these conditions is called *a model.*

In other words, a model is a specific object (in the form of an imaginary described sign means or material system) that is created for the purpose of obtaining and (or) storing information, which reflects the properties, characteristics and connections of an original object of arbitrary nature, essential to the task being solved by the subject.

It should be noted that the model definition is not the only one, which is found in the literature. Numerosity of definitions of the model are given in research [3], which contains an analysis of this issue.

In general, the model is a four-component construction. Its components are: the subject; a task that is solved by the subject; the original object and the language of the description or the method of material reproduction of the model.

Each material object corresponds to an infinite number of equally adequate, but essentially different models, which are connected with different tasks.

The "task-object" pair also corresponds to various models containing the same information, but in different forms of its representation – verbal, tabular, graphic, in the form of a formula, an algorithm, a program for computer technology, etc.

The model is always only relative, close to the similarity of the original object and in the informational sense is simplified by imagination.

There are three basic forms of model representation – *conceptual* (imaginary), *sign and material* from the informational point of view is equivalent, in practice the transition from the conceptual to material or sign, more or less formalized model is always associated with the enrichment of the model, with getting some additional information about the object.

The conditions and requirements of a task solved by a subject generally determine the limitations and assumptions that explicitly or implicitly appear in the process of constructing any model. These limitations and assumptions are organic components of the model.

Any model, regardless of the nature of the task and the object, is an information representation, since the model only makes sense as a source, carrier and mean of reproducing information about the object.

Particular, but very important, is the case in which the role of modeling object is played not by a fragment of the real world considered directly, but by some ideal construction, i.e. in fact, another model created earlier and practically certain.

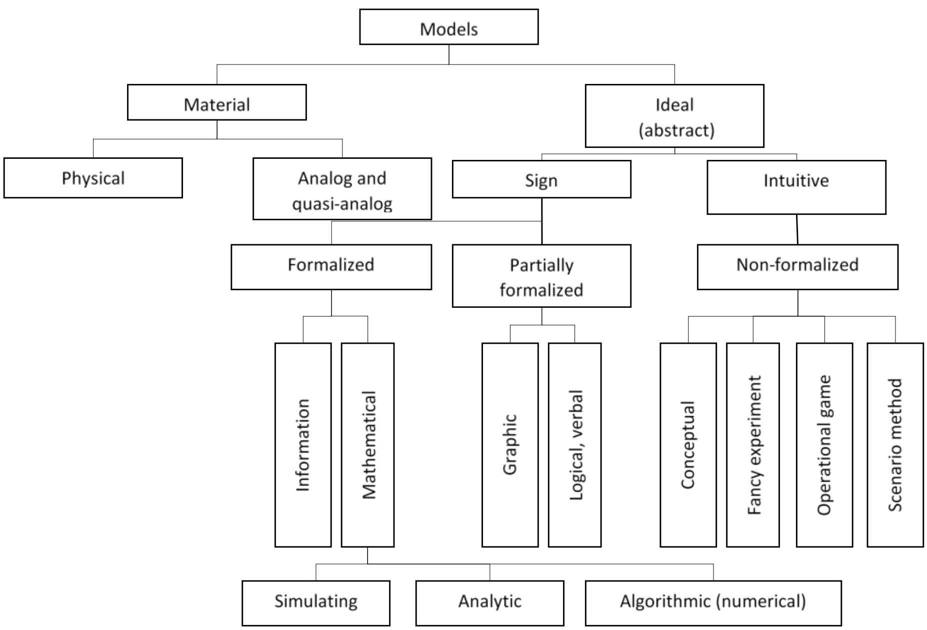
Thus, scientific laws are the foundation for specific analytical and constructional design engineering models.

A similar secondary, and in the general case, *n*-multiple modeling is carried out mainly by theoretical methods, followed by verification of the results of the experiments. There are two prerequisites for *n*-multiple modeling. Firstly, the output "objective" model is a virtually certain generalized description of an object or class of real-world objects. Secondly, the assumptions and limitations contained in the basic and intermediate models are automatically included in the secondary and all subsequent derivative models [4].

As noted above, the number of objects and processes, as well as the number of models that represent them for a variety of possible tasks, is endless. Therefore, the classification of models is equivalent to the classification of surrounding objects on a huge set of possible tasks, and attempts of such classification, as a rule, reflect only certain aspects of researches.

However, it is necessary to highlight some principles for classifying models. Models can be classified by modeling objects (device, element, system, etc.), by modeling purposes (analysis, synthesis), by means (physical, mathematical, etc.), by methods (stochastic, determinate, etc.) and by methods of specific representation of objects (analytical, graphic, etc.), as well as by methods of analysis (experimental, analytical, etc.) [5].

Picture 3.1 shows a simplified classification of models by the form of information representation.



Picture 3.1. Classification of models

Based on this picture, we briefly describe some of the basic methods of modeling technological systems, which include machines and equipment of processing plants.

Material reproduction of nature involves the study of an object on physical models, in which the object under research is reproduced with the preservation of its physical nature, or other similar physical phenomena are used. The model is called isomorphic if its properties are identical to the properties of the real system under research.

A specific case of material modeling is nature tests.

With analogous modeling the phenomenon under research is not studied, but the phenomenon of another physical nature, which is described by mathematical formulas equivalent to the results of the phenomenon under research.

Perfect reproduction is a description of an object in certain symbols, or in natural language. Depending on the formality of the ideal models, they are divided into sign and intuitive.

Intuitive models are formalized and sign models can be either partially or fully formalized.

Until recently, conceptual models were the only type of model that formalized intuitive models, i.e. the systems of object-original concepts that have formed in the human brain. The source material in the formation of such a model is not only the direct results of reflection in the consciousness of the properties and characteristics of the object-original, but also the theoretical baggage of the subject, experience, analogy, logical conclusions, intuition. Synthesis of all these components into a single ideal image is carried out only in the workings of the human mind [6].

Graphic models are also partially formalized. They reproduce the properties and characteristics of the original object by means of graphs, which cannot be observed visually. Such models include graphs, diagrams, and circuits representing generalized observation data and experiments.

A graphic model is also a draft of a technical object, which combines formalized elements determined by standards, laws of technology, and non – formalized, creative elements caused by the temporal individual creative abilities of the author.

Mathematical models are quite formalized. A mathematical model is a set of mathematical (symbolic) objects of the relations between them. A mathematical ratio is a rule that connect two or more mathematical objects. A ratio that establishes a link between one or more objects with another object or set of objects is called a mathematical operation.

A noteworthy detail is that mathematical models of systems theory are very specific. Traditional (constructive) models, such as differential and integral equations, queuing models, etc. are algorithms for calculating the values of one variables by the known values of the other variables.

System models, in contrast, with a weak mathematical structure and, consequently, the ability to describe the most common concepts and phenomena, are unavailable because of the complexity of detailed research. Therefore, system models largely combine the verbal community and the rigour of constructive models, occupying an intermediate position between them [7].

Mathematical models (see picture 3.1) have three main varieties: simulation, analytical and algorithmic.

Simulation models are reproduced in the form of a special modeling algorithm, as a rule, implemented on computer technology, formalized process of functioning of the technical system. The influence on the progress of the process of random factors is simulated by means of random numbers with given or produced probabilistic characteristics in the course of modeling [2].

The group of analytical mathematical models is extremely large and diverse. It includes many abstract mathematical objects together with operations defined over these objects: all kinds of functional dependencies, algebraic and differential equations, vectors and vector spaces, matrix forms, tensors, etc. At the same time, model belonging to this group implies that not only the description of the object of modeling, but the whole process of its research is carried out by analytical methods, i.e. in general form, not numerically.

The impossibility or simply unnecessary complexity of the analytical solution of a model issue means the need to move to numerical methods of mathematical research using computer technology and, accordingly, to transform an analytical mathematical model into an algorithmic (numerical) one.

The group of algorithmic models obtained from transformation from analytical forms, or synthesized directly, is the most versatile tool for mathematical modeling. The only practically important limitation here is the dimension of the model issue, which must correspond to the capabilities of computer technology.

Algorithmic models virtually allow solving any model issues, but only in numerical form. In this case, each calculation gives information about one specific state of the object. In order to research an object at different values of parameters, initial and boundary conditions, external influences, etc., as many repetitions of the computation process are required as many points characterizing the possible states of the object must be obtained. Therefore, the implementation of a numerical algorithmic model requires a much larger amount of computational work than any analytical model that allows you to research the properties and characteristics of the object in the general form, i.e. immediately in all possible states.

All the variety of modeling processes, based on the fact that they occur in space and time, can be divided into four classes: processes, that are variable in time (nonstationary), processes that are not variable in time (stationary); processes with parameters changing in space; processes without spatial change of parameters. Since mathematical models are reflections of their corresponding objects, they are characterized by the same classes. Thus, we can talk about four classes of mathematical models:

- models that are not variable in time – static models;
- models that are variable in time – dynamic models;
- models that are not variable in space – models with lumped parameters;
- models that are variable in space – models with distributed parameters.

Static models reflect the operation of the object in a stationary conditions. Therefore, mathematical description in these models does not include time as a variable and consists of algebraic equations – for objects with lumped parameters, or of differential equations – for objects with distributed parameters.

Dynamic models reflect the change of an object in time. So, the mathematical description of such models necessarily includes a derivative with time.

Models with lumped parameters are characterized by constancy of variables in space. In this case, the mathematical description includes algebraic equations for stationary processes, or differential equations of first-order for nonstationary processes.

Models with distributed parameters are used if the main process variables change both in time and in space. In this case, the mathematical description includes differential equations in partial derivatives.

In the case of stationary processes with one spatial variable, ordinary differential equations can be used in the description [2].

Information models are also quite formalized, very numerous and diverse in nature of the tasks to be solved: data retrieval systems, data banks, automated controlling systems, etc.

A common feature of information models is the use of relatively simple algorithms, mainly of logical nature – such as searching and sampling data on some basis, sorting all data, etc. [3].

Any model, whatever of its class, must adequately reach the goal. Adequacy of the model means that the requirements are imposed for completeness of displaying the properties of the original object, accuracy and truthfulness are met to the extent that is sufficient to achieve the goal.

Depending on the level of detail of the description of complex technological systems and their elements, there are three main levels of modeling:

1. The level of structural or simulation modeling of complex systems using their algorithmic models (modeling algorithms) and the use of specialized modeling languages, theories of sets, algorithms, graphs, queuing, statistical modeling.
2. The level of logical modeling of functional circuits of elements and nodes of complex systems, models of which are represented as equations of direct connections (logical equations) and are constructed using the logical apparatus of two-valued or multi-valued algebra.
3. The level of quantitative modeling of principal schemes of elements of complex systems, whose models are systems of linear and nonlinear algebraic, differential or integro-differential equations, which are researched using the methods of linear and nonlinear algebra, methods of functional analysis, probability theory, and mathematical statistics.

The set of models of technological system at structural, logical and quantitative levels of modeling is a hierarchical system that reveals the interconnection of different sides of the technological system description and provides a systemic connection of elements and properties at all stages of its creation or research.

Moving to a higher rung, the data of the system are surrogate and when move to a more detailed level of description, the data are expanded.

Modeling methods, when creating and researching complex technological systems, the methods of analytical, numerical, simulation, full-scale and semi-scale modeling are applied.

Analytical methods are the transformation of symbolic information, which is written in the language of mathematical analysis. When using analytical methods, a mathematical model of the system is constructed, describing its physical properties by means of mathematical formulas, for example, in the form of differential or integral equations.

Models of this type are called analytical. The analytical model is based on the concepts, symbolism and methods of some theory (for example, molecular-kinetic theory of gases), which determines the class of mathematical analogies, i.e. fundamental mathematical models. In the analytical approach, the necessary dependencies are derived from the mathematical model by the consistent application of mathematical rules.

The irresolubility of the equations in the analytic form, the absence of initial functions for integrands, etc. can appear as obstacles. Therefore, the solution can be obtained in explicit analytical form only with certain properties of the model.

Despite the limited capabilities of the analytical approach, the results obtained in analytical form are of great cognitive value and find a use in solving a wide range of theoretical and applied problems.

Recently, it has become quite important to implement into the engineering practice approximate analytical methods of analysis of nonlinear objects (processes) of different physical nature.

Successful solution of this task became possible by the development of programming systems used for analytical and numerical-analytical calculations on computer technology. Due to the creation of systems of analytical calculations and transformations, which makes it possible to work directly with mathematical formulas, the use of computer technology was profitable for carrying out complex calculations in celestial mechanics, mathematical physics, etc. [8].

Numerical methods are based on the construction of a finite sequence of actions over numbers, which leads to the necessary results. In the presence of a mathematical model of the technological system, the application of numerical methods is reduced to the replacement of mathematical operations and formulas by the corresponding operations over the numbers: replacement of integrals by sums, derivatives – by relations of differences, infinite sums – by finite, as a result of which an algorithm is built that allows accurately or with permissible error to compute the value of the required magnitudes on computer technology.

The result of the application of numerical methods are tables, graphs, dependencies that reveal the properties of the system. Numerical methods in relation to analytical ones allow solving a much wider range of problems, but the obtained results are partial in nature and require additional verification.

The nature of the processes, which are inherent in the technological system and reflected in the model can be so complicated that the construction of a mathematical model becomes a complex task, and the analysis of the model, even by numerical methods, may not be effective, because of the complexity or instability of algorithms in relation to the errors of approximation and rounding of the computation results.

Reproduction of the dynamics of complex spatiotemporal relations in the model between the elements that make up a complex technical system, all the versatility of its connections with the external outside environment, operating of control laws in the system, adaptive properties and traits of purposeful behavior are almost impossible by purely mathematical means.

In the study of such systems using *simulation modeling methods*, models with a meaningful description of technological systems and forms of algorithms are widely used. The descriptions reflect both the structure of the system, which is achieved by identifying the elements of the system with the corresponding algorithm elements, and the processes of system functioning in time, which are presented in a logical and mathematical form.

The descriptions of the system have algorithmic character and the models themselves are programs for computer technology. Models of this type are called *simulative* or algorithmic.

The peculiarity of this approach to modeling is that algorithmic languages are used to construct the models, which are more flexible and accessible means of describing complex systems than languages of mathematical functional relations. Due to this, imitation models of complex technological systems reflect many details and functions, which are forcibly omitted in mathematical models.

The approximate numerical method for analysing of simulation models – the method of *statistical* testing (Monte Carlo method) is widely used in the theory of complex systems with its probabilistic approach to system modeling [8]. The process of constructing and analyzing simulation models using the statistic test method is called *statistical modeling.*

Statistical modeling is a method of obtaining computer-aided statistical data on the processes that take place in a simulated system.

The statistical data are processed and classified using mathematical statistics to obtain the necessary results.

A positive feature of statistical modeling is the versatility that guarantees the possibility, in principle of, analyzing systems of any complexity with any degree of particularization of the phenomena being researched.

The disadvantage of statistical modeling is the complexity of the modeling process, i.e. the need to operate a large number of operations on numbers and the partial nature of the results, which does not reveal dependencies, but only defines it at certain a priori defined points. Simulation experiments are widely used in the practice of designing and researching of complex technological systems, when a real experiment is impossible.

Full-scale modeling is a conducting research on a real object (system) with subsequent processing of the results of the experiment on the basis of the theory of similarity. The patterns of the passage of the real process will be able to identify in the functioning of the technological system in accordance with the stated goal.

It should be noted that varieties of full-scale experiment, such as production experiment and complex tests have a high degree of certainty.

Methods of full-scale modeling are based on measuring of the characteristics of processes that take place in real systems and processing of the results of measurement in order to identify certain patterns of interest of the researcher.

Experimental investigations provide the most accurate information, but they are carrying only partial character. Full-scale modeling can also be conducted on physical models that model real processes. Physical models are based on the theory of similarity.

Semi-scale modeling of complex technological systems is carried out by the use of their combined models. The structure of such models include mathematical formulas that describe the functioning of individual elements (subsystems), as well as real elements (subsystems) or their physical models, which are constituent elements of the system under research.

Optimal interaction between computational and full-scale experiments can be achieved in the course of investigations of combined models. Methods of semi-scale modeling are effectively used in the research of complex technological systems, consisting of elements of different physical nature.

These methods take into account the advantages of mathematical and full-scale modeling.

3.2. THE PROCESS OF PHYSICAL MODELING OF TECHNOLOGICAL SYSTEMS

Basic concepts of physical modeling, i.e. full-scale objects and their models can be used in the course of conducting experimental studies.

The means of the experimental study interact directly with the object of study in a full-scale experiment.

The research is conducted not with the object itself, but with its substitute model in a model experiment. The model plays a dual role here.

Firstly, it is the object of direct experimental study.

Secondly, the model acts as a method of experimental research in relation to the object being studied.

Physical modeling of technological systems is widely used in experimental studies. This method is used to study complex phenomena when it is impossible to construct a satisfactory mathematical model, or to test the adequacy of a mathematical model.

Physical modeling preserves the physical nature of phenomena, but changes their scale. The meaning of physical modeling is that the results of experiments on models can for certain assess the nature of the effects and quantitative relationships between values that determine physically similar phenomena in full-scale conditions.

The basis of physical modeling is the theory of similarity, which is based on the analysis of dimensions. Objects (phenomena, processes, systems, etc.) are similar if, at the appropriate moments in time at the corresponding points of the objects, the values of variables characterizing the state of one object (nature) are proportional to the corresponding values of other object (model).

From this definition, it follows that in such objects, the characteristics of a full-scale object can be obtained by a simple recalculation of the characteristics of a model object, which are usually determined experimentally.

For all values of a certain dimension, such a factor is the similarity factor (the scale conversion factor).

Physical modeling includes mechanical, hydraulic, electrodynamic, thermal and other types of modeling. There are several types of physical similarity: metric similarity (similarity of metric elements of figures or bodies); kinematic similarity (similarity of velocities for considered movements); dynamic similarity (similarity of systems of active forces or force fields of different physical nature – weight forces, pressure forces, etc.).

Mechanical similarity includes metric, kinematic, and dynamic similarities. Electrodynamic similarity is characterized by similarities of currents, voltages, loads, capacities, fields of electromagnetic forces, etc.

The following conditions are common to such objects:

- the model and the full-scale object must be metrically similar;
- acting load on the model must be similar to the load on the full-scale objects;
- dimensionless values (Poisson's ratio, friction coefficient, relative deformation, etc.) must be the same for the model and for the full-scale object;
- materials of the model and the full-scale object may be different, but stress and strains connection must comply with Hooke's law in the investigated field.

Coefficients and similarity criteria. Mechanical modeling distinguishes between simple and extended similarities. In the case of simple similarity, the similarity coefficients for values having the same dimension (e.g. metric dimensions) must be the same.

In the case of extended similarity, these values may have different coefficients of similarity.

The methodology for studying similarity coefficients in the general case is as follows. For example, in mechanics, the main values are the length l and time (mass $t.$ their coefficients of similarity $v_l = l_n / l_m$, $v, = t_H / t_M$, $v_m = m_n$ / mm are chosen arbitrary, where l_n, t_n, m_n are the basic values of full-scale object, l_m, t_M ,, m_m are the corresponding model values).

In these and further dependencies, the indices "n" and "m" refer to the parameters of the full-scale object and model.

Other coefficients of similarity can be obtained on the basis of physical laws. For speed $V_N = l_n / t_n$ and $V_M = l_M / t_M$, the similarity coefficient $V_v = V_N / V_M = l_n t_M / l_M t_n$ can be determined by the similarity coefficients of length v_l and time v_t in the form $v_v = v_l / v_t$. According to Newton's second law, the force F is related to the acceleration w by the relation $F = mw$, then, by analogy with the similarity coefficient for speed, the similarity coefficient for force is determined by the dependence $V_f = v_m v_l / v_f^2$.

In the same way, similarity coefficients can be found for other physical values.

Experimental results and conclusions are summarized using similarity criteria in physical modeling.

The number of such criteria can be smaller than the number of parameters that describe a particular process.

It is possible to reduce the number of parameters describing any phenomenon or process by grouping them into dimensionless complexes consisting of dimensional values, based on the nature and conditions of the studied phenomenon or process. These dimensionless complexes are called *similarity criteria*.

The congruence of all the same criteria of similarity for two physical phenomena (processes, systems) is a necessary and sufficient condition for their similarity.

This is determined by the proportionality of such phenomena, which describe them and belong to the similarity criterion. The dimensional physical parameters that are included in the similarity criteria can vary greatly between each other.

However, only dimensionless similarity criteria characterizing the full-scale object and model should be identical.

This property of such phenomena is the basis for the physical modeling of real objects. If the equations describing the physical phenomenon are known, then the similarity criteria are formed by reducing this equation to a dimensionless criterion type.

In mechanics, a number of classic similarity criteria are used to processes modeling. Newton's well-known law, which describes the motion of a material point under the action of force *F*,in the differential form looks like

$$\frac{d^2x}{dt^2} = \frac{F}{m}, \quad (3.1)$$

where *m* is the mass of the material point; *x* is its coordinate; *t* – time. Taking into account that the differentiation and integration symbols included in the initial equations, can be discarded because they have no dimension, equation (3.1) can be written in the form

$$\frac{x}{t^2} = \frac{F}{m}, \quad (3.2)$$

Now, dividing the right part side of equation (3.2) into the left one, we obtain the criterion of Newton's similarity

$$K_N = \frac{Ft^2}{mx} = Idem,$$

Where *Idem* is, respectively, the same for all objects under consideration.

For rotary motion

$$\frac{d^2\varphi}{dt^2} = M/J\ ,$$

where φ is the angle of rotation; *M, J* – are respectively torque moment and moment of inertia of the body relative to the axis of rotation. In the same way, the criterion of Newton's similarity is as follows

$$K_N = \frac{Mt^2}{J\varphi} = Idem. \quad (3.4)$$

For the system of material points between which the relationship exists, we can note: if the velocities of bodies with different masses moving at the same distances are the same, then the forces acting on them are proportional to the corresponding masses of bodies. With the free fall of bodies, Newton's law can be written as a formula

$$\mathrm{m}\frac{d^2x}{dt} = mg,$$

where g is the acceleration of free fall. Then the criterion of similarity for free fall of bodies has such a formula

$$K_g = \frac{x}{gt^2} = Idem. \quad (3.5)$$

Multiplying this criterion by the square of the criterion of homochrony *Kho = vt / x* (the criterion of the similarity of mechanical motion), we obtain the criterion of similarity, which is known in the literature as the Froude criterion

$$K_{Fr} = \frac{v^2}{gx} = Idem. \quad (3.6)$$

Let us define the criterion of similarity of elastic bodies. The elastic force of the deformed element of the mechanical system (for example, when stretching the elastic rod) can be written in the form

$$F = ES, \qquad (3.7)$$

where E is the modulus of elasticity of the first kind; S is the corresponding cross sectional area of the deformed element. In addition, according to Newton's law

$$F = m\frac{d^2x}{dt^2}. \qquad (3.8)$$

Equating the formulas of forces from dependencies (3.7) and (3.8), we obtain

$$ES = m\frac{d^2x}{dt^2}.$$

Substituting in this equation *m = Sxp* (where *p* is the material density of the element), we have

$$ES = Sx\rho\frac{d^2x}{dt^2}.$$

Applying the rule for determining the criterion of similarity, we obtain

$$K_E = \frac{Et^2}{x^2\rho} = Idem. \qquad (3.9)$$

By dividing the square of the K_{no} homoronicity criterion by the criterion (3.9), we have

$$\frac{K_{HO}^2}{K_E} = \frac{v^2}{E/\rho}.$$

Having obtained the square root of this formula, we find a similarity criterion called the Cauchy criterion

$$K_{CO} = \frac{v}{\sqrt{E/\rho}} = Idem. \quad (3.10)$$

The value of *E / p* represents the speed of propagation of sound (oscillatory) waves in an elastic medium.

Each of the similarity criterion has its own physical meaning. Thus, the last similarity criterion shows the relationship between the speed of body motion and the speed of propagation of sound waves in an elastic medium.

Similarity criteria for physical phenomena, processes, technical systems, etc. independent of each other and their combination gives new criteria that reflect certain physical properties.

Similarity theorems. Interrelations between the parameters of similar phenomena are based on three similarity theorems, which formulate the necessary and sufficient conditions for similarity.

The first similarity theorem establishes the necessary conditions for similarity and is formulated as follows: if the physical phenomena are similar, then the criteria of similarity of these phenomena are equal

$$K_1 = K_2 = \ldots = K_n = Idem \quad (3.11)$$

Indices 1,2, ..., *n* show the number of the phenomenon.

The second similarity theorem establishes the mathematical structure of the equations, in which physical phenomena are described: the functional dependence between the parameters characterizing the phenomenon can be expressed as the dependence between the similarity criteria formed from these parameters.

From this theorem it follows that the experimental results should be processed in the form of generalized dimensionless variables, and the equations using these results should be presented in a criterion form. In this case, the equation solution allows, on the basis of a single experiment data, to generalize under other conditions, even in full-scale experiments.

The third similarity theorem indicates sufficient conditions of similarity: two physical phenomena are similar if they are described by the same system of equations and have similar boundary single-valuedness conditions and their similarity criteria are numerically equal.

The equations in question are basically differential equations of mathematical physics. They represent a mathematical record of fundamental physical phenomena.

Many physical phenomena are described by identical differential equations. Analogical modeling is built on this principle of equation identity. Here, the system of differential equations is a mathematical model of some class of similar phenomena.

When integrating differential equations, we get an infinite number of solutions that satisfy these equations. It is necessary to specify the single-valuedness conditions to obtain solutions that take into account specific features of the phenomenon.

These conditions do not depend on the mechanism of the phenomenon described by differential equations, and are set based on the conditions of the specific issue. Individual phenomena with the same single-valuedness conditions constitute a group of similar phenomena.

The single-valuedness conditions include:

1. geometric parameters that reflect the size and shape of objects;
2. physical and mechanical characteristics of materials of objects (coefficient of thermal expansion, coefficient of friction, modulus of elasticity, etc.);
3. initial conditions, i.e. the system state at the moment of time from which the study of the phenomenon begins. Functions of unknown variables in the coordinates x, y, z are given for the time point, usually $i = 0$;
4. boundary conditions that reflect the nature of the interaction of bodies with the environment. They are given by some functions of time and variable characteristics that change on the surface of bodies, such as surface forces, temperatures, and so on.

Dimensional analysis method of similarity theory. This method is the basis of the theory of similarity by which physical modeling is constructed.

The basis of dimensional theory is the principle of dimensional homogeneity of physical equations: all members of the equations describing physical phenomena must have the same dimension. This was noticed for the first time by the French mathematician J. Fourier.

Any physical process can be described by a functional dependency between dimensional and dimensionless values. A magnitude whose numerical value depends on the accepted system of units is called *dimensional* (for example: length, time, force, energy, etc.).

If the numerical value of a magnitude does not depend on the system of units, then it is called a dimensionless value.

The set of physical values, which are connected with each other or other dependencies, form *a system of units.* All values included in the system of units are divided into *basic and derivative.* Basic values do not depend on other values of this system. Derivative values are formed from basic or other values in accordance with physical laws.

Seven basic units are accepted: metre (m), kilogram (kg), second (s), ampere (A), kelvin (K), mole, candela (cd) in the international system of units SI *(CI)*. The auxiliary units are radian and steradian.

The dimension of value is determined by the product of the degrees of factors that make up the basic units. The dimension formula, which can be considered as a characteristic of the physical nature of the derivative value in any system of units, can be represented by a function of the form

$$[a] = A_1^{\alpha} \cdot A_2^{\beta} \cdot A_3^{\gamma} \cdot \ldots, \quad (3.12)$$

where *[a]* is a derivative unit; $A_1, A_2, A_3, \ldots$ are basic units; *a, b*, y are any real numbers.

When writing the dimension formulas, use symbols of length – *L*, mass – *M*, time – *T*, etc.

For example, the dimensions of the force *F* and the acceleration *w* in the symbolic notation would look like this

$$[F] = MLT^{-2};\ [w] = LT^{-2}. \quad (3.13)$$

The peculiarity of dimensional values is that they change their numerical values during metric transformations (the transition from one system of units to another). Unlike dimensional units, dimensionless units do not change their numerical value at such a transition.

Let us consider the structure of functional connections between physical values that express a physical law that is independent of the choice of a unit system. Suppose we have a magnitude that is a function of the dimensional values $a_1, a_2, \ldots, a_n$.

$$a = f(a_1, \ldots, a_k, \ldots, a_n). \quad (3.14)$$

Among these arguments can be allocated *k* values that will have independent dimensions (the number of basic units should be greater than or equal to *k).* Dimensional independence means that a formula that expresses the dimension of any one of them cannot be a combination of dimension formulas for other values. For example, length dimensions-*L*, velocity dimensions-LT^{-1} and energy dimensions - $ML^2\ T^{-2}$ are independent, and length dimensions - *L*,velocity dimensions - $L\ T^{-1}$ and acceleration dimensions - $L\ T^{-2}$ are dependent, because

$$LT^{-2} = (LT^{-1})^2 \cdot L^{-1} \quad (3.15)$$

Among the mechanical values, there are no more than three with independent differences. We take *k* of independent values $a_1, \ldots, a_k$ for the basic ones and introduce for their dimensions the notation: $[a_1] = A_i$, $[a_2] = A_2$, ..., $[a_k] = A_k$. Then, according to the formula of dimensions (3.15), the other values have the form

$$[a_1] = A_1^{\alpha} \cdot A_2^{\beta} \cdot A_3^{\gamma} \cdot \ldots \cdot A_k^{\chi};$$

$$[a_n] = A_1^{\alpha\, n} \cdot A_2^{\beta\, n} \cdot A_3^{\gamma\, n} \cdot \ldots \cdot A_k^{\chi\, n}; \quad (3.16)$$

Let us move to a new system of basic units b, which are proportional to units *a*. When changing from one system of basic units ($a_1, a_2, \ldots, a_k$) to another ($b_1, b_2, \ldots, b_k$), the nature of the process does not change, but the numerical values of the dimensional values change.

The Structure of Functional connection f, by which physical law is expressed in the new system of units, has the form

$$b = f(b_1, \ldots, b_k, \ldots, b_n) = f\left(l_1 a_1, \ldots, l_k a_k, \ldots, a_n l_1^{\alpha_n} l_2^{\beta_n} l_3^{\gamma_n} \ldots\right). \quad (3.17)$$

Since the choice of the coefficients $l_1, l_2, ..., l_k$ is not limited, let us set them as

$$l_1 = 1/a_1,\ l_2 = 1/a_2, \dots,\ l_k = 1/a_k. \quad (3.18)$$

Then the numerical values of the first *k* arguments in equation (3.17) will be equal to unity, i.e. they will be transformed into dimensionless values

$$b_1 = l_1 a_1 = 1,\ b_2 = l_2 a_2 = 1, \dots, b_k = l_k a_k = 1, \quad (3.19)$$

Also, dimensional values b, bk + 1, ..., bn are converted into dimensionless values. Their numerical values are determined by the dependencies:

$$b = \frac{a}{a_1^{\alpha} a_2^{\beta} a_3^{\gamma} \dots a_k^{\chi}} = K;$$

$$b_{k+1} = \frac{a_{k+1}}{a_1^{\alpha\ k+1} a_2^{\beta\ k+1} a_3^{\gamma\ k+1} \dots a_k^{\chi\ k+1}} = K_1;$$

$$b_n = \frac{a_{k+1}}{a_1^{\alpha\ n} a_2^{\beta\ n} a_3^{\gamma\ n} \dots a_k^{\chi\ n}} = K_{n-k}. \quad (3.20)$$

Thus, as a result of metric transformations, a dimensionless system of units of physical values is obtained, in which the dependence (3.17) taking into account the formulas (3.18) is represented as

$$K = f(1, \dots, 1, K_1, \dots, K_{n-k})$$

or

$$K = \varphi(K_1, \dots, K_{n-k}). \quad (3.21)$$

From the last equation, we can draw several conclusions. Firstly, any physical relation between dimensional values can be formulated as a ratio between dimensionless values. Secondly, the relationship between n + *l* dimensional values a, $a_1, ..., a_n$, independent of the choice of the system of units, takes the form of a ratio between $n + l$-k dimensionless values $K, K_1, .., K_{n-k}$. The number of arguments decreased by *k*, which corresponds to the number of arguments that have independent values.

If the dimensional value is also a function of the dimensionless arguments $a_{n+1}, ..., a_s$, then the equation of the physical process takes the form

$$a = \varphi(a_1, \dots, a_n, a_{n+1}, \dots, a_s). \quad (3.22)$$

For dimensionless arguments, we can note that

$$[a_{n+1}] = [a_{n+2}] = \dots = [a_s] = 1. \quad (3.23)$$

When moving to a new system of units, dimensionless values remain unchanged:

$$b_{n+1} = a_{n+1} = K_{n+1-k}\ ,$$

$$b_s = a_s = K_{s-k}. \quad (3.24)$$

As a result of metric transformations, formula (3.22) takes the form

$$K = \psi(K_1, \dots, K_{n-k}, K_{n+1-k}, \dots, K_{s-k}). \quad (3.25)$$

In the resulting equation, the connection between dimensional and dimensionless values *s + 1* takes the form of a connection between dimensionless complexes *s + 1 - k*.

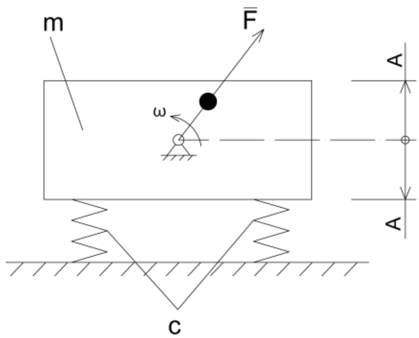
When using the dimensional analysis method, an important element is the technique of bringing the physical equations to a dimensionless form. Let the dimensional physical value *a* be a function of *s* of arguments a_i,

$$a = f(a_1, \dots, a_k, \dots, a_n, \dots, a_s). \quad (3.26)$$

moreover, *n* are dimensional, and *s — n* are dimensionless. Firstly, write out the dimensions of all values. From the number *a* of arguments distinguish *k* arguments with independent dimensions. Formulas (3.20) form dimensionless complexes $K, K_1, \dots, K_{n-k}$, which are complemented by dimensionless arguments (3.24) in the amount of *s - n*. Considering that $K_{n-k+1} = a_{n+1}, \dots \dots, K_{s-k} = a$, the initial equation (3.26) leads to a dimensionless form

$$K = \psi(K_1, \dots, K_{n-k}, K_{n-k+1}, \dots, K_{s-k}). \quad (3.27)$$

Let us consider an example of the application of the dimensional analysis method for the study of mechanical systems.



Picture 3.2. Vibration system scheme

<u>Example 3.3.</u> In the vibration system, some mass *m* performs forced oscillations on the elastic support by the stiffness c under the action of periodic force *F* (*F* – F_0sinwt) with amplitude F_0 and frequency (w) (Picture 3.2)

The amplitude of oscillations *A* will depend on the considered parameters of the vibration system:

$$A = f(m, c, F_0, \omega). \quad (3.28)$$

Let us write out the dimensional symbols of all values of the system: *[A] = L [m] = M; [c] =* MT^{-2}*; [w] =* T^{-1}*; [*F_0*] =* MLT^{-2}. In the issue *n = s = 4,* and all values that affect the oscillation process are dimensional.

For basic values, as for a mechanical system, k = 3 parameters can be taken, for example *c,* F_0, and w. In this case, *n-k = l.* Using the dependencies (3.20), we can form dimensionless complexes:

$$K = \frac{A_c}{F_0}; \;\; K_1 = \frac{m\omega^2}{c}; \quad (3.29)$$

Then dependence (3.28) takes the form of dependence of dimensionless complexes:

$$K = \varphi(K_1) \ \ or \ \frac{A_C}{F_0} = \varphi\left(\frac{m\omega^2}{c}\right). \quad (3.30)$$

As a result of bringing the physical equation to a dimensionless form, the initial number of arguments decreased from four dimensional to one dimensionless.

Bringing the oscillations of the vibrating system to a dimensionless form gives a general nature to the process analysis. There are two ways of conducting experiments.

The first is to sequentially change each of the four arguments m, c, F_0, W, while keeping the others constant. The second way is much easier. It follows from the notation in dimensionless form of dependence (3.28) that it is sufficient to experimentally investigate one function $K = \varphi(K_1)$. Such a study will be reduced to measuring the amplitude of oscillations at different values of mass m.

The process is generally described by the dependency between two dimensionless parameters $A\,c / F_0$ and mw^2 / c, which can be represented as

$$A = \frac{F_0}{c}\varphi\left(\frac{m\omega^2}{c}\right). \quad (3.31)$$

From the obtained notation, it can be affirmed that the oscillation amplitude of the vibration system is directly proportional to the amplitude of the compelled force, and depends on the rigidity of a complex, yet unknown way. Mass influences the amplitude of oscillations in the same way as the square of the frequency of the compelled force.

The dimensional analysis method shows the impact of each argument individually and their compatible effect on the result. However, the analysis of dimensions is not enough to obtain the final results. The specific form of the process function can be obtained experimentally or theoretically.

When using this method, the main thing is to identify the main factors that determine the essence of a studied phenomenon or process.

It is not possible to discover physical laws using the dimensional analysis method.

This method is considered as a means to streamline our ideas about the character of the active regularities in nature.

3.3. BASIC PROVISIONS OF MATHEMATICAL MODELING OF TECHNOLOGICAL SYSTEMS

Basic concepts of mathematical modeling. The formulation of mathematical models is the basis of systems theory. This is a central stage in the research, constructional design or management of any system. All considered stages depend on the quality of the mathematical model.

In the general case, a mathematical model of a technological or other system means any relation that reflects with the required accuracy the behavior of a real system in real conditions.

The mathematical model concentrates the set of our knowledge, ideas and hypotheses about the corresponding object, phenomenon, process or system written in the language of mathematical relations. Since this knowledge is never absolute, and hypotheses can sometimes deliberately leave out some factors, the model only approximately takes into account the behavior of the real system.

The mathematical model can be considered as some operator that puts into conformity the system of the internal parameters of the technical system $a_1, a_2, ..., a_m$ the set of functionally related external parameters $y_1, y_2, ..., y_n$. The form of functional connection depends on the physical principle of the system, and the content of the concepts of internal and external system parameters is determined by its physical essence and method of use.

Thus, it is impossible to obtain absolutely similar (isomorphic) mathematical models for complex technological systems. By formalizing the system, we obtain a simplified model that reflects the basic properties and does not take into account minor ones.

The state of the technological system at any arbitrary time *l* from the given interval $[t_0, t_1]$ can be characterized by a set of values $x_1, X_2, ..., x_l$ – characteristics of the state of the system. When operating a technical system, these characteristics take on values that are functions of time, i.e. $\{x_1 (t), ..., X_l (t)\} = X (t)$, where – X (t) is the state vector of the system.

The projections of this vector can be regarded as the coordinates of a point in the n-dimensional phase space, and the process of functioning of the system as a certain phase trajectory.

The system can be influenced by the vector of input actions $U (t) = \{u_1 (t), ..., u_m (t)\}$, which depend on the characteristics of the state. The system is also characterized by a set of eigenvalues $A = \{a_1, ..., a_p\}$, which are constants in the stationary system and time functions in the nonstationary system. The system may be affected by some random factors | = {£[,...,$£_v$}. It can also have a number of outputs $Y = \{Y_1 (t), ..., Y_n (t)\}$.

Thus, the mathematical model of the technological system is a set of relations (formulas, inequalities, equations, logical relations, etc.) that determine the characteristics of the state of the system depending on its parameters, input actions, random factors, initial conditions and time. The initial conditions are the values of the system characteristics at the initial time moment t_0: $X_{10}, X_{20}, ..., X_{n0}$.

Thus, mathematical models for dynamic technical systems can be differential equations of the form

$$\dot{x} = f(t, x, u, \xi). \quad (3.32)$$

Such models, when given the initial state, determine the trajectory of the process.

Depending on the specific relationship of the characteristics of the system state with its parameters and input signals, the following models can be distinguished:

1. *determinate models* in which at a given point in time the characteristics of the state are uniquely determined by these values. In these models £ = 0;
2. *probabilistic (stochastic) models*, in which by means of the mathematical relations it is possible to determine only the distribution of characteristics of a system state

according to the given probabilistic characteristics (distributions) of its parameters, input signals, initial conditions.

On the basis of further use, mathematical models are divided into analytical and simulation models. Analytical models provide a sufficiently high degree of detail of the system description, but do not always provide conclusions of a general nature about its functioning.

In the case of simulation models, such features of complex technical systems as the presence in the same system of elements of continuous and discrete action, nonlinear relations of any nature describing the connections between the elements, the influence of numerous random factors of complex physical nature, etc., may be taken into account.

Formulation of mathematical models. In practical issues, unlike mathematical issues, it is not always clear from the outset what is given and what needs to be proved or determined.

Such issues include the task of constructing mathematical models of technological systems. Usually a real technological system is specified. It is necessary to build its mathematical model for one purpose or another.

Solving such practical issues begins with the collection of facts and data from scientific observations. On the basis of them, the technical system formalization is conducted and its mathematical model is constructed, i.e. its most essential features and properties are distinguished and their description is made using equations and formulas.

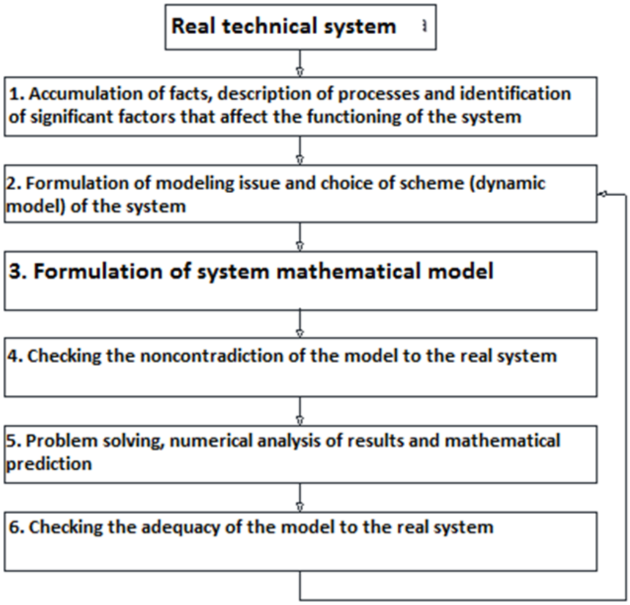
Let us consider the basic stages of mathematical models formulation of real technological systems (picture 3.5).

Stage 1. The process of schematization and idealization of the technological system, i.e. the allocation of its essential factors that affect the functioning of the system occurs when the issue is clarified and stated at the physical level. Some features and factors of the system may be important, while others may be insignificant.

Stage 2. After significant factors are identified, modeling issues are set up and a scheme of interaction between elements of the system is selected. A dynamic model is built for dynamic systems that reflects significant factors. The necessary characteristics are translated into the language of mathematical concepts and values.

A system of parameters is formed, which describes the main factors, and the formation of relations and equations between these parameters and values.

This is the most complex and difficult stage of the modeling process. It uses fundamental physical laws and principles.



Picture 3.3. Stages of mathematical model formulation

<u>Stages 3.4.</u> After model formulation (stage 3), it is necessary to check the contradiction of the model to the real system and the specificity of the problem statement. Here you can use simple and always effective physical dimension rule for all members of the equation that are compiled by conservation laws.

<u>Stages 5. 6.</u> The validity of the model is verified by the results of solving the theoretical problem in accordance with the mathematical model, which are compared with the real results of the technological system. Based on these results, the adequacy of the mathematical model to the real system is tested.

Depth of reflection by a model of a real technological system depends on the purpose of the study.

According to the hierarchy principles of mathematical models, each lower-level model should not contradict the higher-level model. At the lowest level they build mathematical models of concrete processes and the simplest phenomena of the technological system.

<u>The mathematical model</u> is the result of formalization of a real technological system. The process of formalization of the system in the formulation of its model, which consists of three main stages:

1. compiling an informal description of the real system, i.e. a descriptive model formulation;
2. a formalized scheme formulation;
3. a mathematical model development.

<u>The descriptive model</u> is the first attempt at a verbal description of the regularities that characterize the functioning of the technological system, as well as the problem description

or formulation of the study purpose. To build such a model, it is necessary to study the system by observing it and fixing some quantitative characteristics.

In the model formulation of the projected system, the verbal description is made on the basis of experience, as well as on the basis of observations of similar, actually existing systems.

The descriptive model, as a rule, is composed by specialists in a specific field of machinery and technology without active participation of mathematicians on the results of research of the technological system. However, it must include a list of the dependencies to be evaluated, as well as a list of factors that should be taken into account when formulating the model. The descriptive model includes the initial data in the form of tables, graphs, initial conditions. An informal description has no independent value, but serves as a basis for further formalization of the technical system.

Formalized scheme is an intermediate stage between a verbal description and a mathematical model. It is realized in the case when it is impossible for some reasons to make a direct transition from a descriptive model to a mathematical model.

When constructing a formalized scheme, it is necessary to choose a set of characteristics of the state and parameters of the technological system. For the characteristics of the state, it is desirable to choose such functions that provide a convenient opportunity to determine invisible characteristics and allow obtaining a simple mathematical model.

The choice of parameters characterizing the technological system is determined by those factors that must be taken into account when constructing the mathematical model. At the stage of the formalized scheme building of the technical system, the mathematical purpose of the study should be clearly stated.

Further transformation of the formalized scheme into a mathematical model is carried out practically without the inflow of supporting information.

For dynamic technological systems, i.e. systems that change their state over time, a dynamic model is a formalized scheme. The most widely used dynamic models were obtained in the formulation of mathematical models of mechanical systems.

First, a dynamic model of the technological system is built, and then a mathematical model is formed on its basis by formal methods, i.e. the presence of a dynamic model uniquely determines the mathematical model of the technological system.

Dynamic model of mechanical system. In the transition from a real mechanical system (machine) to its dynamic model, neglect those physical factors that are not relevant to this calculation or study.

In the general case, when forming a dynamic model of a mechanical system, it is necessary to take into account the concentrated masses, the masses distributed along the length of the elements, the elasticity of the elements, the dependence of the driving and braking forces of the engines on the rotor speed, the change in the reduced masses, etc.

In each case, some physical factors are basic and others are secondary.

The dynamic model must satisfy two main requirements:

1. to be as strongly as required adequate to a real mechanical system and, as far as possible, reflect its basic physical properties;

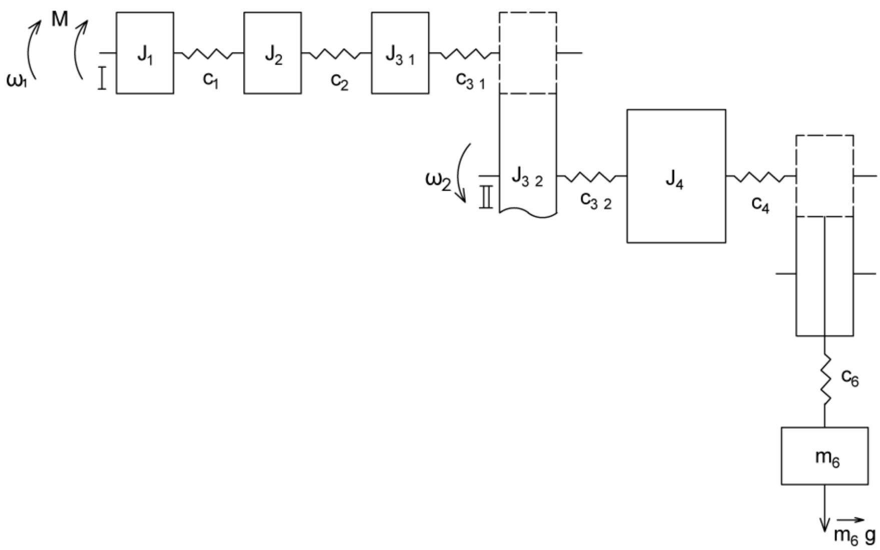
2. to be not too complicated so that the solution is not labour-intensive.

Let us consider the process of developing a dynamic model of the mechanical system by the example of the lifting mechanism of the crane, whose kinematic scheme is shown in Picture 3.1 (example 3.4).

For individual masses of the mechanism, we accept the motor armature 1, the clutch with the brake pulley 2, the gear wheels 3.1 and 3.2 of the transmission mechanism (gearbox) 3, the drum 4 and the load 6.

Here, the individual masses of the shafts and ropes are not taken into account, since their masses are reduced to the corresponding elements which are attached to them. For example, the weights of the input and output shafts of the gearbox are given in accordance with the masses of the gear wheels 3.1 and 3.2, and the weight of the rope – to the load 6. In this mechanism, the masses 1, 2, 3.1, 3.2 and 4 carry out rotational motion and the mass 6 carries out translational motion.

Let us build a dynamic model of these masses, connecting them with each other with inertialess elastic elements and applying current loads to the masses under consideration (picture 3.4).



Picture 3.4. Dynamic model of crane lifting mechanism

The model consists of two sections of an inertialess shaft, each of which rotates at angular velocities w_1 and w_2, as well as an inertialess rope, reel in a drum with velocity v.

The masses of the elements of the engine 1, the brake pulley 2, the transmission mechanism 3 and the drum 4 are shown in Picture 3.6 in the form of conditional disks with moments of inertia J_l, J_2, J_{31}, J_{32}, J_4, and cargo 6 is in the form of a material point of mass m_6. Conditional disks are interconnected by elastic inertialess sections of the shafts with torsional stiffness coefficients C_1, C_2, C_{31}, C_{32}, C_4. Disc J_4 is connected with a load of mass w_6 elastic inertialess rope with linear stiffness c_6 through a polystyrene system 5 with multiplicity *n*.

The angular velocities of the shafts with gear wheels 3.1 and 3.2 are connected by a gear ratio $i = w_1 / w_2$. *M* is the driving torque on the rotor shaft, m_6g is the weight of the load in Picture 3.6.

With the help of the built dynamic model, you can create a mathematical model that will allow you to determine the dynamic loads in the elements of inertialess elastic shafts between the engine and the brake pulley, the pulley and the gear wheel 3.1, the gear wheel 3.2 and the drum, as well as in the rope connecting the drum with load through the polystyrene system.

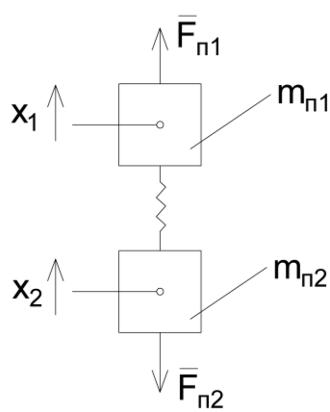
The simultaneous determination of these loads within the framework of one mathematical model leads to a significant complication of the latter.

In some cases, there is no need to consider such a complex mathematical model. It can be replaced by a series of simple models, each of which takes into account only one elastic section of a shaft or a rope.

Thus, if there is a need to determine the dynamic loads in an elastic rope, then a dynamic model is used in which all sections of the shaft are considered rigid and only the rope is elastic.

When bringing the mass of the engine rotor, brake pulley, gear wheels, drum and load to the parts of the rope, which are reel in the drum, the dynamic model of the mechanism of lifting the load has the form shown in picture 3.5.

The following notations are accepted here: $m_{пl}$ shows the mass of the rotor of the engine, brake pulley, gear wheels and drum to the parts of the rope; $m_{п2}$ is reduced weight of the load to the parts of the rope; $F_{п1}$, $F_{п2}$ are forces to the rope from the action of the corresponding driving torque on the engine shaft and the weight of the load, respectively; $c_п$ is the rigidity of the parts of the rope; x_1, x_2 are the coordinates of the centers of mass respectively $m_{п1}$ and $m_{п2}$.



Picture 3.5. A simplified dynamic model of a crane lifting mechanism

The reduction of masses and moments of inertia of bodies of a system is based on the equality of kinetic energy of a given and reduced systems; reduction of forces and moments of forces is based on the equality of works (capacities) that fulfill these forces and moments and their reduced magnitudes; reduction of stiffnesses is based on the equality of potential energies possessed by the elastic elements of a given and reduced systems.

Let us carry out reduction of masses, acting forces and stiffnesses to the parts of the rope, which is reel in a drum for the crane lifting mechanism (picture 3.1.).

Since there is a need to determine the dynamic loads in the parts of the rope, the reduction is carried out on both sides. The upper part of the rope reduces all the elements from the engine to the drum inclusive, and the lower part reduces the load and the rope (picture 3.7).

Let us determine the kinetic energy of the "engine-drum" system (Picture 3.1)

$$T_1 = \frac{1}{2}(J_1 + J_2 + J_{31})\omega_1^2 + \frac{1}{2}(J_{32} + J_4)\omega_2^2, \quad (3.33)$$

where w_1, w_2 are the angular velocities of rotation of shafts I and II (Picture 3.6); J_1, J_2, J_{31}, J_{32}, J_4 are the moments of inertia of the corresponding elements.

The kinetic energy of the reduced system of the considered elements has the form

$$T_{п1} = \frac{1}{2}m_{п1} \cdot v^2, \quad (3.34)$$

where v is the speed of rope reeling on the drum.

Based on the conditions of mass reduction, we equate the right formulas of dependencies (3.33) and (3.34). As a result, we get

$$\frac{1}{2}(J_1 + J_2 + J_{31})\omega_1^2 + \frac{1}{2}(J_{32} + J_4)\omega_2^2 = \frac{1}{2}m_{п1} \cdot v^2. \quad (3.35)$$

Taking into account that $w_2 = 2v/D$ (*D* is the diameter of the drum) and $w_1 = i\,w_2 = 2v\,i/D$, and by performing mathematical transformations, we finally find the formula of the reduced mass of the "engine-drum" system.

$$m_{п1} = 4[(J_1 + J_2 + J_{31})t^2 + J_{32} + J_4]/D^2 \quad (3.36)$$

Similarly, the reduced mass of the "load-rope" system is determined (Picture 3.1).

This system takes into account only the mass of the rope part that is moving. In the reeving system 5 shown in Picture 3.1, two parts of the rope reel in the drum, move from blocks 5.2 and 5.3 to the drum 4 at a speed v, and two parts of the rope from block 5.1 to blocks 5.2 and 5.3 at a certain moment of time are stationary.

When the length H of the moving parts of the rope from the axis of blocks 5.2 and 5.3 to the axis of the drum, the kinetic energy of the system "rope-load" is determined by the dependence

$$T_2 = \frac{1}{2} \cdot 2H\rho v^2 + \frac{1}{2}m_6\frac{v^2}{n^2}, \quad (3.37)$$

where p is the mass unit of length of the rope; *n* is the multiplicity of the reeving system.

The kinetic energy of the reduced system of these elements is determined by the following formula

$$T_{п2} = \frac{1}{2} m_{п2} \cdot v^2. \quad (3.38)$$

Equating the right sides of dependencies (3.37) and (3.38), we get

$$\frac{1}{2} \cdot 2H\rho v^2 + \frac{1}{2} m_6 \frac{v^2}{n^2} = \frac{1}{2} m_{п2} \cdot v^2. \quad (3.39)$$

From the obtained equation, we find the reduced mass of the "load-rope" system

$$m_{п2} = \frac{m_6}{n^2} + 2H\rho. \quad (3.40)$$

To determine the reduced force $F_{п1}$, we need to determine its power in the reduced system and equate it to the power of the driving torque M on the engine shaft. As a result, we will have

$$F_{п1} \cdot v = M\omega_1. \quad (3.41)$$

Taking into account the connection between the velocities v and w_1, we obtain from the last equation

$$F_{п1} = 2M \frac{i}{D}. \quad (3.42)$$

Similarly, we find the reduced force $F_{п2}$, taking into account the equality of its power required to lift the load

$$F_{п2} \cdot v = \frac{m_6 g v}{n}. \quad (3.43)$$

From the obtained equation we have

$$F_{п2} = \frac{m_6 g}{n}. \quad (3.44)$$

Taking into account the transmission efficiency from the engine to the drum n_1 and the efficiency of the reeving system n*2*, then the formulas for the reduced forces can be written in the form

$$F_{п1} = 2M\eta_1 i/D. \quad (3.45)$$

$$F_{п2} = m_6 g/(\eta_2 n). \quad (3.46)$$

To determine the reduced stiffness $c_п$, we use the condition of stiffness reduction of the rope-reeving system c_6 (picture 3.6) to the part of the rope, which is reel in the drum. According to this condition we have

$$\frac{1}{2} c_п x_2^2 = \frac{1}{2} c \left(\frac{x_2}{n}\right)^2. \quad (3.47)$$

From the obtained equation, we find the reduced stiffness of the rope-reeving system

$$c_п = c/n^2. \quad (3.48)$$

Based on the constructional design of the reeving system (Picture 3.1) and considering that the stiffness of the unit length of the rope is equal to *E s* (where *E* is the modulus of elasticity of the rope, *s* is the cross-sectional area), it is possible to determine the stiffness of the rope-reeving system

$$c = 2Es\left(\frac{1}{(n-1)h} + \frac{1}{H}\right). \quad (3.49)$$

where *h* is the distance between the axes of the movable and fixed blocks (picture 3.1).

Similarly, other simplified dynamic models of the load lifting mechanism can be constructed to provide mathematical models for determining the dynamic loads in the elements of inertialess elastic shafts connecting individual masses.

The dynamic model shown in Picture 3.6, has seven degrees of freedom, and in Picture 3.7 has only two degrees of freedom. Such a simplification of a dynamic model of a mechanical system slightly lowers its accuracy, but it greatly simplifies its mathematical model. The decrease in the accuracy of the dynamic model of the load lifting mechanism for determining the dynamic loads in the elastic rope by significantly decreasing the number of degrees of freedom corresponds to the accuracy of determining the moments of inertia, the stiffnesses of the individual elements and the driving torque of the drive.

Methods mathematical models formulation of mechanical systems. The mathematical model of any mechanical system can be constructed by formal methods on the basis of the obtained dynamic model. Mathematical models of mechanical systems are, as a rule, differential equations of motion or interaction of individual elements.

Three main methods are used to obtain differential equations of motion of mechanical systems under their known dynamic models:

1. equilibrium method using the D'Alembert's principle;
2. principle of virtual displacements;
3. Hamilton-Ostrogradsky's principle.

Let us have a look at each of these methods in more detail.

Equilibrium method. Motion equation of any mechanical system in the presence of its dynamic model is an expression of Newton's second law, which establishes that the speed of momentum change of any mass is equal to the force acting on it.

In mathematical form, this is written as the following differential equation:

$$\bar{F}(t) = \frac{d}{dt}\left(m\frac{d\bar{r}}{dt}\right), \quad (3.50)$$

where *F (t)* is the vector of force applied; r is the radius vector of the coordinates of the center of mass *m; t* is the coordinate of time.

The mass can be considered constant over time for most of the tasks of the dynamics of machines and mechanisms. Then equation (3.50) takes on form

$$\bar{F}(t) = m\frac{d^2\bar{r}}{dt^2} = m\ddot{\bar{r}}(t).$$

The obtained equation expresses the condition of equality of the force production of mass for acceleration

$$\bar{F}(t) = m\ddot{\bar{r}}(t) = 0. \quad (3.51)$$

In equation (3.51) the second summand is called the inertial force that resists mass acceleration.

D'Alembert's principle *(mass causes the force of inertia, proportional to its acceleration and oppositely directed to it)* is widely used in the issues of machine dynamics, since it allows to derive the equation of motion on the basis of conditions of dynamic equilibrium. The force F *(t)* may include different types of forces applied to the mass: the force of elastic resistance, which is directed in the opposite direction of motion; damping force, which resists motion speed and independent external forces. If you enter the force of inertia that resists the mass acceleration, then the equations of motion express the condition of equilibrium of all forces that are applied to the mass.

D'Alembert's principle considers the equilibrium of a single mass with the application of all its forces, forces of inertia and reactions of connection with other masses. This method of deriving the equations of motion is the most convenient for majority of simple dynamic models of mechanical systems.

Principle of virtual displacements. When the constructive circuit of the mechanical system is sufficiently complex and contains a number of interacting bodies of finite sizes, the direct derivation of the equilibrium conditions of all forces acting on the system of forces becomes complicated.

Variable forces are often expressed by motion along generalized coordinates, but it is difficult to write down the equilibrium conditions. In this case, the principle of possible (virtual) displacements is used to derive the equations of motion instead of equilibrium conditions.

This principle is formulated as follows: If a system that is in equilibrium under the action of several forces receives a possible displacement, i.e. any displacement that satisfies the boundary conditions, then the full operation of all forces on that displacement is equal to zero.

According to this principle, zero congruence of work force at the possible displacement of the system is equivalent to the equilibrium condition.

A significant advantage of this principle is that the components of the work of forces on possible displacements are scalar quantities and can be added algebraically while the forces acting on the elements of the dynamic model are vectors and can be added only by the rules of vector analysis.

When applying the principle of possible displacements in the case of motion of a mechanical system, the force of friction and the force of inertia for each body are joined to the specified external forces.

The Hamilton-Ostrogradsky's principle. This method does not require vector equations of equilibrium, because it uses scalar quantities of energy in the variational formulation. The essence of this method is that the equation of variation is valid for nonconservative mechanical systems.

$$\int_{t_0}^{t_1}(\delta T + \delta A)\,dt = 0, \quad (3.52)$$

where t_0, t_1 are the start and end moments of the system motion time; *ST* is a variation of kinetic energy; b*A* is the elementary work of forces applied to the system, in the transition from a direct to a bypass path, which has common initial and final conditions with a straightforward way.

If the system is conservative, then b*A* = - *bΠ* (where Π is the potential system energy) and b*T* + *bA* = *b (T-Π)* = *bL.* In the case of the conservative system, the Hamilton-Ostrogradsky's principle involves that

$$\delta\int_{t_0}^{t_1} Ldt = 0. \quad (3.53)$$

An integral

$$I_L = \int_{t_0}^{t_1} Ldt$$

is called an action, according to Hamilton-Ostrogradsky.

This principle can be applied in another form

$$\int_{t_0}^{t_1}[\delta(T - \Pi) + \delta A_1]dt = 0. \quad (3.54)$$

In this case, conservative forces (gravitational and elastic) are expressed as potential energies, and b$A_1$is the elementary work of nonconservative forces (driving and resisting forces while system motion).

The use of the Hamilton-Ostrogradsky's principle in the form (3.54) gives a possibility to simplify the accounting of conservative forces, thus giving the principle greater formalism [10].

The Hamilton-Ostrogradsky's principle can be based on approximate methods for solving problems of machine dynamics, which are widely used in the elasticity theory and in solving complex problems of the theory of vibrations.

Usually the choice of method for any particular mechanical system depends on the type of dynamic model and is determined by the researcher.

To obtain the required results, the differential equations of motion of the mechanical system are to be integrated to determine the characteristics of the state (displacements, speeds, and accelerations) of the individual elements in the function of time.

In the studied system, this characteristic is the driving moment on the motor shaft. The output of this system is the dynamic loads (for example, the reaction) that occur in the elastic elements.

These values can be used to calculate strength in the constructional design process of the system or in the choice of operating modes. Moreover, the obtained dependences of coordinates allow us to predict the behavior of the system in the future at a given interval of motion [t_0, t_1].

All the solved problems of modeling a specific lifting crane mechanism belong to the problems, which are solved in the theory of technological systems.

3.4. ANALYTICAL APPROACHES OF ESTIMATION OF CORRESPONDENCE OF THE CHOSEN MODEL TO THE PARAMETERS OF TECHNOLOGICAL SYSTEM

Methods of models simplification. As a rule, the processes of functioning of real technological systems are so complex that there is a need to simplify their models. The most common are the following methods of models simplification:

1. division of complex technological systems into a number of simpler subsystems (decomposition);
2. isolation of essential properties, actions and consideration of other (irrelevant) factors in parametric form (macromodeling method);
3. linearization of nonlinear processes in some area of variables change by the conventional method of small departures;
4. bringing systems with distributed parameters to systems with lumped parameters;
5. neglecting of dynamic properties of the processes. Let us take a closer look at some of these methods of models simplification.

In the general case, the ultimate goal of decomposition is division of the space of variables

$$\{y_1, y_2, \dots, y_q, z_1, z_2, \dots, z_p, v_1, v_2, \dots, v_r, f_1, f_2, \dots, f_s\}$$

where

$$\vec{V} = \{v_1, v_2, \dots, v_r\}, \vec{F} = \{f_1, f_2, \dots, f_s\}$$

respectively, are observational and unobservable (i.e. uncontrolled) actions on the system.

If in such a system any output has a connection with other outputs, then decomposition is practically impossible, and if there is no such connection, then the model can be divided into as many models as there are blocks of outputs, between which there is no connection.

Only those variables that significantly affect the original ones remain (i.e. are taken into account) in the initial space of variables when using the macromodeling method. Other unaccounted variables can be taken into account in parametric form by changing the coefficients of the variables involved or by introducing free terms.

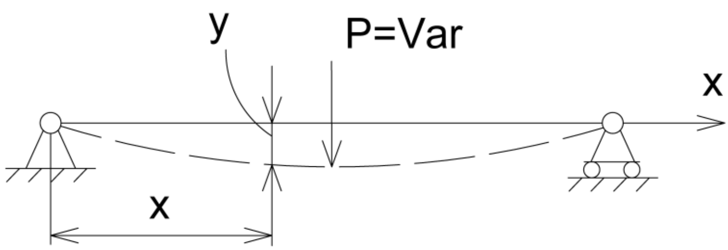
When constructing simplified models with only significant effects, the method of adaptive model is widely used, i.e. models, whose coefficients are substituted in such a way that some degree of discrepancy (disparities) between the outputs of the model and the actual technological system is obtained with acceptable (minimum) values. Criteria of disparities minimizing are used for this purpose.

However, those variables that stabilize and do not change the original variables are not displayed in the model. The structure of a simplified model is called a macromodel, which for the k- output variable is as follows

$$\varphi_k(y_1, \dots, y_q, z_1, \dots, z_p, v_1, \dots, v_r, f_1, \dots, f_s) = 0. \quad (3.55)$$

Having the initial complete model (3.55), it is possible to estimate the degree of influence on the output variable y_k of one or the other action by determining the derivatives of y_k, i.e. $\partial y_к / \partial z_j$, $\partial y_к / \partial \upsilon_i$, $\partial y_k / \partial f_k$. For this purpose it is necessary that the variable $y_к$ in explicit form is determined from (3.55). By the magnitude of the derivative, we can determine the effect of changing one or another action on the process of functioning of a complex technical system.

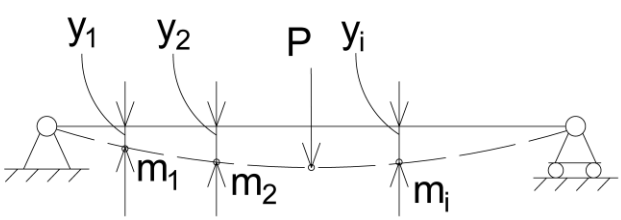
In the initial process, the characteristics of the state of the technological system may depend not only on time, but also on spatial coordinates. From the set of technological systems with distributed parameters it is possible to distinguish systems, whose parameters are reduced to lumped ones. These are systems in which it is sufficient to know the values of input and output variables in a finite number of fixed points of space. For example, linear elements of a technological system with distributed parameters can be structurally represented as a multidimensional linear system with lumped parameters. The picture 3.6 shows a beam on two supports, which, under the action of an external variable force P, oscillates in relation to the position of static equilibrium (example 3.8).



Picture 3.6. Scheme of beam with distributed parameters

In this system, each point of the beam carries out its move y, which depends on the position of the coordinate x. This beam is a system with distributed parameters (masses) along the coordinate x, i.e. here the mass of the beam and its deflection are coordinates of length x: m (x) and y (x). These changes are characteristics with distributed parameters.

The considered system with distributed parameters can be replaced by a system with lumped parameters (picture 3.9).



Picture 3.7. Circuit of beam with lumped parameters

In the substituted circuit the individual elements of the beam are replaced by the masses m_i, m_2, ... and their corresponding coordinates y_1, y_2, ... When considering the oscillations of the beam under the action of the variable force P, the congruence of kinetic energies of systems with distributed and lumped parameters is the condition of equivalence of the schemes shown in picture 3.6 and picture 3.7.

Models analysis. The model of the technological system under study is a formalized and simplified description of it. Only a subset of the set of features that make up the initial description of the system is taken into account.

The type of model is determined not only by the nature of the real technological system, but also by the tasks for which the model is being built, as well as by the required accuracy of their solution.

Therefore, studies of the obtained model are needed in order to determine the area of its most effective application in solving engineering problems and to set limits for changing the parameters in which it is valid.

Model and technological system identity evaluation. A prerequisite for the transition from the study of the technological system to the study of the model and the subsequent transfer of results to the technological system is the requirement of adequacy of the model and of technological system.

Adequacy involves the reproduction of the model of all the properties of the technological system with the required completeness that are essential to this study. Since any model has the character of a particular projection of the technological system, we can never speak of the absolute adequacy in which the model corresponds to the original by all characteristics.

Therefore, the identity estimate can only be based on an estimate of the difference between the model and the original.

The concept of adequacy is based on the mathematical concepts of isomorphism and homomorphism. The technological system under study and its model are called *isomorphic* if there is a one-to-one correspondence between them.

Homomorphism, like isomorphism, involves the preservation in the model of all the properties and connections defined in the technological system. However, here the requirement of one-to-one correspondence is replaced by the requirement of unambiguous correspondence of the model of the technological system, whereas the correspondence of the technological system of the model is ambiguous.

The isomorphic model includes all the features that are theoretically inherent in the original. If you wish to build an isomorphic model, the main obstacle is the lack of transfor-mation, which establishes the necessary one-to-one correspondence.

Homomorphism defines this form of connection between two similar systems, when a one-to-one transformation makes it possible to reduce the initial system to a simpler system, which is homomorphic to the original one. Homomorphism is inherent in the modeling of the technological system [11].

Quantitative characteristics can be used to estimate the level of identity of a model and a technological system. The task of establishing the level of identity of the model and the technological system can be set as follows: for a known technological system, its model is constructed so that when applying the same input actions to the technological system and its model, the output signals are minimally different from each other. The level of deviation of the output signals is determined by quantitative indicators. Among them, we can distinguish a minimum of the average squared error.

When constructing models, either the degree of influence of inputs on the outputs or the form of dependence between the individual input and output variables are quite often previously unknown.

Under these conditions, the regression of the output in relation to all inputs, i.e. the conditional mathematical expectation of the output allows to give the optimal estimation of the model of the technological system using the criteria of the minimum of the average squared error. Adding considered inputs to the model estimation increases the dispersion (squared deviation) of the conditional mathematical expectation of the output.

In the general case, for p inputs and one output we have

$$y^*(t) = M[y(t)/z_1(s_1), z_2(s_2), \dots, z_p(s_p); s_k \in T_k], \quad (3.56)$$

where $z_1(s_1), z_2(s_2), \dots, z_p(s_p)$ input variables that change at finite time intervals T_k, are taken into account i.e. $s_k \in T_k$, k = 1, 2, ..., p; y * (t) is the output value of the model at a fixed time t; y (t) is the measured output value of the technical system.

For a one-dimensional case (one input and one output), the output model variable is defined as:

$$y^*(t) = M[y(t)/z(s); s \in T]. \quad (3.57)$$

The proximity measure of y(t) and y*(t) as random functions of time is the dispersion of the conditional mathematical expectation.

The unconditional dispersion of the output D[y(t)] can be represented in form of two summands:

$$D[y(t)] = D\{M[y(t)/z(s); s \in T]\} + D[y(t)/z(s); s \in T]. \quad (3.58)$$

The first summand in (3.58) characterizes the part of the total dispersion that is determined by the changes in the considered variable; the second characterizes the part of the total dispersion that reflects unaccounted factors.

The correspondence (3.58) follows from equality

$$D(y) = M[y - M(y)]^2 = M[y - M(y/z) + M(y/z) - M(y)]^2 = M[y - M(y/z)]^2 + M[M(y/z) - M(y)]^2 + 2M\{[y - M(y/z)][M(y/z) - M(y)]\} \quad (3.59)$$

As in the congruence (3.59) the last summand is zero, it can be written

$$D(y) = D(y/z) + D[M(y/z)]. \quad (3.60)$$

i.e. the correspondence is obtained to (3.58).

A dispersive measure is accepted as the value of the identity level of the model and the TS.

$$Q_{y/z}(t,T) = \frac{D\{M[y(t)/z(s);s\in T]\}}{D[y(t)]}, \quad (3.61)$$

which is called the correlation ratio.

The nonidentity models and TS measure are used

$$Q_{y/z}(t,T) = \frac{D[y(t)/z(s);s\in T]}{D[y(t)]}, \quad (3.62)$$

Obviously, the congruence Q + Q = 1 is valid.

Let us have a look at some *properties of the dispersive measure*.

1. For a determinate one-dimensional technological system, the conditional dispersion of the output D(y/z) is zero, so the dispersion of the conditional mathematical expectation is equal to the unconditional dispersion of the output, i.e.

$$D[M(y/z)] = D[y(t)]. \quad (3.63)$$

Thus, with all inputs taken into account and in the absence of other effects on the technical system, the mathematical expectation is equal to the output value itself.

In this case

$$Q_{y/z}(t,T) = 1; Q_{y/z}(t,T) = 0, \quad (3.64)$$

of the technical system, the determinate, fully defined, or regular congruences (3.64) are valid.

2. If the output variable y (t) is in no way connected with the input z (s); s∊T, then (since in this case M(y/z) = M(y)) from the expression for the variance of the conditional mathematical expectation D [M (y/z)] = M[M (y/z) – M(y)] ^{2} implies that D[M(y/z)] = 0. Therefore, the congruence is valid

$$D(y/z) = D[y(t)]. \quad (3.65)$$

In this case, the dispersive measure

$$Q_{y/z}(t,T) = 0 \quad (3.66)$$

on the condition that D[y (t)] ≠ 0 of a technological system for which the congruence is valid (3.66) can be called *underdetermined or irregular*.

QUESTIONS FOR SELF-CONTROL:

1. What is a "**model**"? Provide basic definitions and give examples.
2. Describe the process of a "model formulation".
3. What is meant by the term "**similarity**"?
4. What is a "Modeling" process and a "Modeling" method?
5. Provide a model classification for the information presentation form.

6. What are three basic levels of modeling complex technological systems?
7. What "**modeling methods**" are used in complex technological systems?
8. What is the basis for the "**analytical method**" of modeling complex technological systems?
9. What is the basis for the "**numerical method**" of modeling complex technological systems?
10. What is the essence of the "**simulation method**"?
11. What is called "statistical modeling"?
12. What is called "full-scale modeling"?
13. Provide basic principles of "**physical modeling**".
14. What are the "**similarity criteria**"?
15. What is "**mechanical similarity**"?
16. What are the "**similarity criteria**"?
17. Give examples of issues that solve "**similarity theories**".
18. What is the "dimension analysis method"?
19. What is the essence of "**mathematical modeling**" of technological systems?
20. How do "determinate models" differ from "probabilistic (stochastic) models"?
21. Name the algorithm (stages) of "**mathematical models**" formulation.
22. What "**models simplification methods**" do you know?
23. How is the model and technological system identity assessment carried out?
24. What is "homomorphism" and "isomorphism"?

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Chapter 4. Analysis and synthesis in constructional design of technological systems

Contents of Chapter 4

Keywords: synthesis, synthesis process of technological systems, analysis, analysis issues, analysis process of technological systems, machine analysis structure of technological systems, analysis process structure of technological system, description structure of technological systems, a prior information, machine analysis of technological system, synthesis issues of technological system, estimation methods of technological systems, nonoptimal synthesis of technological systems, optimal synthesis of technological systems, methods of morphological analysis and synthesis.

4.1. THE MAIN PROVISIONS OF THE ANALYSIS PROCESS OF TECHNOLOGICAL SYSTEMS

One of the most important issues of technological systems research is the problems of analysis and synthesis. *Analysis* is a method of studying a system that is based on dividing it into parts that are studied separately by abstraction from the influence of other parts.

At the same time, the issues of system research are greatly simplified. In the analysis process of the known structure and parameters of technical systems, its behavior is studied, i.e. the system properties and its characteristics are investigated.

Synthesis is a method of studying a system that is based on the consideration of its parts in interaction with one another, their mutual influence and connections [1]. Synthesis gives a full understanding of the object of study as a coherent system. In this case, the issues of system synthesis compared to the issues of analysis are much more complicated.

The synthesis process of technological systems consists in finding its structure and revealing the parameters according to the given properties.

The issues of analysis and synthesis of technological systems are reciprocal and, as a rule, are solved jointly. Thus, the issues of synthesis as more complex are most often solved using the results of solving issues of analysis.

Issues of analysis. As already known, *analysis* is the process of revealing or investigating the properties inherent in a technological system.

Let the functions and characteristics of elements that make up the system be known and its structure is revealed. It is necessary to reveal the functions and characteristics that are inherent in the system as a set of elements.

Analysis of systems to reveal and estimate their qualitative and quantitative properties is one of the most important issues of the technical systems theory. The analysis allows to estimate the properties of different classes of technological systems, their structures, systems management strategies; characteristics of both individual elements and their totality [2].

Indicators characterizing the properties of technological systems can be revealed in one of two ways:

1. by processing the results of a full-scale experiment;
2. as a result of physical or mathematical modeling of the processes of system functioning.

Studying the system in full-scale conditions is practically advisable only if the following conditions are fulfilled:

- system can operate in modes that enable the goal of the experiment to be achieved;
- it is possible for fixation all the necessary information at no significant cost to sensors and information stores;
- fixation and statistical processing of the received information in real time scale meets the set terms of the experiment;
- changing the operation mode of the system does not cause an accident.

Since in most practical cases these conditions are not fulfilled, the most effective means of analyzing complex technological systems is their mathematical modeling, which is described in detail in the previous section.

The issue of analyzing technological systems involves three stages.

In the first stage, it is necessary to identify the cause and effect connections that are inherent in the system being analyzed, and to build its conceptual (cause and effect) model that reveals the essence of the processes that take place in the system.

When formulating a conceptual model, the dependence presence between the characteristics of the process that interest the researcher and the parameters of the system are established. These parameters should contain the system model.

In the second stage, on the basis of the accepted conceptual or dynamic model, a mathematical model is formulated, which reveals quantitative ratios between process characteristics and system parameters. Such a model can be specified, for example, in the form of a functional dependence $Y = F(X, U)$, where Y is the set of output characteristics of the system; X is the set of parameters taken into account by the conceptual or dynamic model; U is the set of input actions to the system. Quantitative ratios specify cause and effect connections and thus completely define the model of the system.

The study of the dependences $Y = F(X, U)$ allows to reveal the properties of the system, boundary and extreme values of the characteristics, the mutual connections between them.

Since the formulation of the model is carried out by formal methods, there is a need to check the validity of the model and the theoretical results obtained on its basis, which is carried out at the third stage of solving the issue of analysis.

The validity check is carried out by comparing the dependencies obtained from the model with the experimental data or data obtained by other methods of analysis.

The result of the analysis is models of the processes occurring in the systems and the regularities inherent in the processes and systems. Models reveal the cause and effect nature of processes and establish dependencies between their characteristics and system parameters.

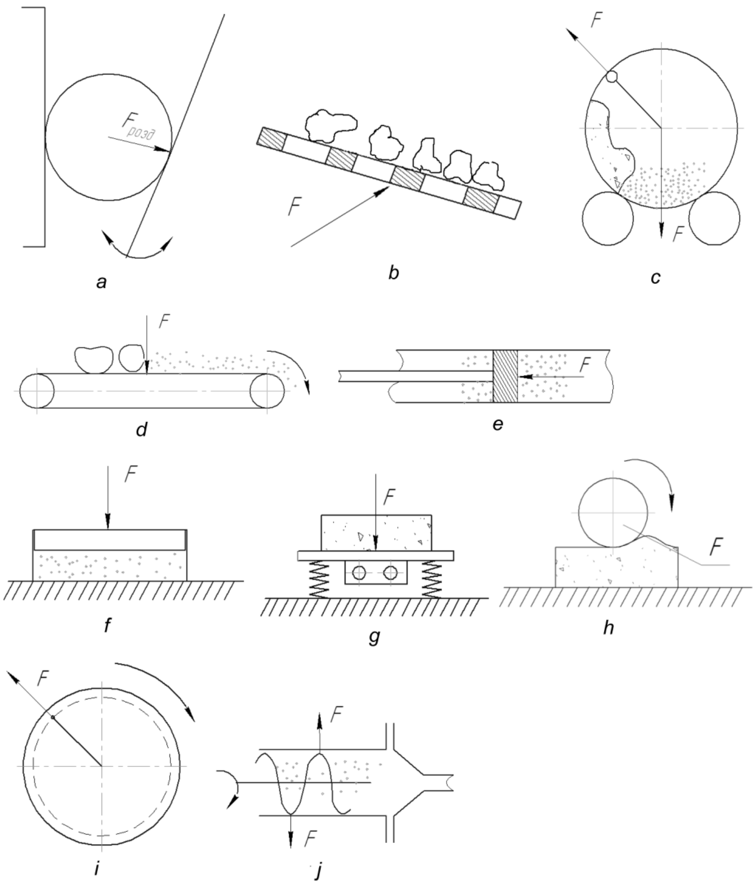
That is the cognitive value of the analysis. The applied value of the analysis is predetermined by the use of the results of the analysis to set the synthesis issue that arise in the constructional design of technological systems.

The study of complex technological systems begins with the analysis of the properties of algorithms, different strategies for managing processes, ways of organizing systems as a whole.

Herewith, models of processes that take place in systems that implement different classes of applied problems based on different structures and strategies of process management are built and investigated. The results of the analysis help to understand the essence of the processes taking place in complex technological systems.

Analysis of technological process. The machine formation, as noted above, involves having a technical specification that sets out the purpose of the machine and the requirements imposed on it. Usually the preparation of the technical specification and, in particular, the technical proposal requires consideration of the information characterizing the properties of the processing environment, the final product, the basic regularities of the technological process, as well as the analysis of designs of similar machines. Regarding the machines of processing industries (picture 4.1), the main phenomena of interaction between the processing environment and the working tool can be reduced to the consideration of contact forces, the determination of which is the output parameter for the calculation of machines in their constructional design.

For crushing machines (picture 4.1, a), the interaction conditions are to determine the material strength characteristics and, on the basis of these, to determine the loads on the crusher plate, and subsequently on all elements of the crusher (for example, for granite grinding with a strength up to 300 MPa, maximum load on the crusher plate q = 2.7 MPa). For bolters (picture 4.1, b), determining the condition of interaction of the working tool and material determines the estimation of the parameters of the technological process (amplitude and frequency of oscillations, efficiency of the sorting workflow, etc.)



Picture 4.1. Scheme of interaction of environments with working tools of machines: a – grinding; b – sorting; c – mixing; d, e – transportation; f – static compaction; g – vibration compaction; h – roller compaction; i – centrifugation; j – extrusion movement

For mixers (picture 4.1, c), the contact issue is important for choosing the number of revolutions of the drum, which ensure high efficiency of the mixing process and determine the load on the support rollers.

When transporting the mixture (picture 4.1, d, e), the contact forces must also be known when choosing the drive power and other technological parameters of the process.

When compacting or moving (picture 4.1 f-j), it is important to know the forces of interaction that determine both the load on the elements of the machine and the parameters choice of the technological process.

The developer finds all this information about the numerical values of the required parameters in the relevant literature (periodic definitions of scientific collections, monographs, catalogs, patents, etc.). However, when forming original types of machines and equipment, or when the machine is created to process new materials, as a rule, there is no necessary data about the properties of these materials and the regularities of the process of interaction of working tools and environments that are processed. In this case, the necessary parameters are found through experimental studies.

Thus, the properties of the process material, its interaction with the working tool of the machines are the main factors for the selection and calculation of the parameters and characteristics of the working tools and the machine as a whole.

The project developer finds all the information concerning the parameters of the processing environment, the machine operating parameters in the relevant literature (journals, scientific collections, monographs, catalogs, patents, etc.).

The analysis of the obtained results is carried out using structural and parametric syntheses.

Formalization and formulation of the analysis issue of technological systems.

Automated (machine) methods of analysis require special attention in describing the tasks facing a research engineer and a constructional design engineer of a specific technological system. In this case, the analysis process should be as strongly formalized as possible. This means that it must obey stiff regularities that do not allow for arbitrary interpretation.

The structure and nature of the input information and information, obtained during the process, should be strongly fixed. In such cases, we talk about algorithmization of the process of the technological systems analysis.

Algorithmization refers to the exact sequence of analysis operations that specifies a computing process that begins with arbitrary input data and is aimed at obtaining a fully defined result from this data.

In some cases, in order to make the process analysis of the technological system more efficient, there is a need to enable the person (engineer) to intervene in the necessary and strictly defined places of this process, in its course, i.e. to re-formalize it. This does not reduce the importance of stiff formalizing of the analysis process, but makes it more flexible.

Let us now consider an arbitrary technological system that is a part of the world around us. The latter has an impact on the technological system and is characterized by the input parameters $u_1, u_2, ..., u_m$, which can be noted by the input vector $U = \{u_1, u_2, ..., u_m)$.

If the input characteristics depend on time t, then U = U(t). Input characteristics may be deterministic or random. A classic and common example of deterministic influence on the system is the sinusoidal oscillations of the form $U(t) = \{A_1 \sin(\omega_1 t + \varphi_i\}, ..., A_m \sin(\omega_m t + \varphi_m)\}$, where $A_1 ..., A_m$; $\omega_1, ..., \omega_m$; $\varphi_1, ..., \varphi_m$ are the amplitudes, frequencies and initial phases of oscillations.

Random actions are sometimes helpful and sometimes have a negative impact on the system. Common to these actions is that they are random (stochastic) and their behavior cannot be accurately predicted in advance.

Until now, we have talked about the impact on the system from the outside, but the purpose of any system is to create a certain technological effect that acts the outside world.

This effect, as well as the input actions, can be described by a set of certain functions of time, which in vector form have the form $Y = \{y_1, y_2, \ldots, y_n\}$. These functions are called system response or output. Output of the technological system can be current, voltage, moving, acceleration, etc.

Based on the considered input and output characteristics, we can say that the task of the technological system is to transform the components of the vector U, which do not interfere with the system, into components of the vector Y, which give a useful effect (picture 1.3).

In order to characterize the issue of analysis, one more and quite important concept is necessary, this is a description of the technological system, which can be represented as a vector function of time $X(t) = \{x_1(t), x_2(t), ..., x_1(t)\}$. The description of the system must be so complete and accurate that the task of analysis can be solved.

Different forms of description are used in different fields of technology:

- differential equations of motion of the mechanical system;
- operator equations of the control system;
- algebraic equations, e.g. Ohm’s and Kirchoff’s laws in electrical engineering;
- drawings with numerical data of machines and mechanisms, etc.

Now we can describe the issue of analysis of technological systems in one of its most famous formulations: given input actions U(t) on the system and its description X(t), we need to find the response or outputs of the system Y(t).

In fact, an engineer or researcher analyzing a technological system usually solves a more complex issue. The fact that determining the response Y(t) is often not the only one and moreover not always the main task of the researcher.

In this connection, the question arises as to what parameters and functions characterize the technological system. In order to answer this question, we introduce a system of concepts that are related to the resulting information of the analysis of the technological system.

This system of concepts includes:

1. a set of functions and numbers that describe the behavior (functioning, dynamics) of the system;
2. a set of functions and numbers corresponding to the characteristics of the system;
3. a set of functions and numbers describing the properties of the system.

In this approach, the functions y_1 y_2, ..., y_n represent the individual cases of functions and numbers that make up the first element of the triad.

Based on the introduced concepts, consider the issue of analysis in its fullest form: given input (useful and unnecessary) actions U(t) on the system, as well as its description of X(t), for example, in the form of differential equations X(t) = f(t,U(t)); you need to find a set of functions and numbers that describe the behavior, characteristics and properties of the technological system.

Traditional ("manual") analysis of finding these functions and numbers is carried out analytically, but this is not always possible. For example, when differential equations of state of the system cannot be analytically integrated.

In this case, you need to use numerical methods of integration and computing means (computer technology).

In addition, in the process of analyzing the technological system, computer technology can carry out ancillary functions: to plot a curve of a function by previously found analytical formula, to check the execution of certain irregularities, to store and accumulate various information, etc.

In computer analysis, the calculation of numbers and functions that make up the triad is completely carried out by computer technology. Highly intellectual aspects of this process remain for the person: choosing the method of analysis, transition to another method, deciding to change the formulation of the analysis issue, comparing the results obtained in different ways, comparing the results of machine analysis with known experimental data, etc.

The process of analyzing technological systems depends on the deterministic or random components of the input action. In the first case, the input actions are given by the usual functions of time U(t).

It is possible to do this, as you know, by means of an analytical formula, a graph, a table of values of a function or an algorithm of its calculation by computer technology. If the component u(t) of the vector function U(t) is random, then methods for describing random functions must be used. It is being done by describing, in the usual way, some specially introduced deterministic functions, such as probability density functions or correlation functions.

When U, in addition to t, also depends on spatial coordinates, then we are dealing with a description of the function of action on many variables. This complicates the issue of the function, but the principles of description remain the same as in the case of one variable.

Analysis technology of technological system. As will be shown later, the task of analysis is much simpler than the issue of synthesis of technological systems. This is mainly due to the fact that the analysis issue is more easily formalized [3].

Here, it is easier to imagine the behavior of a calculator (human or computer technology) in the form of a stiff, predetermined sequence of operations, which, like the operations themselves, does not change. Operations constituents of the analysis can be quite complex, and their number is significant and can be repeated several times in calculations.

But that does not change the point, it just shows the need to use computer technology to analyze technological systems.

The structure of machine analysis of technological systems can be broadly described in several stages as follows.

In the first stage, the researcher enters a description of the technological system into the machine. There are two important points here. The language used to describe the system must be easily accessible to the machine.

It is best when the description of the system is reduced to a sequence of alphabetic, numeric and a few special, predefined symbols. On the other hand, the language should be simple, which can be mastered by a researcher or engineer without special training, considerable time and expense.

The second stage. The calculator machine transforms the system description into a form that is convenient for further analysis operations.

Quite often, the main operation of the technological system analysis is to solve the system of algebraic equations or integrate the system of differential equations.

Therefore, it is necessary to enter into the machine, for example, a system of differential equations describing the behavior of the technological system. When computer technology solves an exclusively mathematical (or it is better to say, formulated as exclusively mathematical) issue, this is obviously the case.

However, if the technological system is analyzed, and especially if it is complex, then this approach is not rational enough.

A description in the language of algebraic, differential or other equations is often compared in complexity with our operations of the analysis process, for example, with the solution of the equations themselves. Therefore, it is desirable to automate the procedure of generating and forming equations describing the behavior of the technological system.

Formation of equations refers to those operations that allow stiff formalization. Therefore, the machine usually copes better with this operation than a person.

This is where we come across cases of human-computer technology interaction. It should be taken into account that ideally such interaction should obey the simple principle: everything that is exposed to a formalization, to a machine, everything that is not (intellectual, intuitive, connected with the accumulation of experience, adaptation, with informal solutions), is exposed to a human. At this stage of analysis, this principle is well used.

The process of transforming the description of the system with the development of its standard universal form is completed. After that, to formulate a description, the machine must calculate certain sets of numbers and functions that differentiate the description of one particular system from another in the form that is taken as standard.

Let us consider a simple example (example 4.1). Let the system of linear algebraic equations be chosen as the standard description form of the technological system:

$$\begin{cases} a_{11}x_1 + a_{12}x_2 + \cdots + a_{1i}x_i = B_1; \\ a_{21}x_1 + a_{22}x_2 + \cdots + a_{2i}x_i = B_2; \\ \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \\ a_{i1}x_1 + a_{i2}x_2 + \cdots + a_{i1}x_i = B_i; \end{cases} \quad (4.1)$$

Here, $\{x_1, x_2, ..., x_l\}$ mean the state vector of the system, and other quantities are real or complex numbers.

More successful may be the writing of equations (4.1) in the matrix form:

$$Ax=B \quad (4.2)$$

Under these conditions, technological systems that can be described in this way will be distinguished by sets of the following numbers:

- by the number l;
- by the l^2 numbers $a_{11}, a_{12}, ..., a_{21}$;
- by the l numbers $B_1 ..., B_l$.

From these data, it follows that the transformation of the system description in our example should be reduced as follows: the system data entered into computer technology is turned into sets of numbers that distinguish between the matrices A and B of different systems.

The third stage. The purpose of the analysis is to calculate a set of numbers and functions that describe the behavior, characteristics and properties of the technological system. These numbers and functions can only appear as a result of processing of the system description by the machine, developed in the second stage of the analysis. This processing, i.e. actually calculations, is the essence of the third stage of analysis.

Most often, in the third stage, the equations that were formulated in the second stage are solved. In our example with linear equations, the third stage is to calculate the vector X. If the description of the system was formulated in the language of differential equations, then the third stage is to integrate them.

Thus, the third stage of analysis seems exclusively mathematical in nature. However, this is not entirely true. Any computing issue, in this case finding the roots of system (4.1), or integrating differential equations, can be solved differently by choosing a particular method of solution.

Then, the computing method does not yet uniquely define the algorithm of solution, i.e. a stiff set of actions in all details. For example, let a certain method of solving an issue contain some similar A in formula (4.2).

It turns out that this operation can be carried out using different algorithms. In carrying out the operations that require the third stage of analysis, we must hold fixed the computing method and algorithm.

In order for the computing process, which is the essence of the third stage, to be actually implemented, it is necessary to choose a computing method that implements its algorithm and numerical parameters of the algorithm. Here again we come back to the problem of human-computer technology interaction in the analysis process.

There are three ways to solve these selection problems:

1. original programmer makes a choice of computing method in advance for all the tasks available to it;
2. computer technology, by analyzing the process of solving the problem and the results obtained, in accordance with the rules introduced in advance, changes the process of solving, which was discussed in the first section;
3. new solutions are not accepted by the computer technology, but by the engineer during the computing process, depending on how this process develops.

All these selection problems are closely related not only to the mathematical aspects of the analysis problem, but also to the physical and technological features of the particular system to be analyzed. For example, the same method of integrating differential equations can be quite successful and completely inefficient, depending on which system.

Taking into account the features of technological systems is very important when reviewing accepted solutions.

The failure or luck of the choice made by a qualified engineer-researcher can, of course, relate not only and not so much to the formal and mathematical features of the system, as to its physical and technical properties and features (sometimes quite incomprehensible to the applied mathematician).

Therefore, the physical interpretation of the results that led to the choice of method, algorithm and algorithm parameters, physical and engineering intuition of the engineer-researcher are quite important and decisive in solving the problems of analysis of technological systems.

However, the desired result of the analysis of the technological system can only be obtained when the possibility of a convenient dialogue between a human and a computer technology is provided. Providing both program and hardware means for such a dialogue is one of the main goals of developers of technological systems analysis and synthesis programs.

Such a dialog mode of the computing process enables the research engineer to actively intervene in the calculations and solve selection problems of methods and algorithms of calculations. Qualitative technological systems analysis programs should ensure inter-communication between human and the machine and make it as convenient as possible, i.e. require a small amount of instructions to control errors and inconsistencies in these instructions.

The fourth stage of the analysis of the technological system is related to the processing of the results obtained in the process of dialogue between human and computer technology: the construction of graphic materials with the help of graphic devices, displaying information on the monitor, printing tables of numbers and text documents, transferring results to databases, where the results of various studies, combined by a common type of technological systems, analysis tasks, etc. are accumulated.

The same results obtained in the third stage can, at the request of the researcher, take different forms in the processing operation. For example, sets (groups) of numbers corresponding to a set of certain curves can be transformed into function tables, graphs, number tables, histograms (estimates of the probability density of random variables), etc. In turn, histograms can be printed and displayed on the monitor in the form of tables, graphs, etc. Instructions about the nature of the processing results of the output information may change in the process of analysis of the technological system.

The stage of analysis associated with the processing of the output information can not be underestimated, because a well-found form of presentation of results allows the researcher to find new ideas that allow to reveal more fully the physical and technical processes in the system, find other approaches to analysis, change the initial description of the system, etc.

Structure of the analysis process of the technological system. In many cases, the information contained in the initial description of the technological system is accompanied by information of another kind, called a prior information. This is all the information that a research engineer has to process and enter into computer technology before calculations begin to make the solution of the analysis task possible with the computer technology resources available. Resources of the computer technology mean a set of values such as machine time, capacity of used memory, etc.

Collecting and processing of the prior information requires some human and machine resources expenses. Therefore, the researcher, when organizing and planning the process of machine analysis, almost always solves the following task: the collection and processing of the prior information or the expenses of resources when computing on the computer technology. The analysis raises questions about the completeness and accuracy of the description of the technological system. The answers to the questions cannot be found before the analysis begins, since many of the conditions and parameters contained in them can only be verified after the analysis process is complete.

The same questions arise about the completeness of a prior information. All this is characteristic of the analysis process of complex technological systems, where it is impossible to predict in advance how the process will pass, with what quantitative errors it is carried out, what character the numbers and functions will have.

Therefore, it is advisable to construct this process as a sequence of specific tests, enabling the research engineer to return to the already completed stages of the process, with changes to the initial information, calculation methods and algorithms, etc [4].

Taking into account these caveats, the procedure for analyzing technological systems can be carried out in the following order.

1. Entering the initial description of the system. Determination of functions and numbers to be deduced after the analysis.
2. Transforming the initial description into a form that is convenient to the computer technology (description formulation).
3. Collection, processing and implementation of prior information.

4. An analysis (calculations on computer technology that aim to deduce the functions and numbers specified in the first section).
5. Verification of the condition, which can be formulated as follows: is there enough information contained in the system description and a prior information? If it is sufficient, the analysis procedure is continued, and if it is not enough, it is necessary to supplement the insufficient information and return to sections 1 or 3 of this procedure.
6. Calculation and output of the analysis results on external storage media.
7. Checking the condition: whether all the objectives of the analysis have been achieved and whether they should be supplemented with new ones.

The analysis of the system is completed, and if is necessary, we return to the beginning of the procedure, specifying a new set of necessary functions of numbers, etc.

Constructed analysis procedure of the technological system is a cyclic structure in which certain operations can be carried out several times.

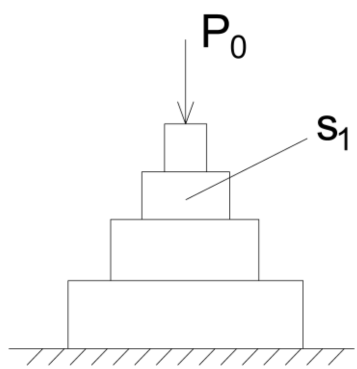
It should be noted here that any solutions that can be accepted by the research engineer in the analysis process have informal nature, so the role of the latter is crucial in this process.

Formation of description of technological system. The requirements for the description form of technological systems by the research engineer and computer technology, dictated by the best organization of the computing process, are significantly different.

First of all, simplicity of description is important to the engineer-researcher, i.e. the form of description should be such that it can be made by a little qualified person.

At the same time, the computing process can only be accomplished when the initial description is transformed into a form, which is convenient to the computer technology.

Let us show this by way of example (example 4.2) and consider a mechanical system – a column of a piecewise constant section (picture 4.2).



Picture 4.2. Scheme of a column of a piecewise constant section (si is a cross-sectional area of the i element of the column, P_0 is a load)

The input action of the system u(t) is the applied external force P_0. The geometry of the cross-section of each i element is fixed. Therefore, the cross-sectional area s_i, fully characterizes this element.

What can be considered here as a system description? Obviously, it will consist of the number of elements that form the column, the lengths of these elements, the sets of constants that characterize the materials of the elements, the set of numbers s_i.

It is easy to see that the formation and entering into computer technology of this information does not require high skills.

However, to solve the problems of analysis and synthesis of the column, it is necessary to form another description of it, i.e. "machine" description. Such a description includes two matrices – stiffness K(s) and mass M(s). Knowledge of these matrices allows us to find, in the individual case, the proper oscillation frequencies of the structure from the equation

$$K(s)y = \lambda M(s)y. \quad (4.3)$$

How is it advisable to organize an algorithm for calculating the matrices K(s) and M(s)? Obviously, the initial data should be the characteristics entered by the engineer-researcher (user). On this basis, computer technology first calculates the K_i and M_i matrices that characterize the i element of a column. Then, given the information about the arrangement order of the elements in the column, the resultant matrices K(s) and M(s) are calculated using some algorithm.

Thus, the description that is required to solve the analysis problems of the column of constant cross-section, is obtained. Similarly, descriptions for other technological systems may be obtained.

A prior information. A prior information is called information that must be collected, processed, and entered into computer technology so that the task of analyzing technological systems can be solved with acceptable machine resources or reduce requirements for them.

Let us consider the definition of a prior information in specific examples.

Example 4.3. Solving the system of finite equations. In many cases, calculations related to the analysis of technological systems in computer technology, require the solution of a system of finite (algebraic or transcendental) equations:

$$\begin{cases} f_1(x_1, x_2, \dots, x_1) = 0; \\ \dots \dots \dots \dots \dots \dots \dots \dots \dots . \\ f_1(x_1, x_2, \dots, x_1) = 0, \end{cases} \quad (4.4)$$

or in vector form

$$f(X) = 0. \quad (4.5)$$

Some computing algorithms allow you to calculate the root

$$X_0 = (x_{10} x_{20}, \dots, x_{i0})\ X_0$$

only when a certain value of the vector X_o close to X is entered into the machine.

Other algorithms lead to the solution of system (4.4) or (4.5) even when nothing is known about X_o, but the value of X_o makes it possible to significantly accelerate the calculation of the root. It is clear that the definition of X_o is naturally interpreted as finding prior information.

Sometimes the predicted values of X_o are practically unknown, then it is necessary to talk about a whole sufficiently lengthen G_x domain in the space of coordinates x_{10}, x_{20}, ..., x_{l0}, which must contain the point necessary for the solution of system (4.4). In such a situation, a prior information is obviously a description of the G_x domain.

An example of a machine analysis of the technological system. During the dialogue with the computer technology, the researcher at the predefined points of the t axis will receive information about the solution X(t) and its periodicity. In the presence of this information, the non-periodicity of the motion process of the mechanical system is possible in two cases:

1. the solution is in fact non-periodic;
2. the solution is periodic, but the calculation of the transition process is not yet complete.

The researcher can find out the reason for the non-periodicity of the process in several ways.

1. Stop the calculation process after some time and thus contribute to the task of analysis – to determine the properties of the system. Making of this decision may be promoted by prior information of other nature than that associated with the G_x domain. Such information may be the time of setting the periodic mode of motion of the mechanical system t_B. If, according to a prior data, the time of establishment of the periodicity of motion must be of a certain magnitude, and the calculated segment of the process contains much larger magnitude of the time before decision making moment, the decision to terminate the computing process is justified. However, the analysis task to calculate the periodicity of motion of the mechanical system remains unfulfilled.
2. Continue the calculation process to find out if the periodic mode of motion will be set in the future. You can also use auxiliary a prior information.
3. Partially stop the calculation process and verify the sufficiency of descriptive and a prior information.

It may be that a prior information is sufficient and descriptive information is not sufficient or vice versa. It may be necessary to specify a prior information, for example the value of t_B. This value may be random.

We think that the technological system and its external actions are deterministic, so t_B must be a deterministic number. However, if the system is complex and the information about t_B is a prior, then it is impossible to determine the value of t_B with sufficient accuracy. Using any method of estimation, it is possible to determine only the range within which the value of t_B must be with certain probability.

4.2. THE ESSENCE AND CONTENT OF THE SYNTHESIS OF TECHNOLOGICAL SYSTEMS

The essence of the problem of synthesis of technological system. The formulation of the synthesis problem is somewhat opposite to the formulation of the analysis problem. In the process of synthesis, descriptions of the input actions and descriptions of behavior, characteristics and properties of the future system are given.

Quite often, system behavior descriptions include outputs descriptions. These descriptions, or parts of them, were not specified in the analysis, but sought. It is necessary to find a description of the system itself and its states in the synthesis problem, while a description of the system is specified in the analysis problem.

Thus, the solution of the synthesis problem is the process of transforming one description into another. This task is similar to the problem of analysis, only the input and output descriptions are different here and the process of transformation of descriptions is also different.

Exactly these fundamental differences make the synthesis process more creative, where a skilled specialist plays an important role, which cannot be replaced by any set of computing means.

However, it is unreasonable to load a specialist with cumbersome and monotonous information that does not require creative abilities and intuition. Therefore, in the process of synthesis of technological systems, it is desirable to organize human-computer technology interaction.

In the process of synthesis of technological systems, the central place is occupied by the problems of choosing the structure of the system and the basic elements. These problems in many tasks are very badly formalized and algorithmized.

This is where the creative power of human intelligence, its ability to use intuition, experience of solving similar or significantly other tasks, etc., should manifest itself.

One of the ways of synthesis of technological systems is to choose a certain structure and basic elements and on the basis of solving the problem of analyzing, the implementation of sounding the parameters of the system and the choice of those that satisfy the desired properties of the system.

If the analysis is directed, it can be constructed in such a way as to approach the desired properties of the system. One way or another, we manage to establish a dependence between the characteristics of the system properties and the parameters of its basic elements.

At first glance, this approach seems quite simple. However, in fact, it is not quite clear to us what kind of system we need to analyze. The system is only being created and we need to find its description, while it must be known for the analysis issue.

So, we deal with the basic contradiction of the synthesis issue, which basically can not be resolved. Creating a system requires information about its behavior, characteristics and properties and it is necessary to find out the system itself.

Before the description of the system is found, this information cannot be obtained and without knowing it, it is impossible to create the system.

The main contradiction of the synthesis process is connected with others, also sufficiently significant reasons, they can be characterized as follows: we can create a system only when we know which system we want to create. However, this knowledge comes only in the process of finding the system we need and, in fact, many questions remain unclear even after the description of the system has been found and it has been carried out.

There are occasions when the statement of the synthesis issue is revealed only after a sufficiently long operation of the system, i. e. when the problem of synthesis itself may no longer provoke interest. Let us consider an example to confirm this idea.

Example 4.4. Let us assume that some mechanical system to be created, for which the oscillatory process is the basic operating mode. The frequency range of this process is known before the start of the constructional design, other initial data is also undeniable.

After the synthesis issue was solved and a description of the mechanical system was found, its research was carried out. As a result, it was found that, in addition to oscillations in a given frequency range, the system performs "parasites", whose spectrum is outside this range and which are inadmissible from the point of view of the normal operation of the system (may destroy the system, affect its interaction with other systems, etc.).

As a result of the consideration of this example, the question arises: Have we solved the issue of synthesis or not? If the solution of the problem of synthesis means finding any system that satisfies the initial requirements, then of course we have solved the issue.

But if the finding of such a description of a mechanical system that satisfies its effective functioning is a purpose of constructional design, then the issue remains unresolved. The contradiction is that to fulfill the formally described conditions does not mean to satisfy the "true" conditions of synthesis.

This example shows that the requirement of absence of parasites had to be included in the formulation of the synthesis issue. However, the importance of this condition became apparent only after an analysis of the created mechanical system.

Prior to that, the engineer, who formulated the issue was unsuspicious of occuring the undesirable processes. A noteworthy detail is that when the analysis was unsuccessful, he simply could not detect undesirable effects at the next stage of system designing.

The experience of creating sophisticated technological systems shows that at the beginning of the synthesis process, it is impossible to formalize all the conditions to consider the system satisfying or, moreover, the best of the possible ones. The certainty in the setting of requirements appears only with an understanding of the behavior, characteristics and properties of the system – the one system, the description of which is unknown and is necessary to be found.

Of course, these contradictions hardly show up in the case of simple systems whose behavior, characteristics and properties are essentially easily predictable, albeit qualitatively.

Of course, if the synthesis process is completed, then the contradiction described above must be eliminated eventually. It is eliminated with a single or multiple access to the analysis process and estimation of its results. Thus, analysis is the main tool for eliminating the contradictions that arise in the process of synthesis of technological systems.

The fundamental difficulties of the synthesis process are the ignorance of what is possible and what is impossible in the system being created and the inability to formalize the wishes of the designer, which can be eliminated by analyzing some variation of the system [5].

On this basis, we can propose the following process structure:

1. To develop a variation of description of the technological system that meets the initial requirements of synthesis.
2. To conduct a thorough analysis of the proposed system. At this stage, a variation of the description of the technological system that meets the initial requirements of synthesis is needed to be developed.

3. To conduct a thorough analysis of the proposed system. At this stage, it is advisable to use a computer technology.
4. To estimate the benefits of the proposed system based on the information received about its behavior, characteristics and properties.

If the system meets the necessary requirements or, moreover, is the best of all possible ones, then the synthesis process must be completed, and if not, there is a need to return to the first item. This structure of synthesis enables human and computer technology to do what brings the best results for each of them.

Everything that requires an informal, creative approach, for example suggestion of ideas, formation of hypotheses, estimation are remain with the human. Anything that algorithmized better is mostly done by computer technology.

But, it is more than that. Each successful step in the iterative, cyclic procedure described above provides an opportunity to understand something new in a system, which is being created, limits of the possible and the impossible are gradually evaluated, underestimated or undetected dangers are revealed, the goals of synthesis are formalized, etc. Thus, obstacles and contradictions are being eliminated step by step.

The described structure of the synthesis process is only the basis of a complex, branched process. For example, specifying a system description requires specifying a structure, elements base and parameters. Does revealing all of these components give you an opportunity to propose a variation of the system description? Basically, it does not.

In any case, a human reveal the system parameters worse than the computer technology. Often, the calculation of the parameters can be represented as a sophisticated algorithm that allows efficient use of computer technology. Then the creative work remains with the human and the results of the system description are supplemented by numerical information from computer technology.

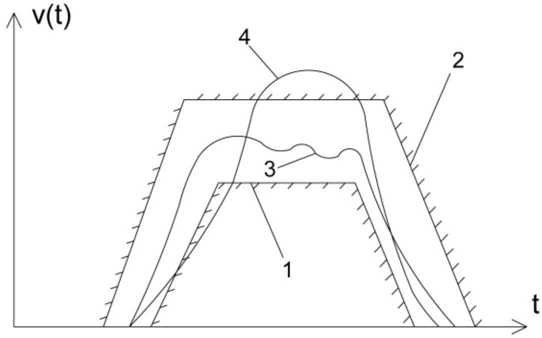
Estimation methods of technological systems. Let us have a look at two basic estimation methods of technological systems that determine both the formulation of the issue and the structure of the synthesis algorithm.

<u>*The first method*</u> involves calculating a set of numbers and functions. In this case, each of the systems corresponds to the same set of numbers and functions, whoever calculated them and whenever they were calculated, and regardless of the conditions of those calculations.

In last example, a set of numbers and functions was made up of one element. After the numbers and functions are revealed, carrying out of the inequalities or other similar formulas by the system is checked.

Such a check always and definitely leads either to the suitability of the system or its unsuitability. In the examples considered, it was enough to find out the validity of one inequality.

In more complex cases, it may be necessary to verify that any characteristic of the system being created belongs to the area previously specified. For example, the developer may require that the characteristic v(t) of all suitable variations of the system be contained in a predefined area (picture 4.3).



Picture 4.3. The characteristics of all synthesized systems should belong to the specified area

Then the estimation of the system suitability is reduced to a point-by-point (for each abscissa t, located between t_0 and t_1) checking that the number v(t) belongs to the corresponding interval, which is limited by brakes 1 and 2 (picture 4.3). Based on this method of estimation of technological systems, characteristic 3 meets the above requirements, and characteristic 4 – does not.

Such a stiffly formalized, unambiguous one, which does not accept any informal moments, is called the cardinal approach to the synthesis of technological systems [6].

The second method. An alternative to the considered method of estimation of the technological systems is the ordinal interpretation of synthesis [6]. It assumes that it is impossible (inappropriately) to use only a set of numbers and functions for the estimation of technological systems, or, on the basis of this set, it is impossible (inappropriately) always and unambiguously to conclude the system's suitability.

Until now, we have considered that the purpose of the synthesis is to find a description of a suitable (satisfactory) system. This approach corresponds to the suboptimal synthesis of technological systems.

However, in many cases, the developer wants to achieve the maximum goal – he does not need a satisfactory one, but he needs the best of all possible systems. Such constructional designing strategy leads to optimal synthesis.

It is easy to guess that the optimal synthesis can not be fulfilled, if we limit ourselves by making a decision about what is satisfactory and we would be unable to compare at least two technological systems in order to choose the best one. Let us assume that two technological systems from a particular set are proposed for comparison and we can make one of three conclusions: the first system is better than the second; the second system is better than the first; in terms of their use, the systems are the same (equivalent).

When cardinally comparing these systems, using a certain set of numbers and functions, as well as the algorithm of their processing, one and only one of three decisions can always and unambiguously be made.

In the ordinal one, the use of a set of numbers and functions, as well as their processing algorithms, is not prohibited. However, there is no formal rule with the help of which is possible to make an unambiguous conclusion about the benefits of a particular system and is not dependent on informal circumstances, qualifications, experience and tastes of the expert, etc.

Suboptimal and optimal synthesis of technological systems. Let us consider the essence of suboptimal and optimal automated synthesis of technological systems using computer technology. Let us assume that the description of the behavior, characteristics and properties of the system are reduced to specifying n real numbers K_1, K_2, ..., K_n as indicators of quality (functioning) of the technological system.

Cardinal decisions about the satisfactory and superiority of certain systems can be completely reduced to processing these n numbers, which form a certain vector K. In ordinal interpretation, this vector may also be useful, although it should not algorithmically lead to unambiguous decisions.

Suboptimal cardinal synthesis. It consists in converting descriptions of influences, required behavior, characteristics and properties of the system into such description of the desired system, for which inequalities are simultaneously fulfilled:

$$\begin{aligned} &K_{11} \le K_1 \le K_1^1; \\ &K_{21} \le K_2 \le K_2^1; \\ &\ldots\ldots\ldots\ldots \\ &K_{n1} \le K_n \le K_n^1. \end{aligned} \qquad (4.6)$$

The real numbers K_{i1} and K_i^1 (i = 1, 2,..., n) are defined together with the make up of the vector $\overline{K}$. Some or all of the numbers K_{i1} can be zeros.

The cardinal approach to synthesis is that each system is uniquely characterized by a set of numbers from a vector $\overline{K}$. The decision on the system's satisfactory requires that each component of this vector satisfies the corresponding inequality (4.6).

Such a synthesis algorithm does not accept any ambiguities. It only accepts the ambiguity of result – it may happen that several systems are satisfactory. The considered synthesis approach does not indicate the algorithm by which one or another variantion of system should be deduced from the obtained satisfactory variations.

Suboptimal ordinal synthesis. There is no formal algorithm for deciding whether the variation of technical system is satisfactory. It is possible to synthesize a system when there is no set of functions and numbers for its estimation.

However, such approach is inappropriate and is not used in the practice of technological systems creation. The method is appropriate, when a set of numbers and functions is stored for the estimation of systems, but the process of selecting the make up of the vector $\overline{K}$ and the boundary limits K_{i1} and K_i^1 in inequalities (4.6) is carried out informally by the developer. Let us consider an example of this.

Optimal cardinal synthesis. We consider that the characteristics and properties of the system are quite fully reflected by the vector $\overline{K}$.

Some of the components must satisfy the system of inequalities in the optimal approach to the synthesis of the system, as in the case of suboptimal synthesis (4.6).

The algorithm of suboptimal synthesis of technological systems. Prior to that, the problems of formulating the issue of synthesis and their solution, based on the general principles that can be used in finding descriptions of technological systems were considered. Now, let us consider some specific synthesis methods that are based on stiffly algorithmic cardinal approaches [6].

Let us assume that the goals of creating a new system and its requirements are well known to the developer and he can determine the quality indicators K_I, K_2, ..., K_n, which fully describe the system, and the limits K_{11}, K_1^1 , ..., K_{n1}, K_n^1 can be specified, in which the relevant indicators should be located. The cardinal problem statement creates absolutely stiff requirements for the future system.

In exchange for it, the developer has the opportunity to translate the entire process of synthesis of the technological system on computer technology, since he does not have to make any informal decisions related to changing the problem statement, except for the synthesis problem would be impossible to solve fully in such a setting.

The synthesis process is divided in a number of stages. The first of them is connected with the synthesis of the structure and the choice of elements base, i.e. a set of elements from which the systems are built. These stages are poorly formalized and are usually operated by a human using a computer technology. However, we will show how the synthesis of a structure could be algorithmic, or, as it is also called, structural synthesis.

Let the transformation of some input u(t) into the output y(t) in an arbitrary physical system be carried out by only three blocks A, B, C and each of them is located behind the other one, as shown in Picture 4.4.

Each of the blocks A, B, C can occupy any position 1, 2, 3.

Picture 4.4. The structure of the system, which is synthesized: 1, 2, 3 are numbers of system blocks

In this highly idealized situation, each block can be viewed as an indivisible element of the system. In total blocks A, B, C form the base of the synthesis elements. At the same time, we consider that the microstructure of each block is selected and fixed, but their parameters are not revealed and are free. Let us denote the corresponding sets of parameters of blocks by A_A, A_B, A_C.

What for the system synthesis? Is it resolved under such conditions?

Firstly, for choosing the arrangement of blocks A, B, C: possible structures are ABC, BCA, CAB, CBA, BAC, ACB. Secondly, for finding all components of the vector and, i.e. for finding the "subvectors" A_A, A_B, A_C. The result of the last calculation should depend on the arrangement of the blocks. Therefore, parameters revealing, which is called a parametric synthesis, cannot be isolated from structure synthesis.

The initial information in the cardinal informal synthesis includes: a description of the structures of the elements (in our example, blocks A, B, C); a description of the G_a domain to which the admissible values of the parameters set a may belong, i.e. the combinations of the sets a_A, a_B, a_C; 2n numbers K_{11}, K_1^1, ..., K_{n1}, K_n^1 that go into inequality (4.9) and determine the already accepted eligibility conditions of the synthesized system.

Synthesis is known for transformation of one description into another. The descriptions that we need to find are as follows: a three-element sequence of symbols that places letters A, B, C in a certain order is a description of the structure of the system; a set of numbers $\overline{a}$, i.e. a description of the system parameters.

The synthesis issue will be solved if the descriptions, which are presented in the original information, turn into the last two.

The synthesis algorithm can be divided into the following stages.

1. Based on the information about such systems and based on the experience and intuition of the developer (designer) or accidentally, the latter produces a fixed sequence of symbols A, B, C and some initial vector of parameters $\overline{a}^{01}$. The system is fully defined by this, if the initial assumptions are followed.
2. A partial analysis of the system selected in the previous step is carried out. The calculation of the vector limits such an analysis $\overline{K}$.
3. The verification of the irregularities п is implemented (4.6) and a conclusion about the satisfactory or unsatisfactory of the system is formed.

If the system is revealed as satisfactory, then the process of suboptimal synthesis can be considered successfully completed. If the inequalities (4.6) are not satisfied, then a new process of selecting a satisfactory system is carried out.

This process is carried out by going back to the first stage if there is information about the previous unsatisfactory system.

Possible variations of the synthesis algorithm differ in the strategy of choice in these conditions of the new system. There are two ways of solution. The first one is to preserve the previous structure of the system, i.e. the sequence of blocks and try to satisfy the conditions of suitability of the system at the expense of a more successful choice of the vector of parameters a, than in the previous case, when we had less information than we have now. It is, basically, an attempt to get out of the position through parametric synthesis.

The second is to consider that the system's unsatisfaction depends on the poor structure and therefore further searches in the parameters space give little chance to succeed. Then the structure changes, i.e. a new sequence of elements A, B, C is selected and a new combination of parameters – a vector, is selected in this structure $\overline{a}$.

If the new system is somehow selected in the new conditions in the first stage, then you can come to stage 3 and analyze if the system is satisfactory.

There are two possible variations: either the proposed synthesis algorithm will lead to a satisfactory system, or the computing resources will be depleted before it happens (in such cyclical calculations often set a certain time limit, and computer technology automatically completes the calculation as soon as the time allotted is used).

In the second case, the developer needs to replace the initial information, extend the limits to the structure, or come to a new synthesis algorithm.

Such solutions require highly skilled developer. The transition to a new algorithm is based on the belief that this synthesis issue in its initial cardinal formulation can be solved, but the previously used algorithm either does not find the solution or searches for it inadmissibly slowly.

It is also possible that there is no structure or combination of parameters that can satisfy the inequalities (4.6). Then all further efforts will fail and computing resources will be wasted.

4.3. THE MORPHOLOGY OF THE PROCESS OF ANALYSIS AND SYNTHESIS OF TECHNOLOGICAL SYSTEMS

The method of morphological analysis and synthesis, developed by the Swiss astronomer Zwicky F. is based on the principles of combinatorics [7]. Its essence lies in the fact that in the technological system or in another object a group of basic structural or other features are distinguished.

Alternative features are chosen for each trait, i.e. possible options for its implementation. Combining them with each other, you can deduce many different technical solutions, including those that are of practical interest.

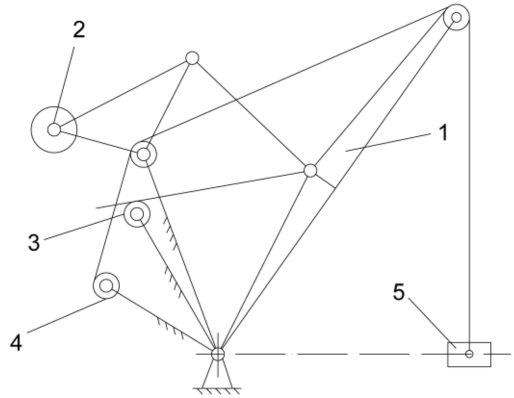
Practical application of the method consists in building a morphological table, filling it with possible alternatives and choosing from the whole set of the most acceptable technical solutions.

The Zwicky method was the most widespread, where the functions of the elements of the technological system are selected for the features and different ways of realization of each function are selected for the alternatives. In this case, the morphological table will have as many columns as the functional elements in the system at the selected level. Then the number of possible technological solutions is determined by the formula

$$N = n_1 \cdot n_1 \cdot \ldots \cdot n_m,$$

where m is the number of functional elements of the system at a given level; n_i is the number of alternatives of the i (i = 1, 2, ..., m) functional element.

Let us have a look at the construction of a morphological table on the example of a building crane arrow system with a horizontal movement of cargo when changing departure (picture 4.5).



Picture 4.5. The scheme of the crane arrow system. The arrow system consists of the following basic functional elements: 1 – arrow device; 2 – mechanism of its equilibrium; 3 – drive mechanism; 4 – equalize mechanism of the cargo trajectory 5.

The morphological table has four columns, which include the functional elements of the arrow system for the system under consideration (tab. 4.1).

The same table in each column lists alternatives of the functional elements of the arrow system.

By choosing one of the alternatives of the technical solutions from each column, we will deduce one of the possible variations of the arrow system, so if we take the alternatives under the first number from each column, we will deduce the variation of the arrow system, which is shown in picture 4.5.

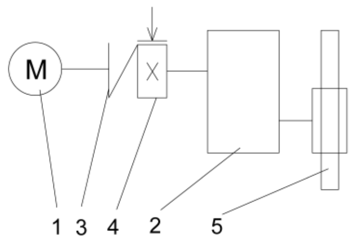
Altogether, from this table you can deduce N = 6·5·6·5 = 900 variations of building crane arrow system with a horizontal movement of cargo.

This table may be supplemented by new possible variations of the functional elements.

Table 4.1. Morphological table of possible variations of the crane arrow system

Alterna-tives	Functional elements			
	Arrow device	Equilibrium mechanism	Drive mechanism	Equalize mechanism of the cargo trajectory
1	Stiff lineal arrow	Four-linked	Rail-tracked	Specialized drum
2	Stiff curvilinear arrow	Six-linked	Screw-shaped	Equalizing beam
3	Component – linked arrow with a lineal arm	Block and tackled	Hydraulic	Equalizing block and tackle
4	Component – linked arrow with a specialized arm	On the arrow	Cranked	Load cable, which is parallel axis of the arrow
5	Lineal arrow with extending sections	Equilibrating carriage	Block and tackled	Load cable, which is parallel axis of guywire
6	Lineal arrow with inserts	–	Crank-and-rocker mechanism	–

Let us have a look at the process of the morphological table compiling at a lower level for the drive mechanism of the building crane arrow system. One of the variations of the drive mechanism can be a rail-tracked mechanism (picture 4.6).



Picture 4.6. Kinematic scheme of the rail-tracked drive mechanism.
This drive mechanism consists of a motor – 1, a transmission mechanism – 2, a coupling device – 3, a brake mechanism – 4 and a rail-tracked mechanism – 5

Table 4.2. Morphological table of possible variations of the drive mechanism of the building crane arrow system

Alterna-tives	Functional elements				
	Motor	Transmission mechanism	Coupling device	Brake mechanism	Operating mechanism
1	Direct-current motor	Spur-gear speed reducer	Pin coupling	Shoe with electro magnetic tappet	Tooth-type
2	Electricmotor of the alternating current with squirrel-cage rotor	Cycloid gearbox	Tooth-type coupling	Shoe with hydraulic tappet	Lantern
3	Electricmotor of the alternating current with slip rings	Worm gearbox	Chain coupling	Conveyor with easy lever control	Worm
4	Hydraulic motor	Waveform gearbox	Double-slider coupling	Conveyor differential	Screw-shaped
5	Internal combustion engine	Bevel gear speed reducer	Hydraulic coupling	Plate-type	Block and tackled
6	—	Combination gearbox	Closed coupling flange	Powdered electro magnetic	Rail-tracked
7	—	—	Cammed	Electro inductive	Crank-and-rocker mechanism

Five functional elements have been removed in the drive mechanism, various alternatives of which form a morphological table (tab. 4.2).

The analysis of the table 4.2 shows that you can deduce N = 5·6·7·7·7 = 10290 variations of the departure change of the arrow system. Not all of these variations of the drive can have practical implementation.

However, a considerable number of alternatives allow to analyze different constructive solutions and to choose from them the most effective and perspective drive constructions in one or another conditions.

QUESTIONS FOR SELF-CONTROL:

1. What is the "process of synthesis of technological systems"?
2. What is the "analysis" as a process?
3. Describe the "analyzing issue of technological systems".
4. Expand the content of an "analysis of the technological process".
5. What is the "formalization of technological systems"?
6. Provide a description of the issues of the developer or researcher, who is analyzing the technological system.
7. Expand the structure of machine analysis of technological systems.
8. What is the purpose of usage of computer technology in the constructional design of technological systems?
9. Provide a procedure of the technological systems analysis.
10. Describe the formation process of the "description of the technological system".
11. What information is referred to as "prior information"?
12. Give an example of a machine "technology system analysis".
13. Provide the essence and content of "synthesis of technological systems".
14. What are the estimation methods of technological systems?
15. What is the "suboptimal synthesis of technological systems"?
16. What is the "optimal synthesis of technological systems"?
17. Name the algorithm of "suboptimal synthesis of technological systems".
18. Give the morphology of the process of analysis and synthesis of technological systems.
19. Name the famous scientists – developers of "morphology of the process of analysis and synthesis".

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Chapter 5. Technological systems management

Contents of Chapter 5

Keywords: technological systems management, decision-making, management issue, management purpose, optimal management method, one-step decision-making issue, classical optimization issue, linear programming issue, nonlinear programming issue, stochastic programming issue, management dynamical issue, adaptive management issue.

5.1. THE CONCEPT OF MANAGEMENT IN COMPLEX TECHNOLOGICAL SYSTEMS

The issues of technological systems management of varying complexity has become increasingly important in recent years. This is due to the fact that technological systems that deal with high energies, high speeds, rapid processes, expensive installations and experiments are characterized by the requirement of the most rational use of resources, the choice of the best features of the program of actions. The problems that are the subject of management theory are defined by all of this.

In technological systems the processes are occuring, the nature of which depends on a variety of contributing conditions and factors. By changing the conditions of the processes, you can influence their nature, modify them, adapt them to one purpose or another.

The essence of management is an interference in the natural course of the process, changing it. Thus, it can be said that management is the organization of one or another process that ensures the achievement of the defined goals [1].

Each process of management can be divided into four stages: appearance of the goal, situation assessment, decision-making and implementation of the decision.

The goal appearance stage appears before the start of the management process, so it cannot be considered. In regard of the management process, the implementation of three main steps can be considered:

1. collecting and processing of information to assess the situation;
2. decision-making on the most focused actions;
3. implementation of the decision made.

A fourth step is also necessary sometimes: control of the decision implementation.

Different types of management issues differ from each other in the technique and sequence in which these operations are implemented.

There are many issues in which the mechanisms for collecting and processing of information and executing of the decision made are sufficiently clear that they may not be thought of at all during the management process. In such issues, all the viewed management processes are essentially considered only in the second stage.

Such tasks are called one-step decision-making issues.

However, in most cases this approach is idealized and simplifies real management. In reality, all stages of the management process are closely interrelated and the decision-making stage requires a detailed consideration of possible ways of implementing the decision.

Sometimes the process of management is divided into several sequential steps and the decision, which is taken at any step, depends on the results of the previous steps.

However, the complexity of solving these issues can be greatly underestimated, if taking the circumstances into account that management processes take place, as a rule, in a complex environment. The implementation of management processes is influenced by a variety of external factors, the set of which is often called the state of nature.

In order to make the right decision about these or other actions, it is necessary to estimate the results of these actions and to do this, you need to know the nature of the situation in which these actions are carried out.

However, the typical case for management issues is when the available information is either insufficient to assess the situation accurately or is distorted by external factors. In this case, lack of information does not leave on the decision-making issue.

The peculiarity of the management issues is that the decision must be made irrespective of whether we are able to accurately estimate the results that the decision will produce or not.

Thus, an important decision-making issue arises in the management process under conditions, where the situation information is either insufficient or distorted. Such task was called the decision-making issue in conditions of uncertainty.

Let us have a look at another specific class of management issues, which is associated with the activities of large industrial enterprises, such as the organizational and production technological system, which was discussed in the second section.

Prior to the Industrial Revolution, a small business could be managed by one person, who made purchases, planned and directed work, sold products, hired, and fired the workers. At the small size of the enterprise, the manager could make organizational decisions without using any scientific methods and based only on his knowledge, experience, intuition.

If some of the decisions made were not good, they did not lead to significant losses or could be quickly corrected.

The consolidation of industrial enterprises made it impossible to carry out administrative functions by one person (heads of production departments, sales departments, finance departments, HR departments, etc. appeared).

Mechanization and manufacturing automation led to a further division of administrative functions. Thus, the production departments were divided into smaller groups, which are dealing with the issues of operation and repair, quality control, planning, supplying, storage of finished products, etc.

Each individual specialized subdivision of a large organization performs a specific part of the teamwork, guided by the general goals of the enterprise. However, each specialized subdivision has its own goals. All these goals do not always correspond and sometimes contradict each other.

The problem of ensuring an enterprise with reserves may be considered as an example. A separate subdivision may be interested in a significant increase of inventory reserves for ensuring the continuous release of its production. But, this will lead to reduction in reserves of other subdivisions due to limited storage space.

As a result, there is an issue of organizational and managerial type – the choice of the strategy towards reserves, which would be the most appropriate for the whole enterprise generally.

When solving this kind of organizational and managerial issues, there should be a very good understanding of the goals of the individual subdivisions and such coordination, so that they do not conflict with each other or with the general goals of the whole enterprise.

If we take into account that making the best decisions in the conditions of a large enterprise can bring considerable losses, it seems clear that when solving organizational and managerial issues it becomes inadmissible to rely solely on personal experience and common sense. Scientific methods are required.

Development of scientific methods of solving organizational and managerial issues is engaged in the scientific discipline, which is called operations research [2].

The operation is understood as some organizational measure, the conduction of which involves a clearly defined purpose, such as the regulation of stockpiled reserves. Conditions that characterize the circumstances of the event, such as inventory requirements and restrictions of storage space in the viewed example, should be specified.

The purpose of operations research is to find and substantiate such methods, to conduct activities that are in some sense the most beneficial.

The specific feature of organizational-managerial type issues is that the consequences of a particular way of solving them can significantly affect the work of the whole enterprise. Therefore, the final decision is always within the competence of the responsible person, the administrator, who is empowered with the relevant rights and is beyond the operations research.

The operations research is intended to give reasoned recommendations to the administrator before making a decision.

Thus, the operations research is a scientific area, aimed at developing methods of analysis of purposeful measures (operations) and an objective comparative assessment of possible decisions. Although operations research is an independent scientific area, it uses cybernetics to solve particular problems.

5.2. MANAGEMENT PROCESS OPTIMIZATION

The criterion of quality management. We will consider the management issue as a mathematical one. However, unlike many other mathematical issues, it has the feature of accepting not one, but many different solutions. This is due to the fact that in management issues there are usually many ways of organizing any process that lead to the achievement of the goals.

In such a way, while launching a rocket to the Moon, you can choose different trajectories for its flight. Therefore, the management issue could be set as the issue of finding at least one of the possible ways of achieving the goal. However, such a statement of a question is insufficient.

If there is a set of multiple solutions of any issue, then it is necessary to talk about the choice of the solution, which from one viewpoint or another would be the best. There are many examples of similar issues. Thus, there are many ways to make a capacity form the sheet of metal of a given size. Obtaining the maximum capacity should be the solution of this issue.

It is possible to deliver building materials to the construction site by rail, water and road transport. The choice of the most favorable type of transport in terms of delivery time, cost, preservation of material properties, etc. will be a solution of the issue. A similar state occurs in the management issues of technical systems.

In cases when the management goal can be achieved in several different ways, the additional requirements can be imposed on the management method, the degree of fulfillment of which can serve as a basis for choosing the management method [3].

In many cases, the implementation of the management process requires the expenses of certain resources, electricity, etc. So, when choosing a management method, it is necessary to talk not only about whether the goal is achieved, but also about what resources should be used to achieve it. In this case, the management issue is to choose from the variety of solutions that ensure achieving of the stated goal, one that requires the least resources.

In other cases, the basis of the choice of management method may be other requirements that imposed on the management system: cost of maintenance, reliability, deviation of the obtained state of the system from the desired, etc.

A mathematical formula that quantifies the degree of use of the requirements imposed on the management method is called *the criterion of quality management*. The method in which the criterion of quality management reaches a minimum (maximum) value will be the most appropriate or *optimal management method*.

When choosing, for example, the flight mode of the rocket, you can accept for the criterion of quality management either the expression for the amount of fuel consumed per unit of path, or the path that the rocket passes at the expense of a unit of fuel.

The minimum value in the first case and the maximum in the second case of the criterion of quality management will match up the most economical, i.e. the optimal mode of motion.

We will consider the definition of optimal management as a preliminary one. A more complete definition will be given after considering the constraints, which are imposed on the management process.

The constraints, which are imposed on the management process. The issue of finding optimal management or management in general should be considered non-existent, if any constraints are not imposed on the the system motion state.

When solving a management issue, it is impossible to ignore the circumstances that the motion of any system is always subject of various constraints.

Let us have a look at a specific example of driving for a more complete picture of the constraint. In the process of driving, the driver must take into account that the car has a limited motor power, which means that it can handle only a limited cargo with a limited speed limit. Due to its inertia, vehicle speed and driving direction can be varied only with limited acceleration. This means that it is impossible to stop or change direction immediately in case of an unforeseen situation and this, in turn, limits the driving speed.

When choosing a route, the driver is forced to reckon with a limited fuel in the tank and the need of refuelling on the road, etc.

In the general case, there are two types of constraints on the choice of management method [1].

The constraints of the first type are the laws of nature, according to which the motion of a controlled system is carried out. In the mathematical formulation of the management issue, these constraints represent algebraic, differential, or difference equations of connection.

The second type of constraints is the resources constraint, which are used in management or other quantities that, due to the physical characteristics of a system, may or may not exceed certain limits. Mathematically, the constraints of this form are usually expressed in the form of systems of algebraic equations or inequalities that connect variables, which describe the state of the system.

Statement of the optimal management issue. A management issue can be considered mathematically formulated if: the goal of management is formulated that defined by the criterion of quality management; certain constraints of the first type, which are systems of differential or difference equations, which limit the possible ways of motion of the system; the second type of constraints are defined, which are a system of algebraic equations or inequalities, taking into account the limited resources or other quantities, which are used in management [4].

A management method that satisfies all the constraints and minimizes (maximizes) the criterion of quality management is called *optimal management.*

5.3. CLASSIFICATION OF OPTIMAL MANAGEMENT ISSUES

One-step decision-making issues. The methods of implementation of the decision are not considered in one-step issues, i.e. the magnitude and nature of the management influence are not determined, but directly the value of the state variable of the system x is determined, which ensures the best achievement of the control goal [3].

A one-step decision-making issue is considered to be given if the space set of uncontrollable external factors $\bar{V}$ with stochastic distribution p ($\bar{v}$) for all $\bar{v}$ is $\bar{V}$, the space of states (solutions) $\bar{X}$ and the criterion of decision-making quality is called *the objective function* in this case. In the literature, the term "objective function" is also referred to as "gain function" or "loss function". A target function that explicitly defines management issues can be considered as an output magnitude in a technical system.

The objective function, which depends on uncontrolled external influences $\bar{v}$ and on the state of the technical system $\bar{x}$, can be written as

$$\bar{y} = \bar{y}(\bar{x}, \bar{v}) \quad (5.1)$$

The solution of one-step issue is finding such $\bar{x}$ is $\bar{X}$ that minimize the function $\bar{y}$, i.e satisfy the condition

$$\bar{x}^* = [\bar{x} \in \bar{X} | \bar{y}(\bar{x}, \bar{v})| = \text{min}. \quad (5.2)$$

If there is an issue not of minimization, but of function maximization $\bar{y}$, then it does not lead to any difficulties, because if $\bar{x}$ is $\bar{x}*$ the function $\bar{y}$ ($\bar{x}$, $\bar{v}$) reaches the maximum, then at the same time the $\bar{x}$ function – $\bar{y}$ ($\bar{x}$, $\bar{v}$) will reach the minimum.

There are a number of methods for solving the one-step decision-making issue. The application of one or another method depends on the way of determining the set of feasible solutions $\bar{x}$, the information about the uncontrolled external influence and the type of the objective function $\bar{y}$. Let us get acquainted with the characteristics of these methods.

An issue is called deterministic, if there is no uncertainty about uncontrolled external influence. In deterministic issues, the space of uncontrolled external influence $\bar{V}$ consists of one element only $\bar{V}$, whose probability is equal to one. In this case, the objective function will depend on the state of the technical system

$$y = y(\bar{x}) = y(x_1, \dots, x_n). \quad (5.3)$$

A one-step deterministic issue is called *a classical optimization issue* [3], if there are constraints in it

$$f_i(x_1, \dots, x_n) = 0, \; i = 1, \dots, m, \; m < n. \quad (5.4)$$

In this issue, it is necessary to find the values of x_1, ..., x_n that satisfy the equation (5.4) and minimize the function y (x_1, ..., x_n).

One-step issues are called *mathematical programming.* These methods make it possible to find the values of variables x_1, ..., x_n that satisfy the constraints

$$f_i(x_1, \dots, x_n) \begin{cases} \le b_i \\ = b_i, i = 1, \dots, m \\ \ge b_i, \end{cases} \quad (5.5)$$

and transform the objective function y (x_1, ..., x_n) to a minimum.

Variables are often imposed by the auxiliary conditions of the inalienability of their values. It should be noted that mathematical programming is not an analytical, but an algorithmic form of solving issues, i.e. it does not provide a formula that determines the final result, but indicates only a computational procedure that leads to the solution of the issue.

Therefore, mathematical programming methods become effective, mainly when using computer technology.

The simplest case of a mathematical programming issue is *a linear programming issue.*

It corresponds to the case when the left-hand sides of constraints (5.5) and the objective function (5.3) are linear functions of x_1, ..., x_n. In the linear programming issue, it is necessary to find the inseparable values of variables x_1, ..., x_n that minimize the objective function

$$y(x_1, \dots, x_n) = \sum_{j=1}^{n} c_j x_j \quad (5.6)$$

and satisfy the constraints system

$$\sum_{j=1}^{n} a_{ij}\, x_j \le b_i, i = 1, \dots, m. \quad (5.7)$$

Any mathematical programming issue that is different from the formulated one is called a *nonlinear programming issue.*

In nonlinear programming issues, either objective function (5.3) or left parts of the constraints (5.5) or both represent nonlinear functions from x_1, ..., x_n. However, the nonlinear programming issue is also one in which the objective function and constraints have the form (5.6) and (5.7), but, for example, the integrality of variables are proposed. This latter issue is called *an integer programming problem.*

A one-step decision-making problem is called *stochastic* if the space of uncontrolled external influences $\overline{V}$ consists of more than one element, so that the actual value of uncontrolled influences is not known $\overline{V}$, but stochastic distribution p($\overline{v}$) on the space is known $\overline{V}$.

Stochastic issues that require finding values of variables that satisfy constraints (5.5) and minimize the objective function (5.3) are called *stochastic programming problems*.

However, in many cases, by another definition of the objective function, stochastic programming problems can be reduced to linear programming issues.

Since uncontrolled external influence $\overline{V}$ is a random magnitude with stochastic distribution p ($\overline{v}$) on the space $\overline{V}$, then the value $\overline{y}$ ($\overline{x}$, $\overline{v}$) for given $\overline{x}$ = (x_1, ..., x_n) will also be a random magnitude with the same stochastic distribution p($\overline{v}$) on the space $\overline{V}$. Therefore, in this case, it is advisable to take the objective function as the mathematical expectation of the function $\overline{y}$ ($\overline{x}$, $\overline{v}$) on the space $\overline{V}$.

Thus, for random processes, the objective function has the form

$$y_1(x) = \sum p(V)\, y(x, v), v \in V. \quad (5.8)$$

Since y_1($\overline{x}$) is a determinate function of $\overline{x}$, so the problem of finding variables x_1, ..., x_n satisfying constraints (5.5) and converting the objective function (5.8) to a minimum, can be solved by linear or nonlinear programming methods.

An important case of a one-step stochastic decision-making issue is the case when the magnitudes x_1, ..., x_n can take only a finite set of values.

Methods for solving such problems are dealt with in the mathematics section, called *Stochastic Solutions Theory*.

Recently, much attention has been given to issues in which the decision is made not by one person, but by several (for example, by two people), and, moreover, the interests of these people are opposite.

An example can be the pursuit problem, in which the distance between a pursuer and who is persecuted, depends on the decisions and actions of both. At the same time, pursuers are interested in reducing this distance as much as possible, and those who are persecuted, are interested in making it as large as possible.

Such problems are called *conflicting situations*, and methods of solving them are considered in *games theory*. Decision makers are called players.

Since, in a conflicting situation, decisions are made by each player regardless of the other player's decisions, the space of decisions must be regarded as a direct product of the two sets $\overline{X}$ x $\overline{Z}$ in the mathematical description of the conflicting situation, where $\overline{X} = \{x_1, ..., x_n\}$ is the decisions space of first player; $\overline{Z} = \{z_1, ..., z_m\}$ is the decisions space of second player.

The elements of decisions space $\overline{X}$ x $\overline{Z}$ will be pairs of the form (x, z), $x \in \overline{X}$, $z \in$, i.e. will be determined by the decisions made by both the first and second players.

Let us assume for simplicity that there is no uncertainty in the state of uncontrolled external influence. Then, the objective function

$$y = y(\bar{x}, \bar{z}) \quad (5.9)$$

depends only on the elements of the space $\overline{X}$, $\overline{Z}$.

The opposite of the interests of the players is that first player who makes the choice of the set $\overline{X}$, tries to minimize the objective function by this choice, while second player who makes the choice of the set $\overline{Z}$, tries to maximize it. Thus, the essence of a conflicting situation is that each player must make the best decision from their point of view, remembering that their opponent will do the same.

Dynamical issues of management optimization. Among management issues, tasks in which the technological system is in a state of continuous motion and changes under the influence of various external and internal factors occupy a significant place. The management issues of such technical systems belong to the class of *dynamical management issues*.

A technological system is called managed if, among the various factors acting on it, there are those by means of which the nature of its motion can be changed. As stated earlier, these purposeful actions are called management and denote $\overline{u}$ (t).

The nature of the motion of a technical system is determined by the system of differential equations

$$\dot{x_\iota} = g_i(\bar{x}, \bar{u}, \bar{v}), \ \ \bar{x_\iota}(0) = c_i \ \ \ i = 1, \dots, n, \quad (5.10)$$

where c_i, i = 1, ..., n characterizes the initial state of the technological system.

Sometimes this system is abbreviated in vector form as a single differential equation

$$\bar{\dot{x_\iota}} = \bar{g}(\bar{x}, \bar{u}, \bar{v}), \ \ \bar{x}(0) = \bar{c}. \quad (5.11)$$

Management $\bar{u}$ (t) is included in equation (5.11), since this equation determines not only the specific motion of a technical system, but only its technical capabilities, which can be realized by using one or another management from the space of admissible management $\bar{U}$.

It is possible to estimate, to what extent, in one management method or another, the set goals are being achieved, by entering the objective function (5.3), which in this case can be conveniently written in the form

$$y = y_v[\bar{x}(t), \bar{u}(t)]. \quad (5.12)$$

So, if u(t) is an instantaneous fuel consumption and a x{t) is an instantaneous car speed, then in terms of fuel consumption, management quality at any time can be characterized by the magnitude

$$y(t) = u(t)/x(t). \quad (5.13)$$

where y(t) is an instantaneous fuel consumption per unit of way.

It should be noted that function y(t) will depend on uncontrolled external influences $\bar{V}$, i.e. a set of external factors that determine the conditions of car motion.

The objective function (5.13) is rarely used because it only estimates instantaneous values of the management process, whereas in most cases it is necessary to evaluate processes in technical systems during the entire management time from 0 to t_1.

In many cases, the objective function can be selected in such a way that the process evaluation in the technological system can be accomplished by integrating the objective function for all management time, i.e. functionally accepted as a management quality criterion

$$I(\bar{u}) = \int_0^{t_1} y_v[\bar{x}(t), \bar{u}(t)]dt. \quad (5.14)$$

Thus, if the objective function has a physical nature of expenses, then formula (5.14) determines total expenses for entire management process.

Sometimes management goal is the desired progress of the process $\bar{Z}$ (t). In this case, the objective function can be taken as the square or the absolute value of the deviation of the actual process $\bar{X}$ (t) from the desired:

$$y(t) = [\bar{x}(t) - \bar{z}(t)]^2; \ \ y(t) = |\bar{x}(t) - \bar{z}(t)|. \quad (5.15)$$

In these cases, the quality management criterion (5.15) will determine the total quadratic or absolute error.

In dynamic management problems, along with constraints $\overline{U}$ = {u_1, ..., u_R}, which define the space of admissible management $\bar{u}$, we have to deal with integral constraints of form

$$\int_0^{t_1} Q_v[\bar{x}(t), \bar{u}(t)]dt \le \mathrm{I_m} = \text{const.} \qquad (5.16)$$

Quite often we have to deal with the constraints boundaries of change of the instantaneous value of some parameter a ($\bar{x}$, $\bar{u}$) in the management process. Denote by a_0 such a value of parameter a, excess of which is undesirable. If subintegral function Q_v ($\bar{x}$, $\bar{u}$), which in this case is called <u>penalty function,</u> is determined from the formula

$$Q_v(\bar{x}, \bar{u}) = \begin{cases} 0, & a \le a_0\ ; \\ [a(\bar{x}, \bar{u})]^2, & a > a_0\ , \end{cases} \qquad (5.17)$$

then integral constraint (5.16) will determine the requirement that the instantaneous value of parameter a may exceed a_0 only briefly and by a small magnitude. This condition will be fulfilled the tougher the smaller I_m. Thus, for I_m = 0, constraints (5.16) will generally not exceed a over a_0.

Constraints of the form (5.16) also arise when it is necessary to deal with limited resources (energy, fuel, etc.).

Based on the above connections, you can give the following definition of optimal management in dynamical systems.

The optimal management is called $\bar{u}$ *(t) management, which is selected from the space of admissible management $\overline{U}$, such that for the system described by differential equation (5.11), it minimizes the quality criterion (5.14) with given constraints on the resources (5.16) used in the management process.

Dynamical management problems, as well as one-step problems, can be <u>*deterministic*</u> if the state space of uncontrolled influences $\overline{V}$ consists of only one element v_0 and <u>*stochastic*,</u> if the space of states of uncontrolled influences $\overline{V}$ consists of more than one element and a prior stochastic distribution p ($\bar{v}$) on the space is given $\overline{V}$.

<u>*Adaptive management*</u> issues have great importance among stochastic tasks, which are used in cases where a prior data on the state of uncontrolled influences are not sufficient for effective management, or when there is no sufficiently accurate description of the technological system itself.

Adaptive management aims to clarify the environmental status data or properties of the technological system directly in the management process by testing of different management methods and finding which one is most effective in the particular conditions.

Management of the final state. In some cases, the motion nature of the technical system in the management process is of no significant interest, and the only important state is that the technical system will take at the moment of ending of the management process.

Examples of such tasks can be delivery of load to a specified time in a given destination, achievement by the technological system to a specified period of a given productivity, etc.

Such tasks are called issues of *finite state management.*

Let us denote by x (t_1) state of the technological system at the finite time instant t_1. Then the objective function looks like

$$y = y_v[x(t_1)]. \quad (5.18)$$

Since x (t_1) depends on the nature of the applied management u(t), the value of y will also depend on the applied management. Therefore, the problem of choosing the optimal management can be formulated for this case as follows: from the space of admissible management U, select such management u *(t), which for the technological system described by differential equations (5.11) minimizes the objective function (5.18) under constraints (5.16) to resources used in the management process.

5.4. OPTIMAL MANAGEMENT AS A VARIATIONAL ISSUE

Mathematical formulation of the optimal management issue. A characteristic tendency in the formulation of modern technological systems is the desire to obtain systems which from certain positions can be considered the best.

When managing technological systems that carry out technological processes, these aspirations are expressed in order to obtain the maximum amount of high quality products with limited use of resources (raw materials, energy, etc.).

When managing transport technological systems seek to minimize time of transportation, amount of consumed fuel, etc. In stabilization systems, it is of interest to achieve maximum accuracy in the presence of various constraints imposed on the coordinates of the technical system.

In all these examples, the management issues are reduced to finding the best of certain process positions from the set of possible processes, i.e. they belong to the class of dynamical optimal management issues.

As shown earlier, the mathematical formulation of dynamical optimal management issues is as follows. There is a technological system as an object of management, state of which is characterized by the instantaneous variable x = (x_1, ..., x_n).

The nature of processes in a technological system can be modified using one or another management u from the space of admissible management U. In the general case, management u is U may also be an instantaneous value u = (u_I, ..., u_R).

The motion nature of the technical system is described by the system of differential equations

$$\dot{x} = f(x, u), x(0) = c. \quad (5.19)$$

Management is accepted as a quality criterion

$$I_0(u) = \int_0^{t_1} f_0\,[x(t), u(t)]dt, \quad (5.20)$$

which is physically expensed. Here t_1 is transmission time of the management process; f_0 [x(t), u(t)] = y_0 (t) are instantaneous expenses at t moment with system state x(t) and management u(t).

Auxiliary constraints may be constraints imposed on the number of resources or limits of change of some parameters determined by the mathematical formula

$$\int_0^t Q\,[x(t), u(t)]dt = I_m, \qquad (5.21)$$

As previously found, the optimal management is called management u from the set of admissible management U, whereby for a system described by differential equation (5.19), with the given constraints on existing resources (5.21), the management quality criterion (5.20) takes the minimum (maximum) value.

Formulated in such a manner, the problem of optimal management belongs to the class of variational issues, solution of which is dealt with by mathematics section, called *variational calculus.* The value of I(u) determined by formula (5.20) is called *a functional.* Unlike a function, such as f(x), whose numerical values are given on the set of values of the argument x, numerical values of the functional i_0(u) are given on the set of all management u(t).

Problems requiring minimization of the functional (5.20) are always replaced by minimization of new functional in the presence of the integral constraint (5.21)

$$I(u) = \int_0^{t_1} f_0\,(x, u)dt + \lambda \int_0^{t_1} Q(x, u)dt, \qquad (5.22)$$

which is subordinated only to the differential formula (5.19). The parameter Q in the functional (5.22), called the Lagrange factor, plays a role of "price" of limited resources in optimal management issues. Its value lies in the boundary conditions of the variational issue.

The application of the variational calculus methods to the problems of finding the optimal management has not become widespread due to a number of difficulties that arise. Therefore, we will not dwell on the methods of solving the variational issue, and send those who are interested in this question, to [5].

Here are some of the points that are important for further discussion.

The most important concept of variational calculus is a concept of *function variation,* which in the study of functionals, plays the same role as the differential in the study of functions.

Problems of solving a variational issue. In finding the most optimal management of variational methods, one has to deal with difficulties that are of principle nature:

1. Variational methods make it possible to find only the relative maxima of functional I(u), whereas the interest is to find the absolute maximum or minimum.
2. Euler's equations for many technological systems are nonlinear, which often makes it impossible to solve a variational issue explicitly.
3. Optimal management of technological systems often has discontinuities. The Lagrange factors method is not able to determine number and location of the

discontinuities points, and in these cases it does not make it possible to find the optimal management.

4. Constraints in the form of inequalities are often imposed on the values of control effects and phase coordinates of technical systems, which makes it impossible to find optimal management by variational methods.

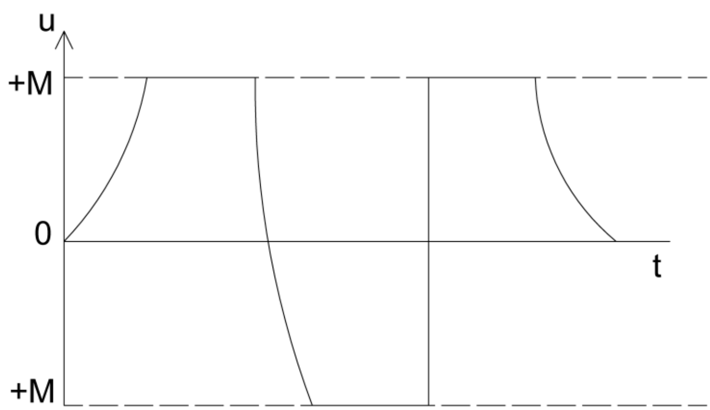
Since the latter circumstance was crucial for the development of new ideas in the field of optimal management, let us dwell on it in more detail.

Typical limitations imposed on management signals are constraints such as

$$|u_i(t)| \leq M_i. \quad (5.23)$$

which mean the need to limit by the magnitude of the management signals. Thus, the constraints may be: voltage supplied to the motor armature, limit angle of rotation of car's steering wheel, limit temperature in the combustion chamber of the internal combustion engine, etc.

At the same time, obtaining optimal processes requires, as a rule, maintaining the management signals at the limit values, which corresponds to the fastest and most efficient passing of processes in the technological system. Typical for these cases is a nature of management change u(t) in the optimal process, shown in picture 5.1.



Picture 5.1. The distinctive appearance of the optimal management signal by the technological system

However, management limit values u(t) lie within boundaries of the admissible management U and are not, of course, internal points of this field, for which only variational methods are veracious.

However, constraints of the form (5.23) can be eliminated by entering new variables v_i, which are related to the variables u_i, by formula $u_i = M_I \sin v_i$. The value $|u_i| = M_i$ will correspond to the variables $v_i = \pm n/2$, which are the inner points of the field of new admissible management. However, such replacement of variables, as a rule, leads to considerable complication of the obtained equations.

These difficulties have contributed to the intensive study of the management optimality problem of technical systems. Pontryagin L.S. and his students, Boltyansky V.G., Gamkrelidze R.V., and Mishchenko E.F. created theory of optimal management [6], which is based on the principle of maximum formulated by Pontryagin L.S. as a necessary condition of extremum of functional under various constraints and conditions.

This principle made it possible to build a theory of optimal management on a strict mathematical basis and opened up great opportunities for its practical application in the management of technological systems.

QUESTIONS FOR SELF-CONTROL:

1. What is the "management process"?
2. What are the main "management issues"?
3. What is the main "management goal"? Describe the process of management implementation.
4. Provide basic stages in the management process.
5. What is "optimal management"?
6. How is the "decision-making" process going?
7. Discover the essence of the "one-step decision-making issue".
8. What issues are referred to "dynamical management issues"?
9. What is the "classical optimization issue"?
10. How can the "optimal management issue" be presented?
11. List "issues of solving a variational problem".
12. What "quality management criteria" do you know?
13. What is the "linear programming issue"?
14. Give examples of "nonlinear programming issues".
15. On what basis is the "stochastic programming issue" formed?
16. What is "games theory"?
17. What is the purpose of "adaptive management"?

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Chapter 6. Basic provisions of the constructional design, process and estimation of technological systems

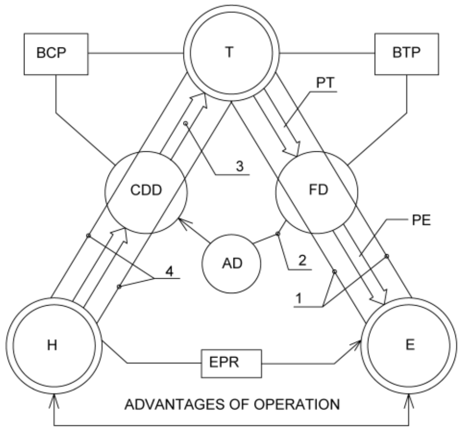
Contents of Chapter 6

Keywords: constructional design, technological system, characteristics, designer, developer, requirements, regularities, principles, processes, blocks, standardization, scheme, development model, cyclic-modular approach.

6.1. CHARACTERISTICS OF ACTIVITY OF THE DESIGNER

Any object of technique, which is a technological system, is created artificially from the materials of nature on the basis of inherent processes and regularities in order to realize certain functions of work and human livelihood. Scientific and technical achievements must be taken into account [1].

The formation and development of an object of technique can be represented by a scheme (picture 6.1).



Picture 6.1. Scheme of the mechanism of technological system development: H – human, T – technique; E – environment; FD, AD, CDD are devices for filtering, analysis and constructional design; EPR is an environmental parameters regulator; BTP and BCP are banks of accumulated decisions on technological and constructional processes; PT and PE are parameters of technique and environment, respectively; 1 is a line of action of the environment on the object of technique with an insignificant mismatch of PT and PE; 2 are environment signals through FD in CCD with the help of AD with a significant mismatch of PT and PE; 3 is a line of constant action H on T; 4 are action signals H on T

Human (H) uses signals of environment *2* and accumulated to development beginning and ready technical decisions BCP, develops the concept of constructional design and implements it with the help of constructional design device CDD, and in some cases through environmental parameters regulator EPR, influences the environment parameters (E), changing them in the right direction (for example, regulates operating mode).

An integral part of constructional design is the constructive and inventive process of creating products in documents (mainly in drafts) on the basis of constructional, technological, operational calculations [2].

6.2. BASIC LAWS OF TECHNOLOGICAL SYSTEMS DECISIONS IN THEIR CONSTRUCTIONAL DESIGN

The main task of the designer is to create machines that most fully meet the needs of customers and have high technical, economic and operational indicators.

According to the theory of technological systems, they develop according to certain laws:

1. increasing the diversity of the developing technological system;
2. limiting the diversity of technological system solutions.

The first law states: "The diversity of technical system in an absence of constraints on its development increases in proportion to the parameters of the intensity of updating Po, integration of P_I and differentiation of $P_Д$ solutions of the system". If at the initial stage the number of decisions is $N_0 \geq 1$, then the total number of performances at the following stages is:

$$N=N_0P_OP_I\,P_Д\ - X_0K_{PB}\,,$$

where K_{PB} is growth coefficient of the number of solutions.

The intensity of updating P_O expresses the amount (number) of changeable components of solutions. Differentiation of $P_Д$ is characteristic for formation cases of new parametric series of products, creation of modifications on the basis of a single basic model. Integration of the P_I of technique object performances into industry is accomplished by unification of components, constructive elements and materials, typing of assemblies, ordering of various types of technique on the basis of combining their properties in a limited number of performances.

According to the second law, "the diversity of solutions of the technical system at any stage of its development is limited". The regulator of a diversity of decisions is FD, by means of which some limited number of necessary decisions are selected from the maximum possible (picture 6.1).

Many technical contradictions arise in the development process of technological system, which require economic, social and environmental constraints for their solving. In view of these constraints, at the initial stage of constructing, they abandon some of the performances, and the remaining ones are accepted by the designer for further functional and economic analysis and selection of options that best meet the requirements of the spheres of production [3].

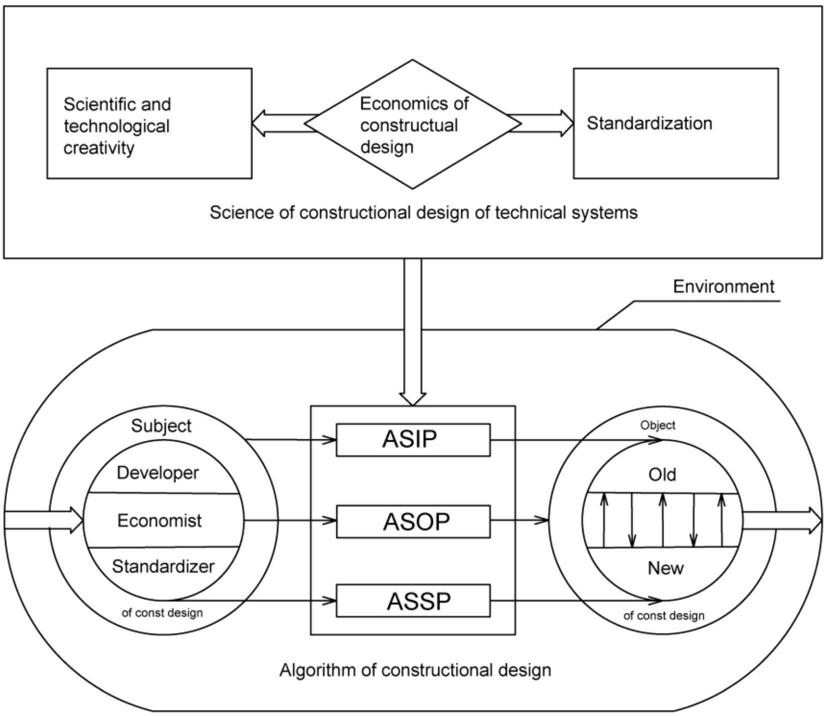
Both laws are based on the following basic principles:

a) unity of variability and repeatability (subordinate principles of expedient continuity, obligatory consideration of the achievements of science and technique, adaptability, compatibility and interchangeability of technical solutions);
b) completeness of components of the system's solutions (their composition should provide the whole complex of basic functions and functions of life support at all stages of life cycle);
c) consistency of components of the solutions (primarily energy, information and functional compatibility);
d) irregularity development of components of technological system solutions (a new system is created and develops inside of "old" system, and the more complex the solution, the more irregularity develops its components);
e) advantages of solutions, i.e. dominance of some options on the grounds of technical, economic and social nature;
f) analogies in the development of systems (such as gearboxes, transmissions, fasteners and other joints that are developed in different industries, similar in form and content, and hence in commonality of development).

6.3. PRINCIPLES AND REGULARITIES OF TECHNOLOGICAL SYSTEMS DEVELOPMENT IN CREATING ALGORITHMS FOR SOLVING INVENTIVE PROBLEMS

Laws and principles for the development of technological systems (technique and processes) determine the interrelation between technical creativity, standardization and economics of constructing [4, 5, 6] (picture 6.2).

The principles and regularities of development of technological systems are laid down in the form of operators or constraints in the structure of algorithms for solving inventive problems (ASIP), algorithm for solving optimal problems (ASOP) and algorithm for solving standardization problems (ASSP). The ASIP unit forms an innovative part of the project, while the ASSP unit provides for the application in new projects of previously developed and repeatedly proven solutions that form part of the scientific and technical potential accumulated in the industry. Typical, unified and standardized constructing elements (fasteners, clearances and landings, standard connections, etc.) are widely used in constructing processes.



Picture 6.2. Scheme of interrelation of scientific and technical creativity and economics of constructional design and standardization

ASOP unit provides processes for selecting the best new ones and using known solutions.

An experienced designer must organically combine traits of an inventor and a skilled technician with the use of standard elements and fully possess the basics of constructional design economics. The combination of these traits gives a developer of new technique and technology an opportunity to eliminate contradictions between technical creativity – a desire for "solid originality" and standardization – a desire for "solid monotony". To do this, a developer must be well aware of:

1. main features of industrial production technology (e.g. processing plant technology), from which applications and technical specifications are directed for the constructional design of a new machine;
2. technical level of the whole machine complex, in which a new machine must operate;
3. technology of plant, which is taken to make a new machine, history of the constructional design of the designed equipment, advantages and disadvantages of the replaced machine, possibilities of using the best solutions for individual units, nodes and details;
4. prospective developments of other organizations.

A designer (developer) should systematically and in-depth study domestic and foreign information, patents and standard documents. Quality and competitiveness of the equipment, as well as timing of development, depend on designer's correct estimates and choice of initial data for the constructional design. Therefore, designer's critical approach to technical task of product designing, its working conditions, requirements and functional parameters is very important.

6.4. CONSTRUCTIONAL DESIGN PROCESS OF TECHNOLOGICAL SYSTEMS

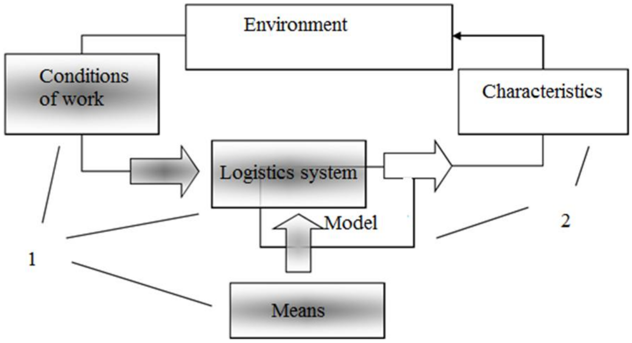
Traditionally, constructional design is regarded as a specific process and as a sequential subsequent representation of a technological system (object) with the help of several types of models discussed earlier. The initial data is transformed into a functional scheme, a functional scheme into a circuit scheme, a circuit scheme into a mathematical model.

The mathematical model is transformed into a structural model, and finally into a real object. Each model is used to solve local constructional design issues with mathematical dependencies, which are written in the form perceived by the computer's operating system. They use programming languages or special programs such as "Mathematics", "Matlab", "Simulink" and others.

The use of mathematical models and computer tools to solve constructional design issues gives the opportunity to see the work of the object long before its full readiness, as well as to form its properties [7].

Here is one of the well-known definitions of a constructional design problem: to develop, under some constraints due to the method of solution, a system or process that ensures the optimal execution of the given task. If details are neglected, constructional design problem is to develop a new system based on known data (Picture 6.3).

Done studies [8] have identified interrelation between the process of operation, formation and properties of an object, which is reflected in regularities, theoretical provisions of the cyclic-modular approach, a new conceptual model of an object and architecture of environment of the constructional design.



Picture 6.3. Scheme of the constructional design issue of the technological system:
1 – known data; 2 – specific data

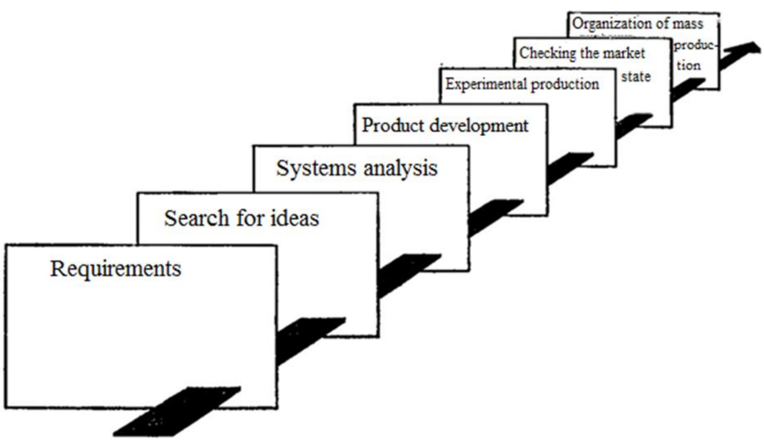
6.5. AN ALGORITHM FOR CONSTRUCTIONAL DESIGN OF TECHNOLOGICAL SYSTEM BASED ON ITS DEVELOPMENT MODEL

The basic stages of creating a new technological system, like any other system, are shown in picture 6.4.

Using the generally accepted basic stages of creating a new technological system (picture 6.4), the constructional design process can be represented as a tracking algorithm of object development in which its properties are formed (picture 6.5.) [9, 10].

Actions of formation of object layers and order of their execution form this algorithm, which is defined by direction of development – from principle to construction.

Object-forming actions are carried out by a developer. The content of the performing actions and order of their execution is defined by the algorithm. The object generation is carried out in layers. Actions and order of their implementation within the layer are also defined by the algorithm. This achieves a complete and correct result, i.e. a ready-made object layer. Layer readiness is verified by comparing state of an object with layer readiness criteria.

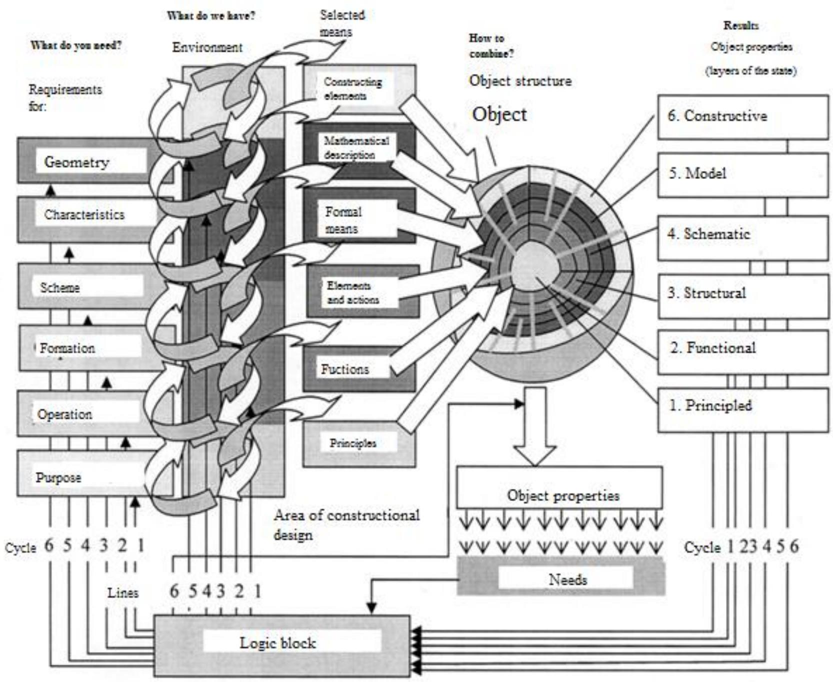


Picture 6.4. Stages of creation of new technological system

The readiness initiates next phase of the object's development, i.e. formation of next layer. In this case, an invariant of the object and all obtained properties form the basis for next layer. A part of the constructional design environment corresponding to the created set of properties is activated with the beginning of the formation of each layer. For example, a library of graphic symbols is activated during transition from structural layer to schematic layer, which reflects the possible formal means for executing the process. The tracking algorithm of the development process also supports creation and development of modules within an object. The algorithm has a multi-cycle architecture [9, 10].

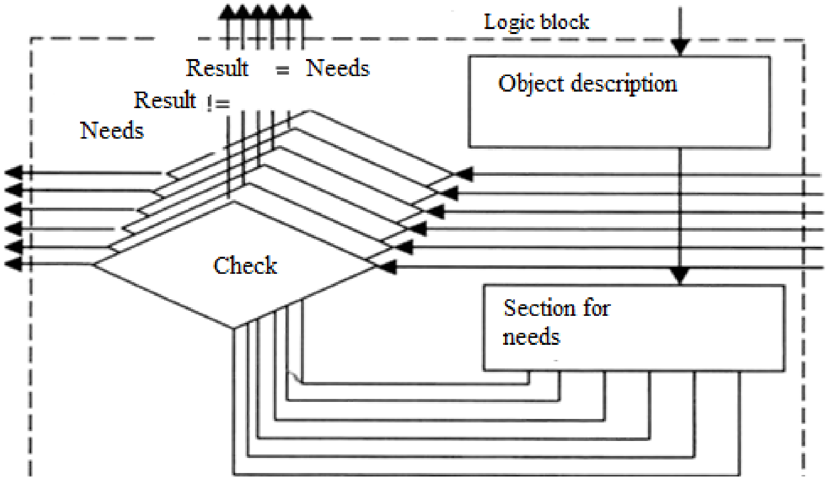
A detailed description of the logical section reveals the shift sequence to switch to the next cycle of the object generation process (picture 6.6).

A separate model layer that reflects a specific state of the object is operated by each cycle. Getting started with an algorithm is triggered by requirements for an object with a given set of properties. Then the object description and a set of requirements for it are generated.



Picture 6.5. An algorithm of constructional designing of the technological system (object) based on its development model.

Then the initial cycle is started. This cycle corresponds to the process of generating the core – the choice of the object operation principle. The chosen principle initiates switching to the next cycle – the description of the ***object functions***. A layer is considered formed if a functional scheme of the object is built.



Picture 6.6. Organization of logical block

Next, we can switch to the next cycle – ***structure process generation*** to implement functions. A layer is considered ready, if the structure of the object's functioning process is described in detail, its structural and logical adequacy requirements are met. In next cycle, a circuit scheme is generated on the basis of structure. Performing the following cycle allows you to generate a mathematical model of the object, which is based on the structure of the operation process and the circuit scheme. Then, they define the indicators of the elements parameters, provide the desired operating features of the object. This is done by processes modeling in the object. In the next cycle, the construction of the object is generated according to the algorithm. Constructional design has an object with a given set of properties. The created object provides the satisfaction of the need that caused starting of the process of its constructional design [9, 10].

The application of the specified sequence of cycles and the method of transformation during transitions between layers of the model allows to keep the structure of the object functioning process unchanged at all stages of constructional design and to reduce the number of iterations. By using the proposed approach, you can get the construction of the object with a set of required properties and operating features in a short time. ***The object model***, the algorithm of the cyclic-modular approach have the following features [9, 10]:

1. application of the functioning process of interconnection regularities, formation and properties of the object;
2. ensuring the structural and logical adequacy of the model at the stage of its construction;
3. ensuring of the portability between stages and modular organization of model layers.

Thus, the developed algorithm for constructional design of new technological systems or any complex objects (robots, manipulators, etc. of complex systems) accompanies the development of the object.

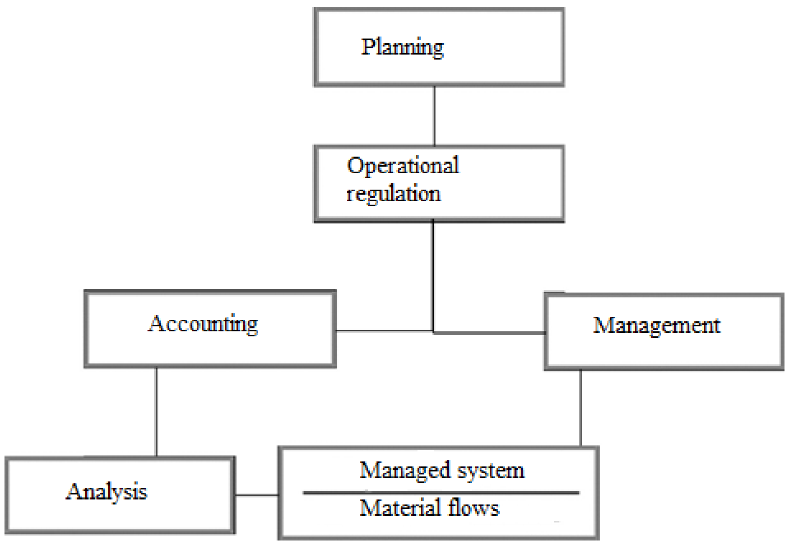
The conceptual model, which reflects the multilayered formation, is represented by a superposition of two parts: unambiguous and developing. Its application makes it possible to formalize the constructional design process to a greater extent. The constructional design process is regarded as the generation of the properties of the object and changes to the object as it develops.

The method of object generation from the first to the next layers ensures that the structure of the functioning process in all subsequent layers of the model is observed.

6.6. METHODS FOR ECONOMIC EFFECTIVENESS ESTIMATION OF TECHNOLOGICAL SYSTEMS USING NEW EQUIPMENT (MACHINES AND MECHANISMS)

The main indicators of economic efficiency of new equipment are the following [11]:

- integrated indicator, the so-called profitability index, which reflects the total economic effect for the whole operational life;



Picture 6.7. Logistic system of flow management synthesis of technological system

- coefficient of technical availability (CTA), coefficient of standard use of C_u;
- turnover coefficient C_{to}, equipment pay-back period coefficient C_{pb} ;
- operating costs coefficient C_o, prime cost and equipment cost.

The profitability index (or simply profitability) is defined as:

$$R_\varepsilon = \frac{Q}{B_\varepsilon}, \quad (6.1)$$

where Q is the actual output, i.e. the actual combined effect of the equipment operation for the entire period of work; B_ε is a sum of costs for the entire period of equipment operation, UAH, (covers energy cost, depreciation costs, preparatory work, installation and dismantling, materials, operation of equipment, pipes, tools, basic wages, services of auxiliary departments, etc., overhead costs, costs due to accidents).

Condition of equipment efficiency $R_\varepsilon > 1$.

Combined economic effect for the whole operating term of the equipment:

$$Q_\varepsilon = Q - P = Q\left(1 - \frac{1}{R_\varepsilon}\right). \quad (6.2)$$

The formula shows that Q_ε is proportional to the actual output Q and depends on the cost of equipment and operating costs. Magnitude Q_ε increases with endurance gaining of the machine and, accordingly, its operational life.

The coefficient of technical use is defined by the formula:

$$T_в = \sum_{i=1}^{N} \varepsilon_i \Big/ N \cdot T_{експ.}, \quad (6.3)$$

where $\sum_{i=1}^{N} \varepsilon_i$ is the total sojourn time of the object in operational condition; N is the number of objects; $T_{експ}$ is a duration of operation, consisting of periods of operation, maintenance and downtime before the onset of the limit state.

The coefficient of standard use is calculated by the formula:

$$K_{нв} = T_0 / T_н, \quad (6.4)$$

where T_0 is the total time the equipment is in operation (including downtime for organizational reasons); $T_н$ is the standard operational life, i.e. the calendar life of the equipment operating, or its depreciation period, hours.

The turnover coefficient $K_{об}$ is the magnitude, which is inverse to the coefficient of the standard use $K_{нв}$ and is defined from the expression

$$K_{об} = 1/K_{нв} = Z/A > 1, \quad (6.5)$$

where Z = A + B + B is the total number (set) of units of enterprise equipment; *A*, *B* and *C*are the number of units of equipment employed directly in the technological cycle, in the preparatory stage (installation – transportation) and preventive repair.

The magnitude $K_{об}$ is regulatory and is usually $K_{об}$ = 1,5 ... 2,1.

The equipment pay-back period $T_{ок}$ is defined as the operating period, during which the actual output Q is equal to the price of the equipment $Ц_0$ or the capital costs for creating it, i.e. $Q = Ц_0$. then the pay-back period is

$$T_{ок} = \frac{Ц_0}{K_{нв}\left(Q_r - B_p - \frac{Ц_0}{T_0}\right)}, \quad (6.6)$$

where Q_r is the annual output or annual economic effect, monetary unit / year; B_p is the amount of annual operating costs, currency units.

Assuming that operating costs are proportional to durability, then the combined economic effect is

$$Q_\varepsilon = Q - T_0\left(B_1 + \frac{B_2}{K_{нв}}\right), \quad (6.7)$$

where B_1 and B_2 are operating costs, proportional to operational life and longevity, currency units / year.

Operating cost coefficient is defined as the ratio of costs for the entire calendar period of the equipment operating B_ε to its cost $Ц_0$:

$$K_{ев} = \frac{B_\varepsilon}{Ц_0} = 1 + \left(B_1 + \frac{B_2}{K_{ти}}\right) \cdot \frac{T_0}{Ц_0}. \quad (6.8)$$

With the increasing of the equipment operating, T_0 the cost percent of equipment in the total cost is decreasing.

Prime cost, planned and limit price of machines and equipment. At the pre-constructional design and constructional design stages, the prime cost of new equipment is defined, based on the change of data on the basic machine or its elements by groups, taking into account the costs of purchased products and constructional design costs. The price of the constructional designed equipment is also defined based on the data of the basic machine. The planned wholesale price $Ц_n$ takes into account the standard component and the additional profit, and it should be within the limits

$$Ц_{нп} < Ц_n < Ц_{вп}, \quad (6.9)$$

where $Ц_н$ and $Ц_{вп}$ are the lower and upper price limits.

The lower limit is found for the second year of production through the planned prime cost of new products $Ц_{п}$ and the standard of profitability P:

$$Ц_{нп} = C_{п}\left(\frac{100+P}{100}\right). \quad (6.10)$$

The upper price limit is defined as

$$Ц_{вп} = Ц_{Б} \cdot \frac{П_{П}}{П_{Б}} \cdot \frac{\frac{1}{t_{Б}} + K_{не}}{\frac{1}{t_{П}} + K_{не}} + \frac{B_{Б} + B_{П}}{\frac{1}{t_{П}} + K_{не}} \pm \Delta K; \quad (6.11)$$

where $П_{П}, П_{B}$ are production programs for constructional design and basic machines; t is operating term; $K_{не}$ is standard coefficient of capital investments efficiency; B are current costs of the consumer when using machines; ΔK are changes of the consumer's capital costs in connection with the replacement of the basic machine for the constructional designed one.

According to the relevant standards, applications and requirements baseline for the creation of new machines and equipment must include requirements for the limit price of the machine $Ц_{л}$.

If the price of new equipment is so $Ц_{0} > Ц_{л}$, its use will be economically inappropriate.

The limit price $Ц_{л}$ is defined on the basis of the choice of an existing analogue and an estimation of the efficiency of using a new type of equipment compared to its analogue. In practice, the limit price is sometimes taken to be 80% of the price at which the economic effect of using a constructional designed machine becomes 0.

The efficiency of new equipment can be estimated by comparing its constructional design prime cost and the actual data costs of the basic equipment by the same indicators. The annual economic effect is usually defined by the formula

$$E = \left(ПB_{1} - ПB_{2}\right) \cdot Q_{2} = \left[\left(C_{1пит} - C_{2пит}\right) - E_{н}\left(K_{2пит} - K_{1пит}\right) \cdot Q_{2}\right]; \quad (6.12)$$

where costs according to basic and constructional designed equipment are given; there is a production output with new equipment for the year; $E_{н} = 0{,}12...0{,}15$ an efficiency of new equipment standard coefficient; $C_{1пит}, C_{2пит}, K_{1пит}, K_{2пит}$ specific indicators of prime cost and capital investments in production funds per unit of production of basic and constructional designed equipment, respectively.

Often, the expected economic effect is calculated taking into account only the cost items that change significantly when using new equipment.

The technical level of excellence (quality) of undeveloped equipment can be estimated comprehensively with the help of integrated indicator by the formula:

$$I_{ін} = \frac{E_c}{\left[K_c \cdot \varphi(t) + B_P\right]}; \quad (6.13)$$

where E_c, K_c are values of actual combined effect (can be in UAH or production units measure) and capital summarized investments (UAH), B_P are annual operating costs; (UAH); $\varphi(t)$ is coefficient of taking into account the equipment operating term and the distribution of capital costs by time (for $t=1$ the year it equals 1; for $t=5$ years $\varphi(t)=0{,}262$).

When it is impossible to highlight the main indicator (for example, annual productivity), the weight-average arithmetical value or

$$I = \sum_{i=1}^{n} в_i \sigma_i, \quad (6.14)$$

geometric value is used

$$I = \sum_{i=1}^{n} в_i \sigma_i, \quad (6.15)$$

where $В_i$ is the weight coefficient of the i indicator, which is defined by the method of expert assessments; σ_i is a relative single quality indicator; n is a number of analyzed single indicators.

The results of the calculation of the integrated indicator values I are recorded in the map of technical level and quality and are a guide for defining the limit price of new equipment and calculating the economic effect.

QUESTIONS FOR SELF-CONTROL:

1. Give the main characteristics of the designer’s activity.
2. Give a scheme of mechanism of technological system development and explain the structure of this scheme.
3. Formulate the basic laws of technological system solutions when designing it.
4. Formulate the basic requirements for the knowledge and skills of the designer.
5. What is the essence of the traditional constructional design process?
6. Provide a common standard scheme for the stages of creating a new technological system and explain the logic of its sequence.

7. Provide a scheme of the constructional design issue of the technological system or process that ensures the optimal execution of the given task. Explain the principle of its formation.
8. What is the constructional design process as a tracking algorithm of an object development in which its properties are formed?
9. Explain the process of creating an algorithm for the actions of forming the layers of the constructional design object and the order of their execution.
10. Provide a scheme and explain a detailed description of the logic block that reveals the switching sequence for transition to next cycle of the formation process of the technological system.
11. What can be done to save when applying the above (see question 10) sequence of cycles and transformation methods during transitions between layers of the model?
12. What is a significant difference between the constructional design process, which is considered as forming the properties of the technological system, and its changes are considered as a development compared to a traditional constructional design system?
13. Explain how economic effectiveness estimation of technological systems is carried out.

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