Conceptual and Formal Models of Usage Effects of Information Operations in Technological Systems

Alexander Geyda
St. Petersburg Institute for Informatics and Automation of the Russian Academy of Sciences
St.-Petersburg, Russia
geida@iias.spb.su

***Abstract*—The article outlines the conceptual and corresponding formal models of the formation of usage effects of information operations. Such models are used, for example, to estimate the usage performance, efficiency, and effectiveness indicators of information technology. In addition, such models could be used for the estimation of dynamic capability and indicators of system potential regarding the use of information technology. The estimation is obtained by plotting the dependences of predicted values of operational properties of the use of information technology against the variables and options of the problems to be solved. To develop this type of models, we analyzed the use of information operations during system functioning. This is done through an example of a technological system. Basic concepts, principles, assumptions, and models are provided for such model construction. The method for the formalization of research problems is provided. The construction process for research problem models is explained. It is based on meta-modeling techniques and the construction of functional graph-theoretic models. Examples of models constructed for the estimation of system potential indicators regarding the use of information operations are given. An example of the estimation of system potential indicators is considered based on diagramming tools for business process modeling.**

I. Introduction

The research on the use of information technologies shall be implemented based on the operational properties of such use. The operational properties of the objects of research are an extensive class of properties of various objects, such that these properties characterize the results of the activity with these objects. Therefore, the operational properties form the basis of the quality of objects under research. These properties are manifested at the boundary of the object in which the activity is implemented (the boundary covers the object of activity, means of activity, and humans) and in the environment (outside the boundary). Operational properties are characterized by the effects (main results) of activity at the boundary, and these effects are compliant with the requirements of the environment.

Activity is always implemented using certain information operations (at least using the senses or speech). Information operations are elements of activity whose objectives are to obtain information, not to exchange matter and energy. Information operations are implemented in accordance with certain information technology whose objective is to describe the use of information operations. However, the mechanisms of the formation of activity effects and the subsequent formation of operational properties, taking into account the use of information operations, including modern (digital) information technologies (IT), have not been studied in sufficient detail in order to predict the effects of activity with mathematical models, depending on the selected characteristics of the information operations used, as mathematical problems of evaluation, analysis, and synthesis. This is primarily because there are no suitable models and methods for analytically describing the effects of information operations and the operational properties. This, in turn, is related to the absence of a universally accepted concept of the manifestation of the effects of information operations, particularly for non-information (material) effects that are obtained by non-information (material) operations, which depend on the information operations under study. The non-information effects of such operations vary with the implementation of the dependencies between environmental changes, further information, and subsequently non-information operations.

Since information operations lead to changes in non-information operations but do not directly lead to non-information effects, it is necessary to develop the concept of information and non-information action dependencies and the concept of effect manifestation as a result of such dependencies. It is the development of the concept of such dependencies that causes conceptual difficulties. Therefore, further research is directed to the description of the dependencies between information and non-information actions and between information and non-information effects, but first of all an analytical description using mathematical models is required.

The mathematical models developed of the formation of usage effects of information operations, including non-information (material) effects that are changed as a result of the information effects, are designed to analytically evaluate the operational properties of the use of information operations. The models are also used to evaluate other operational properties, especially the complex operational property of the system potential, which are measured taking into account the necessary use of information operations. The results presented in this study are aimed at bridging the gap between the need to solve research problems of operational properties based on mathematical models and methods and the lack of the necessary concepts and methodology for solving usage problems of information operations in the sense of formalizing them as mathematical problems of estimation, analysis, and planning by operational properties indicators. The results can be used in solving problems in research on dynamic capabilities [1-3], system potential [4], agile systems [5,6], information technology efficiency [7], exchange properties

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[8], and strategic management [11-13]. Their common feature is the need to solve these problems based on mathematical models [14-16] of the functioning of complex systems [17,18]. For these purpose indicators of system functioning, the quality shall be measured analytically [19, 20]. Such indicators shall reflect the effects of information technology [21] during system functioning [22,23]. For this purpose, the models and methods [25, 26] of research on the effectiveness of system functioning [24] shall be adapted to reflect the use of information operations [27,28].

The paper is structured as follows. The main concepts and principles of the usage of information technology are explained in Section II. The method for the formalization of the research problem is explained in Section III. Section IV contains an explanation of the construction of the model for the research problem. Section V consists of examples of constructed models. Section VI provides an example of a software prototype constructed to solve the research problem.

II. THE USE OF INFORMATION TECHNOLOGY IN SYSTEMS WHOSE FUNCTIONING IS TECHNOLOGICAL IN NATURE: BASIC CONCEPTS, PRINCIPLES, ASSUMPTIONS, AND MODELS

The use of IT is illustrated in such complex systems that the operation of these systems (and hence the use of IT) is technological. We will say that the operation is technological if it is specified by technological operation modes, i.e. descriptions of technological operations in the technical documentation for a complex technological system (hereinafter CTS). In connection with this assumption about the technological form of functioning, not any action in the system is considered but only technological operations. This assumption further allows us to assert that the states of the beginning of CTS operations, the modes of the implementation of technological operations, and the possible resulting states of such operations are described in the technical documentation.

The essence of changes in non-information operations as a result of the use of information operations is that different states of the system and the environment (because of the changing environment) can be implemented and different requirements can be accommodated. These states and requirements can lead to different information operations and their results, i.e. lead to changes in information operations and subsequently to changes in other operations. It is assumed that the number of such changes in operations is finite and can be described by modes of operations. Such modes based on the initial states allow specifying the possible transitions and the corresponding possible final states of the operations.

The modes of technological operations are specified in the technical documentation of a CTS, so this feature can be represented as a feature of the technical documentation, consisting of an exhaustive description of the possible initial states, transitions, final states, and the finiteness of such states and transitions. Accordingly, knowing the possible changes in the environment and their impacts on the CTS, we can build a model of the possible CTS states as a result of the chains of environmental impacts and information operations.

These chains, in turn, can lead to different states of the beginning of non-information operations and, consequently, to different modes of the implementation of non-information (or material) operations. Furthermore, various modes of such material operations can lead to effects that will meet the differential effect requirements of the changing environment.

Information operations in the CTS, thereby, can allow carrying out material actions in the changing conditions of the environment with modes of operations that are better adapted to these changing environmental conditions. If we make certain assumptions about the technological nature of CTS operations (of all types) and the limited number of possible environmental states, we can further assert that the possible chains of ways of implementing information, and dependent on them the modes of implementation of non-information operations, can be modeled. To model the use of information operations and therefore the use of IT describing these operations, it is necessary to perform conceptual modeling of possible sequences of environmental states and information and non-information operations. In these sequences, the states and operations are in causal relationships, and there can be alternative relationships and states. It is further assumed that such alternatives are known and that a measure for the possibility of such alternatives can be constructed.

The basic concepts and their relations necessary to describe the chains of information and non-information operations are given in [29]. The concepts were linked together with IT usage schema. The concepts have been formalized using the Mind Map format of knowledge representation. Such a representation allows us to process concept models using knowledge processing applications. Then, based on the conceptual models obtained, it is necessary to construct mathematical models of possible sequences of environmental and CTS states. Next, it is necessary to obtain models of the effects of CTS functioning, assuming that one of the possible sequences of states and transitions is realized. It is assumed that transitions are described in the technical documentation with the use of functioning laws and the regularities of nature.

To model such possible sequences of relations between states, information and non-information actions, and their subsequent formalization, a method of modeling research problems based on possible sequences of states and operations is proposed.

III. METHOD FOR THE FORMALIZATION OF THE RESEARCH PROBLEM

The method of formalization consists of assigning the main concepts and relations of set-theoretic forms (sets, vectors, relations, mappings, functions) and linking these forms (mathematical objects) with the use of relations. The result of such a set-theoretic formalization would be the set of explications of the set-theoretic forms of the problem, describing the problem in such a way that from the set-theoretic forms it would be possible to go to the parametric and functional formalization of the problem based on the explication of the mathematical objects.

To implement such a set-theoretic formalization, the graph-theoretic model of explication of the main set-theoretic forms of the problem is used. For such an explication, it is proposed to describe the set-theoretic forms so that they correspond to the elements of graph-theoretic models (vertices, arcs, nested graphs) connected by the explicated relations. This makes it then possible to go to the parametric models by parameterization of the graph-theoretic model and to the functional models by specifying and explicating the functional dependencies between the explicated parameters and variables. As a result, the main set-theoretic forms are connected by relations so that by traversing the graph corresponding to the specified forms and performing functional transformations when performing the traversal, the results required for solving the problems of evaluation, analysis, and synthesis by operational properties, mainly system potential indicators, would be obtained.

The feasibility of such model construction is based on the given assumptions and the formalization assumption that causal relations between states can be formalized as sequences of functional relations on graphs.

So, the formalization of the potential research problem can be represented as a regular construction of graphs based on already constructed graphs (extension). Such a construction of graphs can be, for example, in the form of a graph-theoretic model construction based on a conceptual model Next, graphs are constructed that describe algebraic graph-theoretic models of the formation of effects during functioning in a changing environment Following that, the graphs are labeled by variables and parameters of models of algebraic graphs. Then, parameterized graph-theoretic models are created. Finally, graph theoretical models are built in which functional dependency labels are assigned to its elements, with functional dependency labels explicated using regular expressions and programming language.

The graph-theoretic models created differ in that they are functionally consistent with the local graph-theoretic structure (the edges and vertices). This property of the models is further described because such a property, which enables computations according to the type of model and which is associated with edges and vertices, can be ordered as a linear sequence of operations for a given graph structure (and then further linearized).

This linearization refers to a property of models that for the calculation of the functional dependencies of the models, there should always be enough parameters, variables, and functional dependencies associated with the elements of adjacent graph-theoretic models (edges, arcs, hyper arcs). These elements are associated with the functional dependency labels, which are mathematical objects that describe the calculation of effects.

Models with such a property are possible to construct because of the formalization assumptions and the graph traversal properties. In this case, the graph-theoretic model graph must be connected without loops so that it can be traversed to calculate all the required expressions based on the mathematical objects specified at the labels. As a result, the calculations can be performed by traversing the graph (in depth, in width) with the calculation of the functional relations specified.

Based on such linearized graph-theoretic functional models, it is possible to generate a functional model that describes a finite sequence of functional expressions for the calculation of the system's potential indicators depending on the variables of the problems (estimation, analysis, planning) to be solved.

The models obtained can be further described using, for example, computational expressions in the programming language, so such a graph-theoretic formalization can be regarded as a kind of domain-specific programming method.

The features of the generated models are those of linearized graph-theoretic functional models, and a large number of such models, structured with the use of graphs (trees), can be constructed. The linearization property of graph-theoretic functional models allows compiling graph-theoretic model to corresponding programs.

There are many models because to model the results of information operations in a changing environment and to calculate the system potential, one should describe many possible chains of information and non-information operations, depending on the number of possible impacts of the environment. Due to these properties, it makes sense to use automation tools for constructing the required models. Such tools can be based on meta-modeling techniques.

The model generation is terminated and the model realized when the obtained graphs are able to compile the obtained model of the problem to the program for problem-solving or to the formal description of the problem for use with a solver of mathematical problems (for example, an optimization problem solver) or to other applications that can solve the problem. Such a (terminal) model for the problems of evaluation, analysis, and synthesis can be, for example, a program in any programming language, a spreadsheet table for solving problems, or a problem description text in a language of optimization modeling (e.g. an Algebraic Mathematical Programming Language, or AMPL).

IV. FORMULATION OF THE CONSTRUCTION OF THE RESEARCH PROBLEM MODELS

The problem of the research can be formalized as a set of tasks of estimation, analysis, and synthesis of the CTS and of its functioning in terms of system potential [4-8]. Each task is formalized with the corresponding models of the task, from the conceptual model to the terminal one.

Graph-theoretic conceptual models can be constructed on the basis of the conceptualization of the research problems by the researcher. Knowledge representation software can be used to represent conceptual models; in particular, the format of Mind Map concept representation was used. Models of different objects u and types z are designated as M_z^u.

The main objects u to be modeled are system states S^k of various origin k, environmental models M^{cp}, CTS functioning models M^{pcp}, models $M^{cгp}$ of the relations on the border of the CTS and its environment. Each model can have different types z constructed sequentially, as described below.

Graph-theoretic algebraic models are constructed on the basis of the conceptual models. At the same time, the additional concepts describing the elements of the graph-theoretic models and their relations with the conceptual models shall be added. The purpose of the creation of such new models with additional concepts is to generate the final models later. The final models make it possible to obtain instructions for solving the problem (for example, in the form of the text of the program in an imperative language). For this purpose, models of the sequences of states of different origins were structured in such a way that the sequential calculation of the characteristics of the states could be carried out. Graph-theoretic parametric models are constructed on the basis of algebraic graph-theoretic models by data (for example, data from a database) assigned to the graph elements. Numbers, random values, and variables may act as data.

Graph-theoretic functional models are constructed on the basis of graph-theoretic parametric models by specifying the functions that connect variables and parameters and associate them with the graph elements. This can be done by using a general programming language.

The CTS potential Ψ or ψ can be estimated based on a functional $M^{сгр}$ model of the states of the CTS on the border with the environment. Thus, modeling the task of CTS potential estimation can be formalized as a sequence of model constructions:

$$\mathrm{M}_u^{cp} \to \mathrm{M}^{cp}; M_u^{pcp} \xrightarrow{m^{cp}} M^{cp};$$

$$(\mathrm{S}_k^H, \mathrm{S}_k^{О\kappa}) \xrightarrow{m^*} \ldots (M_u^{pcp}, M_z^u) \xrightarrow{m^{**}} M_u^{сгр}.$$

The first model in a given sequence of model constructions is the realization of the appropriate concept model. Mappings of models are model constructions. They are built according to the appropriate concept model of the formalization. The models of different objects M_z^u in sequences of models and their mappings $M_{z_1}^{u_1} \xrightarrow{m^{**}} M_{z_2}^{u_2}$ are parameterized by the characteristics of the CTS and by the characteristics of the technology of functioning (stored, for example, in the database). The relations of the variables and parameters of the models are described by the functions associated with the elements of models.

The representation of the functions is such that a sequence of functions corresponding to the traverse of the graph-theoretic model can be constructed.

As a result of the traverse, the values Ψ, ψ of the CTS potential indicators are calculated.

Determine

$$\Psi < \mathrm{M}_u^{сгр}, u = \overline{1,U}; \mathrm{M}^{cp} >, \psi(\{\mathrm{M}_u^{сгр}, u = \overline{1,U}\}, \mathrm{M}^{cp}).$$

Then determine according to one of the criteria whether the value of the CTS potential meets the criterion.

Find Ψ and ψ by traversing the functional graph-theoretic models $\mathrm{M}_u^{сгр}$, M^{cp}, with the necessary calculations during such traversing.

Modeling the research tasks of analysis and planning can be formalized in a similar way, in fact, as a model of model construction based on conceptual models. The construction of these models is realized on the basis of the modeling methodology of the research problem. It is realized with the concepts and principles of the modeling methodology, by setting modeling requirements, by specifying models and methods of modeling for the specified research tasks, and by descriptions of the modeling techniques and methods of problem solutions with the use of models.

It is implemented through a systematic application of the constructed conceptual models of the problem under study and of the conceptual models of the modeling methodology.

The basis for the application of the modeling methodology is the schemas specified in the form of diagrams (in conceptual modeling) and, subsequently, the schemas in the form of (marked) finite graphs describing the realization of the concepts and the realization of the concept relations.

The basis for model development is the conceptual model of the operation primitive. It describes the laws of nature for obtaining the effects of the possible mode of operation. This model is such that it is not subject to further division into operations and states associated with the cause-and-effect relationships of the mode of operation. In the operation primitive, each possible initial state has one mode of action but may have a few resulting alternative states. For the operation primitive, all parameters and functions are defined by the technical documentation, as one of the possible operation realizations under the defined conditions.

The scenarios for changes in the CTS environment are specified based on the possible states and transitions specified for the environment. Based on these scenarios, possible changes in the functioning goals of the CTS are specified as possible plans of environmental functioning. These plans are used to construct the required sequences of states on the border with the environment. Such sequences can be formalized as a tree of required states and transitions (changes) under the different scenarios of environmental functioning. In the tree of required states, for each branch, a fixed model of the functioning of the CTS is built, provided the branch of required states is implemented. This model is a model of sequences of CTS states and transitions, provided the branch of required states is implemented. A part of each sequence of CTS states and transitions modeled by the appropriate branch is a sequence of states on the boundary of the CTS and its environment. Sequences of CTS states and transitions are represented in the form of the tree, which is built provided the branch of required states is implemented. As a result, a complex model of the required states and corresponding CTS states and transition tree is built. It can be presented as a complex tree, which includes possible sequences of states on the boundary of the CTS and its environment, for possible environmental changes. Traversing this model with the required computations performed in the labels leads to the evaluation of the CTS potential indicator.

Let us describe the main models that are built with this modeling methodology.

V. EXAMPLES OF MODELS CONSTRUCTED

An algebraic structural model of the CTS describes the elements and structure of the workplaces (WP): $e_{jk} - k -$ th element on $j -$ th WP, according to the technical documentation; $e_{jk} \in E_j$, where $E_j -$ workplace $j = \overline{1,J}$;

Realizations of states and WP in appropriate sets fulfilled according to the created concept model. At a given moment t, part or all the WP are functioning; that is, those WP where technological operations (TlOp) are implemented. TlOp, implemented on the WP according to one of the possible modes, can begin only if the specified state of the WP is reached. Such TlOp can lead to different states as a result of TlOp implementation, depending on the environmental conditions. The set of states of $E_j -$th WP at each moment forms a state of the CTS:

$$Q(t) = \bigcup_{j=\overline{1,J}} Q_{E_j}(t)$$

System states $Q(t)$ at moment t are manifested and checked at the boundary of the system (CTS) and its environment. A mathematical model of states at the CTS boundary is built in the form of an algebraic model of sequences of CTS states on the boundary of the CTS and transitions of such states. It is assumed that the number of checked states on the boundary is limited. The algebraic model can be represented as a geometric graph.

Then, from the constructed algebraic model, a functional model of correspondence between the states of the CTS and its environment is generated on their boundary. The peculiarity of this model is that it unites the model of CTS, the model of states at the boundary of the CTS, the model of states on the boundary of the CTS environment, and the model of the environment. It is the last model that needs to obtain the functional relations for the calculation of the CTS potential indicators. We assume that both the number of states at the boundary of the CTS and its environment and the possible number of transitions between such states are finite. States at the boundary are checked with special information operations. The results of these information operations are a measure of the CTS and the correspondence of the environmental states. Thus, the sequence of such information operations on the border is finite, and this sequence shall be used to determine the CTS potential indicators, according to its definition.

As a result of the research, the main types of relations between states were identified. These types of model relations are arc, hyper arc, and nested graph at the tree of states. Transitions are a special case of relations that are associated with the mode of operations in this tree. In particular, relations belong to two main classes: relations of possible joint realizations of states (simultaneity relation) and relations of possible transitions between states. The first class arises from the possible implementation of TlOp on several WP at the same time. The second class of relations emerges by the completion of TlOp and, consequently, the transition to the state of TlOp termination. Let us introduce relations classes. They correspond to the arcs of tree classes:

O_1 – States jointly implemented through the execution of technological prescriptions during non-information (material) operations (TNIO) on various WP. As a result, the relation characterizes the composition of WP states during TNIO execution (composition, combinations of states in the implementation of complex TIO on complex RM);

O_2 – The transition from one (initial) state to another (final) state due to the execution of the prescriptions by TNIO at WP. It is the transition from the initial WP material state, including TNIO prescriptions (information), to the final material state of the executed prescriptions. This transition can be realized by a person or a device (for example, the actuator);

O_3 – The transition between non-information and information states. It consists of the measurement and checking of the (material) state. This transition can be realized by a person or by a device (for example, a sensor or a computer);

O_4 – The transition between states, consisting of the transfer of information (for example, prescriptions transfer). This transition can be implemented by a person or by a technical device (communicating device, networking device);

O_5 – The transition between states, consisting of obtaining prescriptions according to the results of the state checking. This transition can be realized by a person or by a technical device (computer).

O_1 , in turn, can be divided into two types:

O_{11} – States may be observed together at some time in some circumstances;

O_{12} – This is a non-zero measure of the possibility of observing states together at a given time;

These relationships can be further divided into types depending on the types of states that can be implemented together.

Relations O_2, O_3 require input (initial) and output (final) states of different types (information, non-information) during the transition. Thus, they shall form sequences with relations of information types. We assume that other relations can form chains of information relations. Each of the possible finite sequences of states and relations (transitions) checked on the boundary of the CTS and the environment is part of a particular branch of the tree. It is assumed that the number of such sequences (tree branches) can be L; that is, the set of possible sequences of CTS states has L power: $C^{CTC}: \ |C^{CTC}| = L$.

The sequence of states is assumed to be such that for different initial states before testing, states on the boundary correspond to different modes of implementing technological non-information operations (TIO). The mode of TIO execution functionally depends on the state before the start of the TIO, on the IT used, and the plan of operations. If the state before the start of the TIO, the information technology, and the plan of operations are known, then the mode of TIO will be known as well. The mode to execute the TIO of checked states on the border of the environment, in turn, may correspond to the mode of environmental state changes if the environmental state changes are modeled accordingly. It is assumed that the modes of environmental operations are not known for sure, but the resulting state sequences, their relations (transitions), and the measure of the possibility of implemented transitions are known. Therefore, as a result of a sequence of environmental state transitions and a sequence of modes of implementation of the CTS operations, we can get a pair of states on the border whose correspondence can be measured and whose possibility of actualization can be measured as well. In the sequences of C^{CTC} states, each pair of states on the boundary corresponds to different branches of the tree of environmental states and the tree of CTS states.

Let's fix the sequence of environmental states and transitions. To do this, assume that the actions and states of the environment do not depend on the operation modes and the states in the CTS, but the CTS states, of course, depend on the sequence of environmental states. Then the specified sequences of the environmental states can be presented without taking into account their connections with CTS functioning. As a result, the sequences of environmental states can be presented in the form of a tree of possible sequences of environmental states before a tree of CTS states is constructed, which depends on these sequences.

In this tree, the edges correspond to the transitions of environmental states that happen due to modes of actions in the environment (possibly unknown). The states correspond to the states of the environment on the border of the environment with the CTS.

The number of sequences of the states of the environment is a result of some modes of action of the environment, M. Let's denote a set of possible sequences of environmental states as a result of some modes of environmental actions as C^{Cp}. Accordingly, $|C^{Cp}|=M$ and the elements $c_m^{Cp} \in C^{Cp}$ are associated with the branches of the tree of environmental states, $m=\overline{1,M}$.

The functional model of the environment is first constructed by parameterization of the sequences $c_m^{Cp} \in C^{Cp}$, associated with the branches. This means a parameterization of states and their transition dependencies and then a parameterization of sequences of states, including a parameterization with the probabilities of states and transition actualizations. Subsequently, functional relations are assigned that connect the parameters, the measures of the probability of the states, and the transitions in the branches of the tree, as well as the dependent characteristics of the states of the environment.

A mathematical model of the environment under the assumption of independence of the activities of the environment from CTS operations is connected with a mathematical model of the compliance of CTS states with its environment on their boundary by relating states to the appropriate TIO of state checking on the boundary. These relations are specified between the nodes of the CTS states tree as a result of the CTS functioning and the nodes of the environmental state tree. Since the state of the CTS during its functioning depends on the states of the environment and such a dependency in the study of the potential cannot be neglected, each method of implementation of the checking TIO on the boundary of the CTS is related to (associated with) the branch of the tree of possible states of the environment. A complex model of the CTS and the compliance with environmental states can be constructed as a result. It allows measuring the CTS potential.

In this regard, the set of branches of the CTS state tree is constructed under the condition that the branch $c_m^{Cp} \in C^{Cp}$ is given, that is $|C^{CTC}(c_m^{Cp})|=L_m$. Further, speaking of the branch $l \in \overline{1,L}$, we will assume that it is built for $c_m^{Cp} \in C^{Cp}$, i.e. $l_m \in \overline{1,L_m}$. This means that a relationship is defined between each branch $c_m^{Cp} \in C^{Cp}$ and the corresponding $C^{CTC}(c_m^{Cp})$. As a result, a new tree can be constructed that includes a branch $c_m^{Cp} \in C^{Cp}$ before the root of the $C^{CTC}(c_m^{Cp})$ tree. The relations of environmental states and the CTS states shall be hidden on such a tree but will be shown by a separate model. This tree has the property that traverses can be set on this tree, extending the bypass of the $C^{CTC}(c_m^{Cp})$ tree. The extension is understood in the sense that one traverse includes the set of other traverses with the use of the tree structure.

The resulting model, corresponding to all the branches $c_m^{Cp} \in C^{Cp}$, $m=\overline{1,M}$ and corresponding to each branch $C^{CTC}(c_m^{Cp})$, is used to create the functional model and then the terminal model to calculate the CTS potential.

The number of states in the state tree branch $l \in \overline{1,L}$ is assumed to be variable because the number of operations that caused transitions and, accordingly, the number of resulting states could be different because of the impact of the environment. In addition, due to the same environmental impact, the duration of the state transitions and the duration of the sets of actions on different WP are different as well. As a result, the number of required state checks at the system and environment boundaries may vary. Let the number of such states be Q_l for a given branch $l \in \overline{1,L}$ of the tree.

Each state check number on the CTS border $q_l \in \overline{1,Q_l}$ corresponds to the implementation of the checking TIO in the specified mode, and the only state corresponding to this mode is $q_l \in \overline{1,Q_l}$. Each of the states $\hat{S}_{l.q} =< \hat{y}_{1.l.q}....\hat{y}_{k.l.q}...\hat{y}_{K.l.q} >$ checked at the boundary of the CTS and its environment is fully described by the effects of functioning by the time the state check starts. This state is compared with the environmental state, which specifies the requirements $S^{\partial}_{l.q} =< y^{\partial}_{1.l.q}....y^{\partial}_{k.l.q}...y^{\partial}_{K.l.q} >$ values (these may be random, but for simplicity they are considered non-random). Then, a probability measure $P_{l.q}$ of the compliance of states $\hat{S}_{l.q}$ with the requirements of the environment $S^{\partial}_{l.q}$ can be defined:

$$P_{l.q} = P(\hat{A}_{l.q}) = \\ = P(<\hat{y}_{1.l.q} r_l y^{\partial}_{1.l.q} ... \hat{y}_{k.l.q} r_k y^{\partial}_{k.l.q} ... \hat{y}_{K.l.q} r_K y^{\partial}_{K.l.q} >),$$

where r_k is the required relationship between the predicted values of the effect characteristics and their required values (e.g. <,>).

The probability measure is calculated using a functional model for calculating the correspondence at the boundary of the CTS and the environment.

$P(\hat{A}_{l.q})-$, the probability of an event consisting of the fact that when checking the state $\hat{S}_{l.q}$ for one of the possible branches of the tree, performing a single checking TIO by the defined mode is required by the environmental characteristics of the effects, will be achieved.

This event means that the result of the checking TIO achieves the required intermediate goal of the CTS functioning, given that the states of environmental changes are fixed (the intermediate goal of the CTS is achieved in the current environmental circumstances).

Since such checking TIO of states $\hat{S}_{l.q}$ corresponding to the modes of checking TIO in one branch of $C^{CTC}(c_m^{Cp})$ is less or equal to L, and all of them are expressed in the model, the measure of compliance for the implementation of the entire sequence of checking TIO for one branch $c_m^{Cp} \in C^{Cp}$, the corresponding measure for the whole (but one) branch of $C^{CTC}(c_m^{Cp})$ can be calculated as the probability of a complex event $\hat{A}_l$, which means all the intermediate goals are achieved in the given environmental circumstances.

Event $\hat{A}_l$ probability is:

$$P(\hat{A}_l) = P(\bigcup_{q \in \overline{1,Q_l}} \hat{A}_{l.q}).$$

If the probabilities of compliance for each of the checking TIO are conditionally independent in their sequence, then

$$P(\hat{A}_l) = \prod_{q \in \overline{1,Q_l}} \hat{A}_{l.q}.$$

Let the probability of an event $\hat{B}_{q,p}$, consisting of the fact that the transition $a_{q,p}$ will be executed $\hat{B}_{q,p} = (\hat{S}_{l.q}, \hat{S}_{l.p}) : \exists a_{q,p} : q,p \in \overline{1,Q_l}$, be equal to $P_{q,p} = P(\hat{B}_{q,p}) \sim a_{q,p}$, i.e. the probability $P(\hat{B}_{q,p})$ is associated with the transition $a_{q,p}$.

Then the probability of implementing a branch $v_l : l \in \overline{1,L}$ of the tree $C^{CTC}(c_m^{Cp})$ is

$$P_l = P(\bigcap_{a_{q,p} \in v_l} \hat{B}_{q,p}).$$

If these events of transition executions are conditionally independent,

$$P_l = \prod_{a_{q,p} \in v_l} P(\hat{B}_{q,p}).$$

Then, as a scalar indicator of the CTS potential ψ, we can take the expected probability of the event that whatever branch $c_m^{Cp} \in C^{Cp}$ and corresponding branches of $C^{CTC}(c_m^{Cp})$ are implemented, there will be the right correspondence between the expected and required states as measured by the checking TIO. This means that whatever changes in the environment happen, and whatever operations are conducted to fulfill the changing goals, the changing goals of the CTS will be achieved:

$$\overline{\psi} = P(\hat{C}) \approx \sum_{l \in \overline{1,L}} (P_l \cdot P(\hat{A}_l)).$$

In general, the probability $P(\hat{C})$ of a specified event can be represented as a random variable ψ, not its expected value $\overline{\psi}$. ψ discrete distribution $f_{\hat{\psi}}(l)$ is described by the vector of pairs:

$$f_{\hat{\psi}}(l) = (P_l, P(\hat{A}_l)).$$

This vector of pairs can be used as a vector function of the CTS potential:

$$\Psi = < f_{\hat{\psi}}(l), l = \overline{1,L} >.$$

These indicators describe the different characteristics of the CTS potential, given that the functioning of the CTS is terminated. In the same way, indicators can be constructed for any moment during functioning. Variants of the CTS potential indicators can be used, for example obtained by using the criteria of optimism or pessimism. These indicators make sense of the different characteristics of the complex probabilistic measure of compliance of the predicted effects with the requirements of them. With this compliance measured at the boundary of the CTS and its environment at different times, while taking in account the possible changes in the environment, the appropriate changes in the CTS that are caused by these environmental changes can be found.

The mathematical model of such correspondence on the boundary is the basis of the mathematical model of the CTS potential estimation task. To obtain a mathematical model of the tasks of potential estimation based on the specified model, it is necessary to construct models that reveal the values $< \hat{y}_{1.l.q} ... \hat{y}_{k.l.q} ... \hat{y}_{K.l.q} >$ and $< y^{\partial}_{1.l.q} ... y^{\partial}_{k.l.q} ... y^{\partial}_{K.l.q} >$ with the use of labeled (parametric and then functional) graph-theoretic models.

In fact, such a task can be interpreted as a special kind of graph extension, namely its disclosure, which describes the calculation of the functioning effects. Under the disclosure of marked graph-theoretic (initial) models is understood a sequence of operations on these models such that as a result of operation, the element of the model, which is associated with the disclosed value (parameter, variable), is calculated based on the composite traverse of the disclosed model and the initial model. With the use of the proposed graph-theoretic models in the form of hierarchical trees and graphs, the properties associated with the elements of the models are found by replacing the node of the original tree with a composite tree.

In this regard, the model of effect manifestation $< \hat{y}_{1.l.q} \ldots \hat{y}_{k.l.q} \ldots \hat{y}_{K.l.q} >$ under the given requirements $< y^{\partial}_{1.l.q} \ldots y^{\partial}_{k.l.q} \ldots y^{\partial}_{K.l.q} >$ changes, and models of requirement changes should be created as trees parameterized with operation and state characteristics. Functional dependencies on the trees must be specified in such a way that by traversing the models and by computations of functional dependencies, it will be possible to calculate the required values.

VI. PROTOTYPES OF SOFTWARE FOR THE ESTIMATION OF OPERATIONAL PROPERTY INDICATORS OF IT USAGE

Modeling of operational properties of IT usage requires the creation of multiple system functioning models under multiple scenarios of environmental functioning. The creation of multiple models may be quite complex. Therefore, I propose to use diagrammatic means. Graph-theoretic, diagrammatic models transformed into parametric models by adding parameters and variables to the graph-theoretic models are built. A database of parameters and variable restrictions is used for this purpose. In the example considered, diagrammatic models were created with the ARIS (Architecture of Integrated Information Systems) toolset modernized so as to use nested parameterized diagrams with functional expressions embedded to reflect graph-theoretic models of different types. Next, parameterized models are transformed into a functional model by adding formulas to the elements of the ARIS models. Then, nested diagrammatic models are transformed into Microsoft Excel spreadsheets, as shown below. The resulting spreadsheets constitute a program model of an IT-enabled estimation of a system's dynamic capability. Examples of diagrammatic models are shown below. They are based on common subprocess models (Fig. 1).

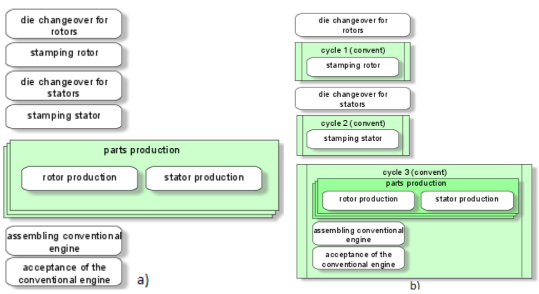

Fig. 1. Diagrammatic ARIS models to estimate the operational property indicators for unique (a) and serial (b) production

The simplest models available were used. For example, only four scenarios of environmental functioning are possible, and there are four changing goals as a result. Diagrammatic model of functioning could be built for each goal. The use of an IT is modeled with relevant IT operations, resulting in a change of the course of functioning. Such operations require additional resources and time when a functioning goal is altered due to a change in the environment (Fig. 2, Fig. 3).

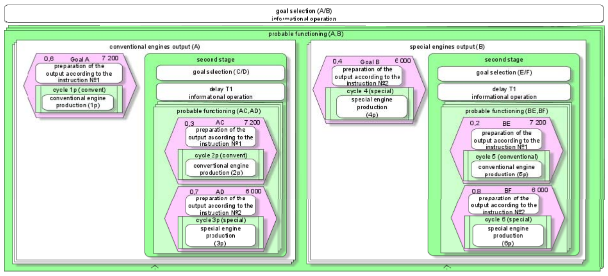

Fig. 2. Diagrammatic ARIS Model Version 1 for estimating operational property indicators

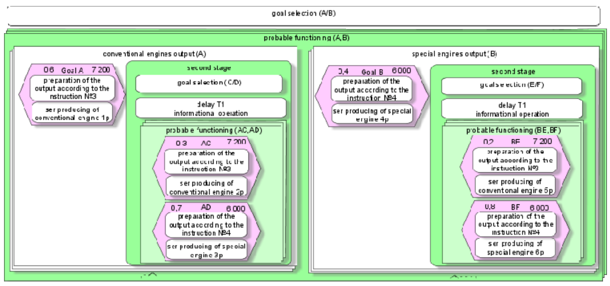

Fig. 3. Diagrammatic ARIS Model Version 2 for estimating operational property indicators

Next, an indicator of IT-enabled dynamic capability is estimated as a probabilistic mix of system functioning efficiencies, with IT used for functioning changes according to four different scenarios of functioning change.

Different model versions are considered. Version 1 (Fig. 2) differs from Version 2 (Fig. 3) by their respective TIO characteristics according to the different IT used. The resulting Microsoft Excel table (Fig.4 **Ошибка! Источник ссылки не найден.**) consists of a program model for the estimation of operational properties of IT usage and the corresponding dynamic capability indicators. It was obtained automatically, using model-driven meta-modeling [30-35] and the possibilities in ARIS to generate a program code.

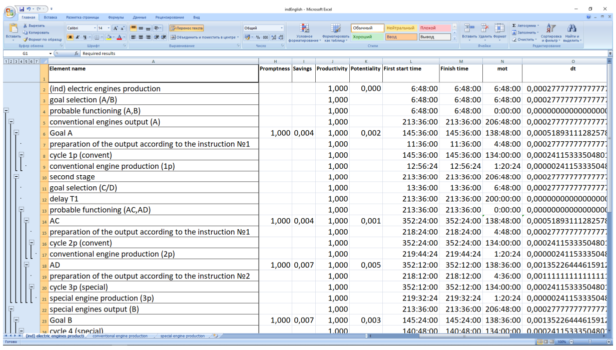

Fig. 4. Program model for estimating operational property indicators

VI. Conclusion

The results obtained enable the evaluation of the predicted values of the operational properties of systems. Corresponding IT-usage indicators, dynamic capabilities, or system potential indicators can be estimated as a result. Analytical estimation of such indicators becomes possible depending on the variables and options in the mathematical problems to be solved. This could lead to a solution to contemporary problems in research using predictive analytical mathematical models and mathematical methods. Examples of such research problems are problems related to IT productivity and efficiency and the estimation, analysis, and synthesis of the dynamic capabilities of systems. Possible aspects include choosing the best information operations and choosing IT and TIO characteristics for the optimal implementation of new IT.

It makes it possible, as a result, to overcome the existing gap between the need to solve research problems in operational properties (especially regarding information operations) based on mathematical models and methods and the lack of the necessary concepts and methodology for solving such problems. An example of such a problem is optimal usage of distributed ledger technologies for business processes, robotic technological process optimization, and choosing cyber-physical system characteristics.

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