Models of Monitoring as an Information Analysis Tool for Management of Social, Economic, Engineering and Natural Systems

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ABSTRACT
This paper discusses an attempt to enhance the efficiency of information-analysis support of the process of managerial decision-making in management of social, economic, engineering and natural systems. The authors propose a generalized structural-functional model of monitoring based on a formal representation of the information processing cycle implemented within the framework of the Integrated DEFinition (IDEF0) methodology. A colored timed Petri net (CTPN) has been developed as a dynamic interpretation of the structural-functional model. The paper provides a methodological ground for the tools used to determine the requirements meant to ensure highly efficient information-analysis support of management operations, based on cross-analysis and exhaustive enumeration of the procedures and supporting factors of the monitoring system, as represented in the form of stages and elements.

Keywords
Monitoring, Petri Nets, dynamic model, structural-functional model

1. INTRODUCTION
A complex and many-valued category, the quality of a managerial decision depends strongly on the reasoning behind it, which, in its turn, is based on parameters of the data used during the preparation. The current practices in information-analysis support of managed entities' operations show a significant degree of variation. They include various methodological approaches and tools that are most often designed to study the changes in the managed entities and are used as benchmarks for their future states.

For example, improvement of the quality of life is a paramount and universally recognized goal of social and economic development. The achievability of this goal can be assessed only through constant monitoring of efficiency indicators that underlie the measurement procedure, and through their comparison to the target state. Such approach makes it possible to utilize interim analysis and identify the degree of deviation from the scenario projected for the managed entity at the stage of goal-setting and, in case of critical deviation, to preemptively adjust its operations and / or parameters (where necessary) without having to wait till the period affected by the managerial decision ends. The situation is similar in other areas of public administration: state and municipal services, management of individual municipal facilities, currency exchange regulation, etc.

Data recording and analysis also play an important role in management of complex industrial facilities and engineering systems, and in assessment of anthropogenic impact on the local environment and human health. For example, systematization of accumulated data (meteorological and environmental parameters and properties collected through processing of satellite data, etc.) makes it possible to assess the spatial-timed regularities in changes of the micro- and macro-environment of a territorial entity, to identify the place of origin and likelihood of spread (development) of chronic infectious and non-infectious diseases.

This concept of information-analysis support of the managerial decision-making process can be implemented through organized monitoring. It is commonly believed that monitoring initially was utilized by and developed in physical sciences, eventually being adopted by researchers in engineering and social sciences. As a consequence, the majority of publications on this topic focus on its application for the needs of biology [1], medicine [2], ecology [3, 4], geography [5], economics [6], etc. It should be noted that these academic fields have at their disposal a well-defined methodological framework of monitoring, a set of developed measuring tools, the organizational structure necessary for the associated procedures, and the appropriate regulations establishing the status of monitoring (e.g., state environmental monitoring provided for by Federal Law as of 10.01.2002 № 7-FZ). Among social sciences, motioning is used most extensively and developed most actively for the purposes of sociology, psychology and pedagogy [7-10]. Thus, normally the main focus is on the subject matter (as related to the subject of research), even though monitoring results are almost always used at various levels of managerial decision-making. As a result, it becomes necessary to define the essential, technological and organizational characteristics of this tool.

The managerial essence of monitoring manifests itself through its application for the purposes of decision-making, since only information that is exhaustive, accurate and timely can be efficiently used as a basis for planning, execution management, control and adjustment of human, technological, administrative and business processes. In this context, this study attempts to model a monitoring system as a tool for in-formation-analysis support of social, economic, engineering and natural system management.

2. FROM ESSENCE OF MONITORING TO ITS FUNCTIONAL MODE
Given the current diversity in interpretations of monitoring and its variance in the context of specific areas of knowledge, the category in question will be discussed through the following perspective. Monitoring is a dedicated information support tool used in management to control, assess, analyze and forecast development of the managed entity based on an uninterrupted process of data organization procedures (collection, processing, storage, display and distribution), each relying on its own methods. Monitoring as a management tool is implemented only as a certain interconnected sequence. Its structure can be explored through a formal model of social and economic system decomposition where [11] identifies the following elements: process of operations, object of operations, end product, means of operations, subjects of operations. That serves as the basis for a structural-functional model of a monitoring system (Table I).

TABLE I. ELEMENTS OF A MONITORING SYSTEM

Formal element	Element of system of monitoring
Activity process	Monitoring procedures
Object of activity	The initial information received from sources
Means of activity	Methodical tools of realization of monitoring procedures; Organizational regulations; Program technical means
Subjects of activity	Carriers of monitoring functions
Final product	Results of monitoring

The procedures of monitoring stem from the model of the information processing cycle. Essentially, it is a functional monitoring system that can be represented graphically in a generalized form using the IDEF0 notation (Figure 1). Each block in Figure 1 can be decomposed further.

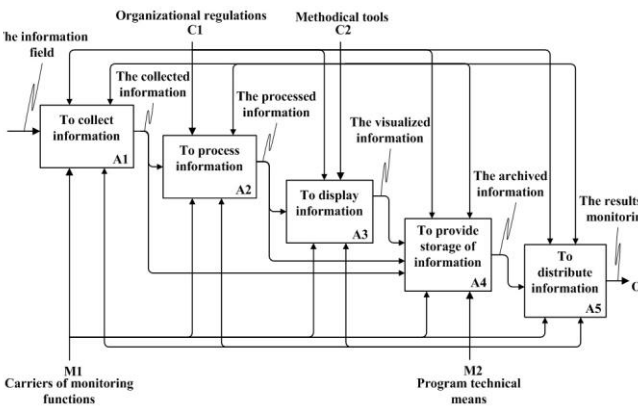

Figure 1. Generalized model of a monitoring process

Monitoring indicators reflect a set of base (object of operations) and target (end product) values that represent social, economic, engineering and natural systems and their changes. A specific list of indicators is determined by the managerial goals, performance criteria and the methods employed to control, assess, analyze and forecast the monitored object.

Authority (rights, obligations and responsibilities) is assigned to the parties responsible for the monitoring procedures based on organizational rules which also specify the mechanism for their interaction. The associated set of tools includes the description of specific methods used to collect, process, store and display information.

The efficiency of the whole system can be enhanced with the help of appropriate software and hard-ware solutions. Moreover, modern information technology makes it possible to bring monitoring to an entirely new level of development as it expands the service potential of each stage. More specifically, it can be used for calculations, allows larger volumes of information to be stored and processed and offers new opportunities for presentation. The monitoring functions are supported by various organizations, divisions and individual employees.

Despite the overall transparency of the notion, the content of these components is far from being a trivial problem. Therefore, the authors propose to lay down a set of standard requirements for organization of monitoring systems. Let S= $\{s_i\}$, Z = $\{z_j\}$ be sets of monitoring procedures and supporting elements of the monitoring system, correspondingly. By relating S to Z element by element, we arrive to a product of sets of the monitoring system. Each such combination $\{s_i, z_j\}$ can be matched to the requirements (Table II).

TABLE II. FRAME OF A NORMATIVE MODEL OF REQUIREMENTS FOR MONITORING SYSTEM ORGANIZATION

Monitoring process stage	Elements of system of monitoring				
	1.Program technical means	***2.Metho-dical tools***	***3.Organiza-tional regulations***	***4.Subject of activity***	***5.Monitoring indicators (the initial and transformed information)***
1.Collecting			s_1z_3		
2.Processing		s_2z_2		s_2z_4	
3.Display	s_3z_1				
4.Storage					
5.Distribution					s_5z_5

However, these requirements are not equally necessary for all combinations. For example, in monitoring of subjects that are physical (natural) (e.g., meteorological, space monitoring), software/hardware requirements are crucial at the stage of information collection, while monitoring of territorial social and economic development tends to be significantly less reliant on these limitations. The essence of requirements is discussed at the level of content. This approach makes it possible to cover all potential aspects of complex systems engineering.

As an illustration, let us consider the following examples of synthesized requirements for monitoring of territorial social, economic development: s_3z_1 – requirements to software used to visualize monitoring results; s_2z_2 – requirements to adequacy of methods employed for assessment, analysis and forecast of social and economic development; s_1z_3 – instructions on interaction procedures for entities supporting the monitoring functions (customers on the one part, record keepers, interviewers, etc., on the other part, and information holders, on the third part) at the stage of information collection; s_2z_4 – competence and professional requirements for employees responsible for assessment, analysis and forecast of social and economic development; s_5z_5 – requirements to the quantity of the provided information to different categories of users.

3. DYNAMIC SIMULATION OF THE EXTENDED MONITORING PROCESS

The resultant structural-functional model represents the organization of the processes of monitoring, collection, processing and storage of information without regard to the process dynamics. By utilizing the mathematical tools offered by Petri nets, we can proceed to dynamic simulation of the extended monitoring process and optimize operations of the appropriate monitoring services. The classical Petri net structure is determined by its places, transitions, input and output functions and is formally represented as follows [12]:

$$C = (P, T, I, O) \qquad (1),$$

where $P = \{ p_1, p_2, ..., p_n \}$ is a finite set of places, $n \geq 0$; $T = \{ t_1, t_2, ..., t_m \}$ is a finite set of transitions, $m \geq 0$; $I : T \to P^\infty$ is the input function (a mapping from transitions to bags of places); $O : T \to P^\infty$ is the output function (a mapping from transitions to bags of places). The sets of places and the sets of transitions do not intersect: $P \cap T = \emptyset$, and the cardinality of the set P is n, and the cardinality of the set T is m. We denote an arbitrary element of P by p_i, $i = 1,\dots, n$, and an arbitrary element of T by t_j, $j = 1, \dots, m$.

Since the monitoring process possesses various timed characteristics, the most important of which is the time required for collection, processing, delivery (distribution) of information, it appears reasonable in this case to utilize the tools offered by timed Petri nets which are based on defining the firing time for a specific transition, for which purpose we shall first define the start and end time of transition firing, the duration of firing, and the time of early and late firing. By using colored Petri nets, we can study the technology of monitoring up until the moment it is implemented. Moreover, the behavior of a Color Petri Net (CPN) model can be analyzed with the help of computer simulation.

For a colored Petri net, the functions I and O are multivariable, i.e. $I=(I^1, I^2, ..., I^L)$, $O=(O^1, O^2, ..., O^L)$, where $L=|D|$, $D=\{d_1, d_2, ..., d_L,\}$ is a set of colors (labels). A function $\mu(P)$ is defined on a subset P as a totality of nonnegative integers that determine the number of colored tokens (marks) in places. In such case, the CTPN is defined by the following six parameters: $C=(P, T, I, O, \mu, \tau)$, where τ is one of the ways to set the time parameters for the elements of the set T. The time parameters are set as follows: the duration of each monitoring task and the start times of the first task; the duration of each task and the end time of the last task; the duration of each task and the start and end time of each task.In our situation, the time parameters will be set through the task duration, its start time and end time. In the general case, simulation of the monitoring process requires the following changes in the initial conditions (in terms of Petri nets) [13-15]: periodic changes of the CTPN status through change of the token colors; change of the time or resource parameters by the user.

The first task is addressed with the help of the Petri net marking algorithm, where the initial marking μ_0 corresponds to the initial status of the net. A transition of the net is enabled (a certain event will happen), and the appropriate task is active if all conditions are satisfied (all necessary tokens are available). The conditions for transition firing can be determined as follows: tokens appear in output places immediately after any of the tasks in the appropriate stage is marked as completed, while the rest of the tasks of the stage are marked as completed within the timeframe reserved for the stage. This is necessary in order to avoid a deadlock situation in transition firing for subsequent simultaneous transitions. If the time reserved for the stage lapses while some tasks remain unexecuted (a task not executed on time), the net user can make a decision regarding further actions. Completion of a stage creates a new marking μ of places and determines the conditions for enabling of subsequent transitions.

An important approach to visual perception of Petri nets and the quality of the simulated processes analysis is through graphical representation of Petri nets. A classical Petri net structure includes two types of nodes: **O** is drawn as a circle and represents a place, | is drawn as a bar and represents a transition. Places and transitions are linked through oriented arcs. An arc from a place p_i to a transition t_j, determines the place that serves as a transition input.

Conditions, i.e., the logical states of the system taking the TRUE or FALSE values, are simulated by places, while events or actions in the system are simulated by transitions. Fulfillment of a condition (TRUE value) is represented by a token in a place corresponding to the condition, and when transition fires, the enabling tokens that define preconditions are removed, and new tokens are created that defines post conditions. It should be noted that in a Petri net, nonprimitive events are visualized as a rectangle, making it possible to simplify some types of Petri nets.

When switching from an IDEF0 diagram to a Petri net, the functional block of the diagram is replaced with a Petri net fragment that emulates its operation. Places in the net are formed by various data streams and system objects that are subjected to the action, control data, mechanisms (actor or tools), and the result of the incoming streams being subject to the action. Let us utilize these terms to represent a colored timed Petri net describing a dynamic model of the monitoring process (Figure 2). Based on the functional model (Figure 1), the interconnection of the Petri net elements is described as follows: t_1 – collect information: $I(t_1)=\{p_1,\ p_2,\ p_3\}$ is an input function where p_1 is the information field; p_2 are the actors supporting the monitoring functions; p_3 are the software and hardware tools; $O(t_1)=\{p_4,\ p_2,\ p_3\}$ is an output function where p_4 is the collected information. t_2 – process information: $I(t_2)=\{p_4,\ p_2,\ p_3\}$, $O(t_2)=\{p_5,\ p_2,\ p_3\}$ where p_5 is the processed information; t_3 – display information: $I(t_3)=\{p_5,\ p_2,\ p_3\}$, $O(t_3)=\{p_6,\ p_2,\ p_3\}$ where p_6 is the visualized information; t_4 – ensure storage of information – this transition fires if there are tokens in one of the places: p_4, p_5, or p_6 and if there are tokens in the places p_2 and p_3: $I(t_4)=\{p_4,\ p_5,\ p_6,\ p_2,\ p_3\}$, $O(t_4)=\{p_7,\ p_2,\ p_3\}$, where t_7 is the archived information; t_5 – distribute information: $I(t_5)=\{p_7,\ p_2,\ p_3\}$, $O(t_5)=\{p_8,\ p_2,\ p_3\}$ where p_8 is the result of the monitoring.

As a result, we have constructed a free-choice colored timed Petri net. The position p_4 of the net can have different meanings (depending on the color of its marking), making it possible to use it to fire various transitions: if p_4 describes information that requires further processing, then the information proceeds to the input of the transition t_2; if p_4 describes information that requires security (without additional processing), then such information proceeds to the input of the transition t_4. Similarly, a variety of characteristics can be assigned to the position p_5: if p_5 describes processed information that needs to be visualized, then the information proceeds to the input of the transition t_3; if p_5 contains information that requires security (without visualization), then such information proceeds to the input of the transition t_4

Modern software designed to emulate the operation of a colored timed Petri net (e.g., Design/CPN) makes it possible, through manipulation of the net's timed components and changes in the number and color of tokens in places, to simulate various situations that occur in the process of monitoring. For example, a company manager responsible for monitoring can, using the dynamic model, allocate the human resources and the timing budget to perform a specific task depending on the volume of information collected, the time required for processing and the types of the actors supporting the monitoring functions.

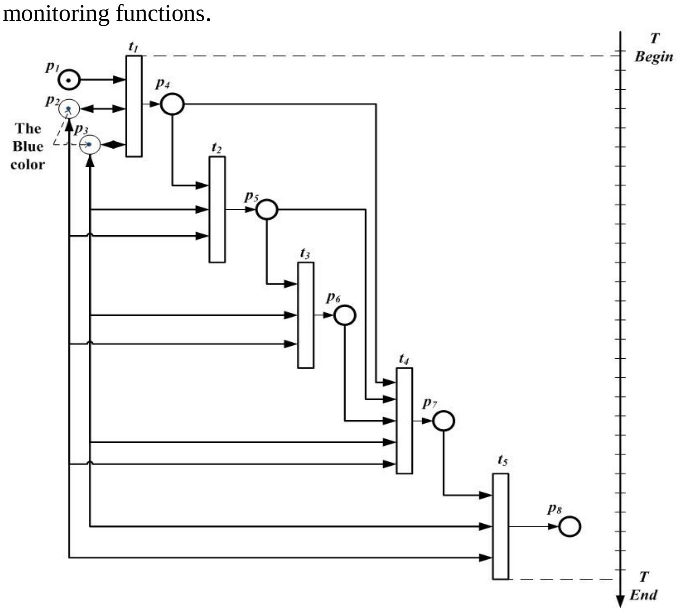

Figure 2. Petri net describing a generalized monitoring process

The timed component of the net τ_i carries an important meaning. For example, the start time of the transition t_3 depends directly on the duration of collection and processing of information – the transitions

t_1 and t_2. And, finally, the transition t_5, will only fire after the tasks at the preceding transitions have been completed and tokens have appeared in the places p_7, p_2 and p_3, if necessary, dynamic simulation can be run for all stages of the generalized monitoring process. Such Petri nets will essentially be decompositions of the corresponding transitions in the basic net.

4. MONITORING OF ENTITY OPERATIONS IN THE SMALL AND MEDIUM ENTERPRISES SUPPORT INFRASTRUCTURE

The above structural-functional and dynamic models have served as the underlying element for an Information technology (IT) solution for monitoring of operations of entities integrated in the small and medium enterprise (SME) support infrastructure in Tomsk region. The development of such IT solution is driven by the need to assess the efficiency of allocation and application of funding and other resources (including state-granted resources) committed to developing a favorable environment for SME, facilitating effective cooperation between SME and business entities in other Russian regions and international partners, and developing a favorable investment climate in Tomsk region.

The IT solution for monitoring is based upon a distributed model of interaction between the support infrastructure organizations and the SME Development Fund of Tomsk Region whose responsibilities include centralized collection and analysis of monitoring data. The model makes it possible for local experts to enter the input data through remote access, and for the Fund employees to keep centralized records of all data for further analytics delivery to the regulatory authorities. Figure 3 shows a generalized functional diagram of the IT solution.

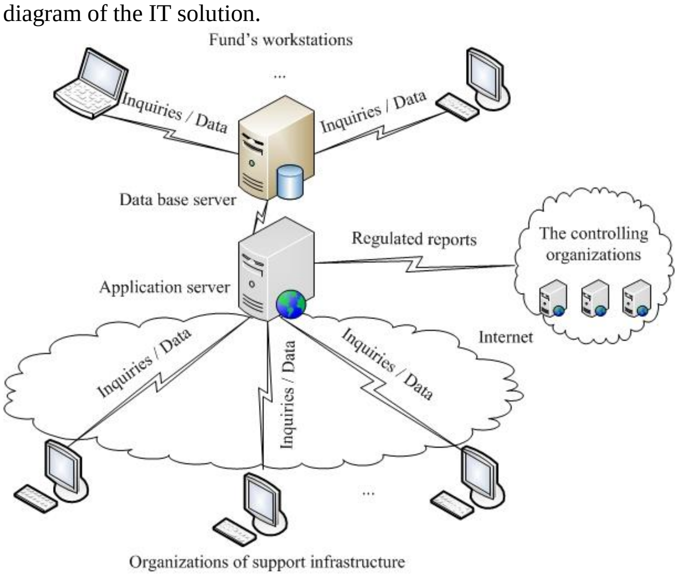

Figure 3. Generalized functional diagram of the IT solution for monitoring

The following functional objectives are addressed with the IT solution-based software (system):

- generation of the input data from the monitoring information filed and storage of the input data: a list of organizations within the entrepreneurship support infrastructure; a list of types of support associated with specific entities within the entrepreneurship support infrastructure; records of applications (from SME of Tomsk region); primary data on applicants, stored and maintained in a database;
- processing, display and presentation of monitoring results: user access to primary data on applicants and all personalized applications registered in the system; information on the number of SME granted government support (total); information on the SME granted government support, activity-specific; information on the types of support granted to each SME; records on the measures implemented by the organizations within the SME support infrastructure, total, activity-specific and organization-specific; summarized information on the number of jobs supported in SME; various summarized information on consulting services provided by users to SME in Tomsk region;
- support of system operations: regulation of access and functionality of the System; registration of user groups in the System; creation of new users connected to one of several organizations; designation of user authority; prioritization of user organizations and utilization of user organization priorities in application forms; authorization to collect summarized monitoring data on all organizations; user activity audit.

The monitoring results are delivered in digital and hard copies to the regulatory authorities and the founder of the SME Development Fund of Tomsk Region, the State Property Fund of Tomsk Region. Adoption of the above IT solution for monitoring has helped optimize the process of data collection, analysis and control for all types of support granted to SME in Tomsk region and, ultimately, accelerate the delivery of monitoring results. This effect was reached as a result of implementation of the rules of carrying out the monitoring determining its procedural and material bases. Setting standards and their binding to the methods of stimulation increased the level of coherence of the processes of participants by 15%, which was determined by timing.

5. CONCLUSION

The structural-functional and dynamic models discussed in this paper can be used as a basis for problem statement and development of software solutions designed to facilitate state and municipal authorities in monitoring of social and economic development of municipalities, technological and natural processes (e.g., condition of utility systems, anthropogenic effect on regional environment, occurrence, development and spread of diseases of various origin, etc.).

The mathematical tools of Petri nets used in simulation of the above task can be helpful in the process of monitoring, serving as an auxiliary instrument for the individuals responsible.

Emulation of a Petri net (Figure 2) with additional places and transitions for solution of specific problems allows the manager to determine the quality, quantity and workload of actors engaged in the monitoring process. When used in the decision-making process, the simulation results offer an additional ground for the manager's decisions in monitoring.

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