Models of Information Processing Optimization for Technical Interoperability in a Network of Distributed Situational Centers

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Abstract. The problems and directions of development of distributed information services of situational systems are considered. A method for assessment the interoperability of distributed situational centers is proposed. The urgency of creating a network of distributed situational centers based on convergent technological solutions is substantiated. Models and algorithms for providing technical interoperability between participants of the process of situational management in the network of distributed situational centers have been developed. The potential for further improvement of situational management systems for strategic planning based on the management (control) of the capabilities of the target systems is shown.

Keywords: system of situational management, network of distributed situational centers, convergence of information technologies, interoperability optimization, system capability

1 Introduction

An urgent issue for the development of information technologies and systems is the task of creating a Network of Distributed Situational Centers (NDSCs) based on convergent technological solutions. In this regard, it is of particular importance to develop information services for information and analytical systems based on NDSCs to support and make decisions at different levels of state governance. Developing and implementing into practice the system of situational centers (SC) for solving public administration tasks is an integral part of the creation of effective governance systems for different levels of the country's economic complex.

Standard ISO/IEC 10746 [1] defines the essential concepts necessary to specify reference model of open distributed processing (RM-ODP) systems from five prescribed viewpoints. It provides a well-developed framework for the structuring of specifications for large-scale, distributed systems.

The framework for system specification provided by ISO/IEC 10746 has four fundamental elements:

- An object modeling approach to system specification;
- The specification of a system in terms of separate but interrelated viewpoint specifications;
- The definition of a system infrastructure providing distribution transparencies for system applications;
- A framework for assessing system conformance.

The RM-ODP framework provides five generic and complementary viewpoints on the system and its environment:

- The enterprise viewpoint, which focuses on the purpose, scope and policies for the system. It describes the business requirements and how to meet them;
- The information viewpoint, which focuses on the semantics of the information and the information processing performed. It describes the information managed by the system and the structure and content type of the supporting data;
- The computational viewpoint, which enables distribution through functional decomposition on the system into objects, which interact at interfaces. It describes the functionality provided by the system and its functional decomposition;
- The engineering viewpoint, which focuses on the mechanisms and functions required to support distributed interactions between objects in the system. It describes the distribution of processing performed by the system to manage the information and provide the functionality;
- The technology viewpoint, which focuses on the choice of technology of the system. It describes the technologies chosen to provide the processing, functionality and presentation of information.

In context of ISO/IEC 10746 standard interoperability notion is defined as capability of objects to collaborate, that is, the capability mutually to communicate information in order to exchange events, proposals, requests, results, commitments and flows [2].

2 Formal statement of the problem

When implementing the information-analytical process of information processing during the alternatives preparation and decision-making in NDSC, there is rising the task to administrate the sequence of information processing and control flows such that the system of the SC associated with one same problem could provides the necessary level of interoperability in the processes of information, analytical and expert servicing for participants of situation management processes (PSMP) at a minimum cost of time. The PSMP set includes experts, analysts, decision-makers, and other involved stakeholders and sites. The information and analytical process is formed in the form of an application that determines the need for information resources and analytical and expert capabilities and time of service of each SC. The convergent approach involves the composition of heterogeneous components in a single system [3], ensuring compliance with 12 basic interoperability principles [4]: 1) subsidiarity and proportionality; 2) openess; 3) transparency; 4) reusability; 5) technological neutrality and data partability; 6) user-centricity; 7) inclusion and accessibility; 8) security and privacy; 9) multilingualism; 10) administrative simplification; 11) preservation of information; 12) assessment of effectiveness and efficiency.

These basic principles are divided into the following 4 categories:

- Principle setting the context for governance actions on interoperability (1st principle);
- Core interoperability principles (2nd to 5th principles);
- Principles related to generic user needs and expectations (6th to 9th principles);
- Foundation principles for cooperation among public administrations (10th to 12th).

A heterogeneous network of SCs is considered. Let M be the set of users (PSMP) of NDSC; n is the number of SCs (in our case, $|M| > n$, that is, multi-user and content-different nodes of monitoring and analysis of the information being processed (economic, environmental, military, etc.); c_k is estimation of the k-th user information needs ($k \in M$); R_i is the bandwidth estimation of the i-th SC of the NDSC; P_{ij} – the flow of information redistribution among i-th and j-th SCs ($i, j=1,2,\ldots,n$) in the network; q is the maximum permissible information flow among two SCs.

We introduce a variable

$$x_{ki} = \begin{cases} 1, \text{if the } k-\text{th user is served by the } i-\text{th SC of the NDSC}, i = 1,...,n \\ 0, \text{otherwise} \end{cases}.$$

The formalized view of the model for actual loading H_i of the i-th SC (i=1,2,…,n) in NDSC during of user's servicing in NDSC is as follows:

$$H_i = \max_i \sum_{k \in M} c_k x_{ki} \to \min, \tag{1}$$

$$\sum_{k \in M} c_k x_{ki} \le R_i, i = 1,2,...,n, \tag{2}$$

$$\frac{1}{M} \sum_{i=1}^{n} x_{ki} \le 1, k \in M, \tag{3}$$

$$P_{ij}(x_{ki}, x_{kj}) \le q; k \in M; i \ne j; i, j = 1,2,...,n. \tag{4}$$

Condition (2) expresses the limitation on bandwidth information of the i-th SC, condition (3) is a requirement of obligatory service of all users (PSMP) and belonging of the user to the service group of local SC, condition (4) regulates the service flows between users (PSMP) of NDSC .

The problem in statement of (1) - (4) is the problem of zero-one integer programming (Boolean integer programming). To solve problem (1) - (4), an algorithm is proposed that implements the search method with local optimization [5], which allows one to obtain a solution of problem (1) - (4) with acceptable accuracy for practical operation of the NDSC.

3 Literature review

The problem of efficient distribution of tasks in automated computer systems (ACS) network was considered in other works by Glushkov [6], Morozov [7] and others. NDSC is a development and extension of the concept of ACS network to date. One of the key mechanisms for the effective functioning of NDSC is to ensure interoperability among its constituents.

According to the definition of interoperability in accordance with ISO/IEC 24765 [2] and the interoperability framework (EIF) adopted at the EU [4], the basic level of interoperability is technical interoperability (Fig. 1).

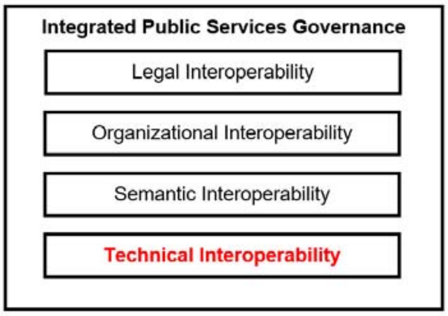

Fig. 1. Four levels of interoperability

On the basis of the EIF [4] the European Interoperability Reference Architecture (EIRA) was developed [8]. Various aspects of interoperability have been considered in [9-13].

4 Models of optimization of technical interoperability

4.1 Model of optimization of loading of NDSC

The paper proposes models and algorithms for providing technical interoperability between PSMPs in NDSC. Consider the problem of PSMP service in a distributed system, which can consist of several local (regional) SCs and aimed at solving various content problems. As a rule, when organizing the interaction of many SCs, appropriate expert assessments and calculations of their loading are conducted in order to serve the needs of the PSMP in a timely manner. However, over time, uploads can change significantly (for example, through the introduction of new tasks and management information flows), and NDSC will not be able to meet PSMP requirements at the right time and volume. The challenge is to redistribute the load of NDSC in order to ensure a uniform load on organizational, human and technical and information resources for timely and qualitative decision-making in SCs that cater to PSMPs at various levels.

The outputs for solving problem (1) - (4) are formed in the form of matrix A. The rows of the matrix represent the estimation of information needs of PSMPs served by the NDSC. The columns of matrix A are the actual loading of the NDSC, i.e. H_i (i=1,2,…,n).

The algorithm for solving the problem of customer service in NDSC is presented in the form of the following five steps.

Step 1. If all the columns of matrix A are revised, then proceeds to step 5. Otherwise go to the next step. In the analysis, matrix A is searched for the column with the maximum sum of rows, that is, with the maximum load of a specific SC. Let such a column be the column i. The next step is to fix an area of three columns i, i+1, i–1 (i=1,2, ...,n). If i + 1 or i–1 do not exist (for finite elements), then the column i neighborhood will be truncated.

Step 2. In the i-th column there is a non-zero element $c_k x_{ki}$ and the possibility of shifting this element to the right or left according to conditions (2) - (4) is checked. If such shifts are possible, they are executed. To remember the movements of elements of matrix A in the next step of the algorithm (in order to determine possible movements in the next step) is an auxiliary matrix B, which elements are numbers from the set (–1, 0, 1). Initial values of matrix elements are equal 0. When moving the element $c_k x_{ki}$ to the location of the element $c_k x_{ki-1}$, the e_{ki} element of the matrix B takes a value of –1, when moving the $c_k x_{ki}$ to the location $c_k x_{ki+1}$ the e_{ki} element takes the value +1, otherwise the value of the e_{ki} element remains equal to 0. If the following iterations of the algorithm necessitate the displacement of some element $-c_k x_{ki-1}$ of matrix A in place of the element $c_k x_{ki}$, and the element $-e_{ki}$ of matrix B has a value of –1, as well as the need to move the element $-c_k x_{ki+1}$ of matrix A to the location of the element $c_k x_{ki}$, and element $-e_{ki}$ of matrix B is +1, then these movements are not made and go to row k +1 of matrix A.

Step 3. In this step, check which of the three options (original and two received) gives the best result by criterion (1). If the shift was possible only to the left or only to the right, then both variants are subject to verification – initial and obtained. If, at the m-th iteration, it is found that $H_i^m=H_i^{m-1}$, then the process is completed and H^m is taken as an approximate solution for column i. The corresponding changes are made to matrix A, matrix B and vector $H = \{H_i\}$ (i=1,2,...,n). Thus, the i-th column is excluded from consideration and proceeds to step 1 of the algorithm. Otherwise, step 4 is performed.

Step 4. Go to row k+1 of matrix A and step 2 of the algorithm. If all rows was reviewed, then the process ends, the value of H_i^k is taken as an approximate solution for the problem with resolved column i and the corresponding changes are made to matrix A, matrix B and vector $H = \{H_i\}$ (i=1,2,...,n). Thus, the i-th column is excluded from consideration and step 1 of the algorithm is performed.

Step 5. After all the columns of matrix A have been revised, the solution of problem (1) - (4) ends. A new pin has been obtained for users in the local SC.

The above algorithm for solving problem (1) - (4) of servicing the PSMP in the NDSC is finite due to the finite number of SCs in the network.

The results for the 9-node loading redistribution algorithm for the first 5 iterations are presented in Fig. 2. The graph number in the diagram corresponds to the iteration number. The horizontal axis shows the numbers of the NDSC nodes, along the vertical axis the volume of nominal information flow for a specific decision making on a given problem, which should be processed within the regulated time limit.

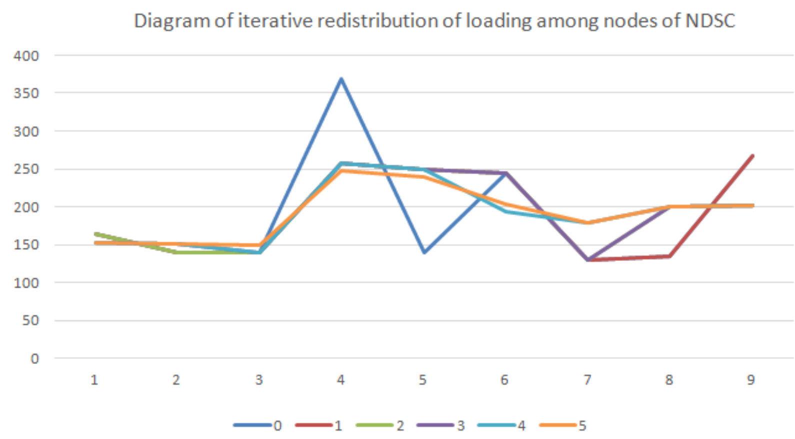

Fig. 2. Results for 5 iterations of loading redistribution for NDSC with 9 nodes

Thus, the algorithm for solving the problem (1) - (4) of optimization of loading for NDSC based on zero-one programming allows to increase qualitatively the level of information service of users in the NDSC and thereby to increase the efficiency of its functioning. This example is a prototype of PSMP servicing in NDSC by different criteria and experts assessments in the relevant monitoring and analysis areas stored in distributed data warehouses.

4.2 Model of minimization of servicing time in NDSC

When implementing the information-analytic process of information processing for downloading the corresponding SC, the task of managing the sequence of processing of information and control flows arises, so that the complex of SCs provides the maximum convenience of information, analytical and expert service to users (PSMP) with the minimum time consuming [7]. Such a problem is dual to the primal problem discussed above. The information-analytical process is formed as request that defines the need for information resources and analytical and expert capacities and time of service in each local SC. Such a task is formulated as follows.

Consider the common distributed information resource of the NDSC, which exists in n SCs $A_1, A_2,..., A_n$, which can provide various information, analytical, expert or forecast (foresight) services. The SC system executes some request for information, analytical or expert service for PSMP. An request is considered serviced if it is serviced by each local system SC sequentially, starting with SC of A_1. Suppose that the time of service of an application in the i-th SC is an independent random variable with a distribution function $F^i(t)$ and a distribution density $\varphi_t(t)=F^i(t)$. The system works like this. The request is serviced at SC A_1 as soon as it arrives. At the time of arriving of request to SC A_2 there are two possible cases:

1) the application was serviced by SC A_1 earlier than SC A_2 was involved and is awaiting response from SC A_2. This pays some fine for a delay of request servicing;

2) the application was serviced by SC A_1 later than the request was sent to SC A_2, that is, SC A_2 is awaiting the completion of servicing of the request in SC A_1. In this case a fine is paid for a delay of SC A_2. In this way, interaction between other SCs is performed.

Obviously, the fine f_i is a random variable. It is necessary to determine such moments $x_1, x_2, ..., x_n$ of switching on of SCs $A_2, A_3, ..., A_n$, that the mathematical expectation of the total fine (penalty) equal to the sum of fines paid due to the discrepancy of moments x_i of switching on of the i-th SC with the moment η_{i-1} of termination of service of the request in the i-th SC was minimal.

Let α be the unit cost of idle time of request and let β be the unit cost of idle time of Situational Center. Then the penalties related to the discrepancy between moments x_i of switching on and moments η_{i-1} of termination of service of the application in (i–1)-th SC are determined as follows:

$$f_1(\eta_1, x_2) = \begin{cases} \alpha(x_2 - \eta_1), \eta_1 \le x_2 \\ \beta(\eta_1 - x_2), \eta_1 \ge x_2 \end{cases}, \tag{5}$$

where $\eta_1 = \tau_1$,

$$f_2(\eta_2, x_3) = \begin{cases} \alpha(x_3 - \eta_2), \eta_2 \le x_3 \\ \beta(\eta_2 - x_3), \eta_2 \ge x_3 \end{cases}, \tag{6}$$

where $\eta_2 = \max(\eta_1, x_2) + \tau_2$,

$$f_{n-1}(\eta_{n-1}, x_n) = \begin{cases} \alpha(x_n - \eta_{n-1}), \eta_{n-1} \le x_n \\ \beta(\eta_{n-1} - x_n), \eta_{n-1} \ge x_n \end{cases}, \tag{7}$$

where $\eta_{n-1} = \max(\eta_{n-2}, x_{n-1}) + \tau_{n-1}$,

$$Mf_1(\eta_1, x_2) = (\alpha + \beta)\int_0^{x_2} F(u_1)du_1 + \beta(M_{\tau_1} - x_2), \tag{8}$$

$$\begin{aligned} Mf_2(\eta_2, x_3) &= (\alpha + \beta)\int_{x_2}^{x_3}\left(\int_{x_2}^{u_3} F(u_1)\varphi_2(u_2 - u_1)du_1 + \beta(M_{\tau_1} - x_2)\right)du_2 + \\ &+ \beta\left(M_{\tau_1} + M_{\tau_2} + \int_0^{x_2} F(u_1)du_1 - x_3\right) \end{aligned}, \tag{9}$$

$$Mf_3(\eta_3, x_4) = (\alpha+\beta)\int_{x_3}^{x_4}\left(\int_{x_3}^{u_3}\left(\int_{x_2}^{u_2} F(u_1)\varphi_2(u_2-u_1)du_1\right)\varphi_3(u_3-u_2)du_2\right)du_3 + \\ +\beta\left(M_{\tau_1}+M_{\tau_2}+M_{\tau_3}+\int_0^{x_2}F(u_1)du_1+\int_{x_2}^{x_3}\left(\int_{x_2}^{u_2}F(u_1)\varphi_2(u_2-u_1)du_1\right)du_2 - x_4\right), \tag{10}$$

$$Mf_{n-1}(\eta_{n-1}, x_n) = (\alpha+\beta)\int_{x_{n-1}}^{x_n}\left(\ldots\left(\int_{x_2}^{u_2} F(u_1)\varphi_2(u_2-u_1)du_1\right)\ldots\right)du_{n-1} + \\ +\beta\left(M_{\tau_1}+\ldots+M_{\tau_n}+\int_0^{x_2}F(u_1)du_1+\int_{x_{n-2}}^{x_{n-1}}\left(\ldots\left(\int_{x_2}^{u_2}F(u_1)\varphi_2(u_2-u_1)du_1\right)\ldots\right)du_{n-2} - x_n\right). \tag{11}$$

The total fine is equal

$$F(x) = \sum_{i=2} Mf_{i-1}(\eta_{i-1}, x_i) \tag{12}$$

The use of the classical approach to minimize the function $F(x)$ is due to the need to calculate multiple integrals and the value of the laws of distribution $F_i(t)$, which is not always possible. However, these difficulties can be eliminated by using methods of stochastic programming [14], in terms of which we formulate the problem. The problem is to find the minimum of function

$$F(x) = Mf(\eta, x) \tag{13}$$

under condition

$$x_{i+1} \geq x_i \geq 0,\ i = 2,3,\ldots, n\ , \tag{14}$$

where

$$f(\eta, x) = \alpha\sum_{i\in I}(x_i - \eta_{i-1}) + \beta\sum_{j\in J}(\eta_{j-1} - x_j) \tag{15}$$

moreover

$$\eta_i = \max(\eta_{i-1}, x_i) + \tau_i, i = 2,3,\ldots,n\ .$$

We note that function (15) is convex with respect to x_i for fixed η_{i-1}.

Problems (13) - (15) are a special case of the stochastic programming problem. To solve them, a stochastic quasi-gradient projection method [14] can be used, which is described by the procedure

$$x_i^{s+1} = \pi_x\left(x^s - \rho_s W_i^s\right), s = 0,1,\ldots,i; i = 2,3,\ldots,n\ , \tag{16}$$

where s is the iteration number; X is the projection area intersected by the constraints of (14); $\pi_x(\bullet)$ is an operator that maps each point $x \in R^{\pi}$ to a point $\pi_x(x) \in X$ so that $\|x - \pi_x(x)\|^2 \leq \|y - x\|^2$ for any $y \in X$; ρ_s is a step multiplier; W_i^s is a random vector such that $M\left(W_i^s \middle| x_i^0, x_i^1, ..., x_i^s\right) = F_x^A\left(x_i^s\right), s = 0,1,...,i; i = 2,...,n$, where $F_x^A\left(x_i^s\right)$ is the gradient (generalized gradient) of the function $F(x)$. The sequence $\left\{x_i^s\right\}, s = 0,1,...,i$, conditioned by procedure (16), converges with probability 1 to the solution of problems (13), (14).

The computational scheme for solving the problem is formalized as follows. Let x^s be given on the s-th iteration (initial x^0 is given). The following steps are required to obtain the $(s + 1)$-th approximation.

Step 1. Observe the implementation of x_i^s of the value x_i.

Step 2. Calculate the vector W_i^s.

Step 3. As a result of performing a design operation on the area $X = \{x_i : x_i \geq x_{i-1} \geq 0\}$, the following approximation is determined as follows:

$$x_i^{s+1} = \max\left(0, \max\left(x_{i-1}^s; x_i^s - \rho_s W_i^s\right)\right), s = 0,1,...,i; i = 2,3,...,n .$$

The above algorithm is easy to implement and does not depend on the type of law of distribution of random service time of the PSMP application.

It is convenient to use the value of the smoothed mean

$$Z^{s+1} = Z^s + 1/W^s\left(f\left(\eta^s, x^s\right) - Z^s\right),$$

which is an estimate of the mathematical expectation of a random function $f\left(\eta^s, x^s\right)$.

The algorithm defined for managing the load on the SC is thus an effective tool for managing the NDSC in order to provide maximum convenience in the implementation of information, analytical and expert services to PSMP with minimization of information processing time.

5 Conclusion

Proposed models allow to solve the problems of technical interoperability in terms of ensuring efficient loading and minimizing the time of servicing applications in distributed information systems by resolving the primal and dual problems of mathematical programming.

To resolve the primal problem, the use of the zero-one integer programming method is justified and an algorithm for its implementation is proposed. To resolve the dual problem, the use of stochastic programming method is justified and an algorithm for its realization is proposed. The algorithm defined for managing the load on the SCs is thus an effective tool for managing the NDSC in order to provide maximum convenience in the implementation of information, analytical and expert services to PSMP with minimization of information processing time.

Proposed models of technical interoperability support and algorithms for managing the information and analytical environment of NDSC create opportunities for further improvement of systems for strategic planning based on the capabilities management of complex situational systems.

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