Polish Academy of Sciences
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Faculty of Production Engineering

ECONTECHMOD

AN INTERNATIONAL QUARTERLY JOURNAL ON ECONOMICS IN TECHNOLOGY, NEW TECHNOLOGIES AND MODELLING PROCESSES

Vol. 4, No 3

LUBLIN–RZESZÓW 2015

All the articles are available on the webpage:
http://www.pan-ol.lublin.pl/wydawnictwa/Teka-Motrol.html

ISSN 2084–5715

All the scientific articles received positive evaluations by independent reviewers

Linguistic consultant: *Mikhail Suknov*
Typeset: *Tetiana Serhiienko, Adam Niezbecki*
Cover design: *Hanna Krasowska-Kołodziej*

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Edition 200+16 vol.

ECONTECHMOD. AN INTERNATIONAL QUARTERLY JOURNAL – 2015, Vol.4, No.3, 3-12

ABOUT ONE PROBLEM OF OPTIMAL STOCHASTIC CONTROL OF THE MODES OF OPERATION OF WATER MAINS

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Received June 19.2015: accepted August 04.2015

Abstract: The problem of increasing of the efficiency of operation of the water mains in modern conditions while the transition to a three-tier tariff for the electricity is examined in the present work. An effective method for solving this problem, based on the use of specific features of the water mains as stochastic objects operating in the stochastic environment is offered. The mathematical formulation of the problems of optimal stochastic control of the modes of operation of the water main with probabilistic constraints on the phase variables is presented. A new strategy for the optimal stochastic control of the modes of operation of the water main, the use of which has allowed to develop an effective method for solving the examined problem is proposed in the present work. It is shown that the transition from the classical deterministic problems of control of the modes of operation of the water mains to stochastic ones, provides a significant (up 9%) decrease of financial expenses for the electricity.

Key words: optimal stochastic control, probabilistic constraints on the phase variables, water main, pumping station.

INTRODUCTION

A water main (WM) is a complex technical system designed to transport water over long distances. WM consists of the sequence of multishop pumping stations (PS) and multiline main pipelines. [1] There are clean-water reservoirs (CWR) at the entrance of each PS. In CWR of the first PS of WM prepared water is supplied from one or several ascents. At the exit of WM, as a rule, there are CWR of large capacity used as the sources of water supply for cities and towns [10, 11, 12].

The main controlled elements of WM are pump units (PU) of PS. Each shop of PS is represented by several connected in parallel PU. Control of the operation of PU is carried out by switching on / off PU of PS, by changing the position of the adjustable valve (AV), by adjustable speed control of the drive motors of PU. Control of the operation of WM is carried out by changing the modes of operation of PS [5, 10, 13].

The actuality of the problem. Spur increase of electricity tariffs and the introduction of a three-tier tariff created necessary conditions for the transition to energy-saving technologies of WM control.

The purpose of this work is the development of a method of optimal stochastic control of the modes of operation of WM, the implementation of which provides a significant reduction in financial expenses for the electricity.

To develop more adequate mathematical models of the modes of operation of WM and more effective account of the specific features of WM as an object of control, WM is considered as a stochastic object operating in the stochastic environment. The presence in WM of CWR of sufficiently large capacity is such specific feature. The use of this feature of WM allows to build the strategy for optimization of the modes of its operation, based on the maximum possible use of the whole capacity of the reservoirs. The main point of this strategy is that the water supply into CWR from WM must be minimal at the time interval with the maximum rate and maximum at the time interval with the minimum rate. Using of such a strategy leads to the need in introduction of additional extreme constraints on the phase variables (water levels in CWR): by the time of the transition of the tariff for the electricity from smaller to larger - the mathematical expectations of water levels in CWR should be maximum possible, and before the start time of the minimum rate, the mathematical expectations of water levels in CWR should be minimal. Moreover, to prevent the occurrence of accidents at any time intervals $t \in [0, T]$ the probability of overflow or emptying of the reservoirs must be close to zero.

The application of this strategy has led to the need to develop problems of optimal stochastic control of the modes of operation of WM with extreme and probabilistic constraints on the phase variables of a new class.

THE MATHEMATICAL FORMULATION OF THE PROBLEM

The main criterion of the effectiveness of the operation of WM is the value of the mathematical expectation of the total cost of the electricity consumed by all PS at a predetermined interval of operation [0, T], on condition that WM provides water to all consumers in the required (predicted) volumes.

For the formulation of the problem of optimal stochastic control of the modes of operation of WM we will use the stochastic model of quasi-stationary modes of operation of water supply and water distribution systems [19 - 23].

Hydraulic resistances of the sections of water main are unknown a priori, so they are estimated according to the experimental data. As the evaluation is carried out on samples of the experimental data of the final length, these estimations are random variables, statistical properties of which depend both on the statistical properties of the errors of flow measurement q and water head h, and the estimation method and sample size. It is supposed that the errors of measurement of the variables h and q are normally distributed random variables. As the method of estimating, the maximum probability method is used, so the obtained estimates of random variables $S_i(q_{ik}(\omega))$, $(i = 1,\ldots, v + \eta_2 + \xi_1 - 1)$ are unbiased, efficient, having normal distribution.

The initial data for the problem of optimal stochastic control of the modes of operation of WM are the interval of control [0, T] (one day), which is divided into 24 subintervals corresponding to each hour of the period of control k = 0, ..., 23. At each k subinterval of the time the predictions of consumption of all consumers of WM are known in the form of conditional mathematical expectations $\overline{q}_{i0}(l) = \underset{\omega}{M}(q_{il}(\omega))$ and their variances $\sigma^2_{q_{i0}}(l) = \underset{\omega}{D}(q_{il}(\omega))$, calculated at the time interval k=0 proactively l=1,2,…,23; the prediction of daily water consumption from CWR $\overline{q}_{zvihl}(l) = \underset{\omega}{M}(q_{zvihl}(\omega))$, the measured values of the water level in the z CWR $H_{zk}(\tilde{\omega})$; the actual number of switched PU, and static data: the structure of WM, lengths, diameters, geodesic marks of the sections of the pipeline, the estimates of the parameters of the model of PU on each PS, the physical size of CWR, the estimates of hydraulic resistance of AV on each PS.

The objective function of the problem of optimal stochastic control of the modes of operation of WM per day we can present as the mathematical expectation of the total value of the electricity consumed by all PS of WM at the interval of control [0, T]:

$$\underset{\omega}{M}\sum_{k=0}^{23}\sum_{i=1}^{n}\sum_{j=1}^{m_i} N_{ijk}(q_{ik}(\omega))\cdot r_k \to \min_{u(k)\in\Omega}. \tag{1}$$

The area of restriction Ω is determined by the stochastic model of quasi-stationary modes of water supply [7, 8, 23]:

$$\underset{\omega}{\mathrm{M}}\left(h_{rk}(q_{rk}(\omega)) + \sum_{i\in L} b_{1ri} h_{NAik}\ (q_{ik}(\omega)) + \sum_{i\in R} b_{1ri} h_{RZik}\ (q_{ik}(\omega)) + \sum_{i\in M} b_{1ri} h_{ik}\ (q_{ik}(\omega))\right) = 0,$$
$$(r = v,\ldots,v+\eta_2-1;\quad k = 0,...,23), \tag{2}$$

$$\underset{\omega}{\mathrm{M}}\left(h_{NSjk}(\omega) - H_{zk}(\omega) - h_{NAjrk}(q_{rk}(\omega)) + h_{RZjrk}(q_{rk}(\omega)) + \sum_{i\in M} b_{1ri}(h_{ik}(q_{ik}(\omega)) + h_i^{(g)})\right) = 0,$$
$$(j = 1,...,n;\ r = 1,\ldots,\ \mathrm{m};\ z = 1,...,Z). \tag{3}$$

$$q_{ik}(\omega) = \underset{\omega}{\mathrm{M}}\left(\sum_{r=v}^{v+\eta_2-1} b_{1ri} q_{rk}(\omega) + \sum_{r=v+\eta_2}^{e} b_{1ri} q_{rk}(\omega)\right),$$
$$\left(i = 1,\ldots,v-1\right), \tag{4}$$

$$q_{ik}(\omega) > 0,\quad i\in L. \tag{5}$$

$$h_{ik}(q_{ik}(\omega)) = sgn\, q_{ik}(\omega) S_i(\omega) q_{ik}^2(\omega),\quad i\in M, \tag{6}$$

$$h_{NAik}(q_{ik}(\omega)) = a_{0i}(\omega) + a_{1i}(\omega) q_{ik}(\omega) + a_{2i}(\omega) q_{ik}^2(\omega),\quad i\in L, \tag{7}$$

$$\eta_{NAik}(q_{ik}(\omega)) = d_{0i}(\omega) + d_{1i}(\omega) q_{ik}(\omega) + d_{2i}(\omega) q_{ik}{}^2(\omega),\quad i\in L, \tag{8}$$

$$N_{NAik}(q_{ik}(\omega)) = \frac{9{,}81\cdot h_{NAik}(q_{ik}(\omega))\cdot q_{ik}(\omega)}{0{,}9\cdot \eta_{NAik}(q_{ik}(\omega))},\quad i\in L, \tag{9}$$

$$h_{RZik}(\mathrm{q}_{ik}(\omega)) = \frac{\mathrm{q}_{ik}(\omega)\mathrm{C}_i(\omega)}{\mathrm{E}_{ik}^2},\quad \mathrm{i}\in \mathrm{R}, \tag{10}$$

and the models of reservoirs

$$H_{zk}(\omega) = H_{zk-1}(\omega) + c_{zk}(q_{zvhk}(\omega) - q_{zvihk}(\omega)),$$
$$(z = 1,...,Z), \tag{11}$$

with probabilistic constraints on the phase variables:

$$P\left(H_{zk}(\omega) \le H_z^{\max}\right) \ge \alpha,$$
$$P\left(H_{zk}(\omega) \ge H_z^{\min}\right) \ge \alpha,$$
$$\alpha \approx 0{,}97, \tag{12}$$

and extreme values of constrains for fixed time intervals k=6 and k=23:

$$\underset{\omega}{M}\{H_{z6}(\omega)\} \to \max_{q_{zvhk}\in\Omega},\ (\mathrm{k} = 0,\ldots,6), \tag{13}$$

$$\underset{\omega}{M}\{H_{z23}(\omega)\} \to \min_{q_{zvhk}\in\Omega},\ (\mathrm{k} = 0,\ldots,23), \tag{14}$$

where: $u(k)$ - vector of control which determines the amount of operating PU, the position of AV; $H_{zk}(\omega)$ - water level in z CWR at a given k time interval, $H_z^{\min}$ - minimum allowable water level in z CWR, $H_z^{\max}$ - maximum allowable water level in z CWR.

Random variables characterize: $q_{ik}(\omega)$ – water consumption on i section of the pipeline at k time interval; $h_{NSjk}(\omega)$ – water head at the output of PS, $h_{NAik}(q_{ik}(\omega))$ – water head of i PU. $S_i(\omega)$ – evaluation of the hydraulic resistance of i section of the pipeline ($i\in M$); $h_{RZik}(\mathrm{q}_{ik}(\omega))$ – evaluation of the head fall on i AV; $\eta_{NAik}(q_{ik}(\omega))$ – evaluation of the coefficient of efficiency of i PU; $a_{0i}(\omega), a_{1i}(\omega), a_{2i}(\omega), d_{0i}(\omega), d_{1i}(\omega), d_{2i}(\omega)$ – evaluations of the parameters of PU ($i\in L$); $C_i(\omega)$ – evaluations of the parameters of AV ($\mathrm{i}\in \mathrm{R}$); E_{ik} – rate of the opening of AV (E ϵ (0,1]); $h_i^{(g)}$ –geodesic mark of i section of the pipeline ($i\in M$), b_{1ri} – cyclomatic matrix element; $N_{NAik}(q_{ik}(\omega))$ - power rating of PU; n - number of PS; m - number of PU on the selected PS; $\underset{\omega}{M}\{\cdot\}$ - mathematical expectation of the random variable {.}.

For the solvability of the problem (1) - (14) for k=0 the predictions of the expenses as conditional mathematical expectations, calculated at time interval k=0, proactively l=1,2,…, 23 all incidental consumers $q_{ik}(l)$, receiving water from WM and final consumers $q_{jk}(l)$, receiving water from the reservoir at the output of WM must be known additionally; water levels in each z CWR – H_{z0}.

The problem of optimal stochastic control of the modes of operation of WM (1) - (14) belongs to the class of nonlinear problems of optimal stochastic control with discrete time [2, 3, 4, 9, 17, 18], and probabilistic constraints on the phase variables. There aren't any exact solutions of the problems of such a class nowadays. The approximate method of solving the examined problem by the transition from stochastic problem (1) - (14) to its deterministic equivalent the decision of which is carried out by the modified method of branches and bounds is presented in this work.

The cost of the electricity is determined by a three-tier tariff shown in Table 1.

Table 1. The electricity rate according to the hours

Hours	6.00-8.00	8.00-10.00	10.00-18.00	18.00-22.00	22.00-23.00	23.00-6.00
Coefficient	1,02	1,68	1,02	1,68	1,02	0,35

The deterministic equivalent of the problem of optimal stochastic control of the modes of operation of WM at the time interval [0, T] takes the form:

$$\sum_{k=1}^{24}\sum_{i=1}^{n}\sum_{j=1}^{m_i}\bar{N}_{ijk}(\bar{q}_{ik})\cdot r_k \to \min_{u(k)},\ k=0,...,23, \quad (15)$$

$$\bar{h}_{rk}(\bar{q}_{rk})+\sum_{i\in L}b_{1ri}\bar{h}_{NAik}\ (\bar{q}_{ik})+\sum_{i\in R}b_{1ri}\bar{h}_{RZik}\ (\bar{q}_{ik})+$$
$$+\sum_{i\in M}b_{1ri}\bar{h}_{ik}\ (\bar{q}_{ik})=0,$$
$$(r=v,\dots,v+\eta_2-1), \quad (16)$$

$$\bar{h}_{NSjk}-\bar{H}_{zk}-\bar{h}_{NAjrk}(\bar{q}_{rk})+\bar{h}_{RZjrk}(\bar{q}_{rk})+$$
$$+\sum_{i\in M}b_{1ri}(\bar{h}_{ik}(\bar{q}_{ik})+h_i^{(g)})=0,$$
$$(j=1,...,n;\cdots r=1,\dots,\ \mathrm{m}). \quad (17)$$

$$\bar{q}_{ik}=\sum_{r=v}^{v+\eta_2-1}b_{1ri}\bar{q}_{rk}+\sum_{r=v+\eta_2}^{e}b_{1ri}\bar{q}_{rk},\ (i=1,\dots,v-1), \quad (18)$$

$$\bar{q}_{ik}>0,\quad i\in L. \quad (19)$$

$$\bar{h}_{NAik}(\bar{q}_{ik})=\bar{a}_{0i}+\bar{a}_{1i}\bar{q}_{ik}+\bar{a}_{2i}\bar{q}_{ik}^2,\quad i\in L, \quad (20)$$

$$\bar{\eta}_{NAik}(\bar{q}_{ik})=\bar{d}_{0i}+\bar{d}_{1i}\bar{q}_{ik}+\bar{d}_{2i}\bar{q}_{ik}^{\ 2},\quad i\in L, \quad (21)$$

$$\bar{N}_{NAik}(\bar{q}_{ik})=\frac{9{,}81\cdot\bar{h}_{NAik}(\bar{q}_{ik})\cdot\bar{q}_{ik}}{0{,}9\cdot\bar{\eta}_{NAik}(\bar{q}_{ik})},\ i\in L, \quad (22)$$

$$\bar{h}_{RZik}(\bar{\mathrm{q}}_{ik})\ =\ \frac{\bar{\mathrm{q}}_{ik}\bar{\mathrm{C}}_i}{\mathrm{E}_{ik}^2},\quad \mathrm{i}\in\mathrm{R}, \quad (23)$$

$$\bar{h}_{ik}(\bar{q}_{ik})=sgn\,\bar{q}_{ik}\ \bar{S}_i\bar{q}_{ik}^2,\quad i\in M, \quad (24)$$

$$\bar{H}_{zk}=\bar{H}_{zk-1}+c_{zk}(\bar{q}_{zvhk}-\bar{q}_{zvihk}),\qquad (z=1,...,Z), \quad (25)$$

$$H_z^{-*}\le\bar{H}_{zk}\le H_z^{+*}\ ,\ (\mathrm{k}=1,2,...,23), \quad (26)$$

$$\bar{H}_{z6}\to\max_{q_{zvhk}\in\Omega},\qquad(\mathrm{k}=0,\dots,6), \quad (27)$$

$$\bar{H}_{z23}\to\min_{q_{zvhk}\in\Omega},\qquad(\mathrm{k}=0,\dots,23), \quad (28)$$

where: H_z^{-*}, H_z^{+*} - calculated values of the minimum and maximum water levels in z CWR, where for $\forall\omega\in\Omega$ probabilistic constraints will be fulfilled (12).

As a result of the solving the problem (15) - (28) of optimal stochastic control of the modes of operation of WM for each time interval k, we obtain:

1. vector of control $u(k)$ which, for each time interval k includes: the number of operating PU, the position of the operating point of each PU;
2. estimates of the mathematical expectations of water levels in all CWR;
3. estimates of the mathematical expectations of the expenses and pressure drops in all sections of the pipeline;
4. estimates of the mathematical expectations of the expenses for the electricity and its value in accordance with the three-tier tariff, by all the operating PU on all the PS of WM.

At the time interval k=23, we obtain the estimates of the mathematical expectations of the total value of the electricity consumed by each PS at the interval [0, T].

RESULTS AND DISCUSSION

The evaluation of the effectiveness of the proposed method was carried out for the WM, the structure of which is shown in Fig. 1.

The examined WM includes three pumping stations of the first ascent (PS11, PS12, PS13), three PS of the second ascent (PS21, PS22, PS23) and PS of the third ascent. PS of the second ascent PS21 and PS22 supply water to the PS of the third ascent, and PS of the third ascent and PS23 supply water into CWR5 and into the water supply of a city.

To solve the problem of optimal stochastic control of the modes of operation of WM, PS of the second and third ascents and CWR4 and CWR5 have been examined.

The initial data for the problem of optimal stochastic control of the modes of operation of WM at the time interval [0, T] are:

• static data including the structure of WM; lengths; diameters; geodetic marks of the sections of the pipeline; estimates of the parameters of the mathematical models of PU for each PS; estimates of the hydraulic resistances of AV on each PS; physical dimensions of each CWR;
• dynamic data, including the prediction of the daily water consumption from CWR5; the prediction of water consumption by incidental consumers of the city, by-passing CWR5.

PS of the second ascent PS21 and PS23 are equipped with four similar, connected in parallel PU with the same characteristics, PS22 and PS of the third ascent are equipped with five and seven similar PU with the different characteristics correspondingly. Approximated parameters of PU are shown in Table 2, passport characteristics of PU are in Fig. 2, Fig. 3. The net graph is shown in Fig. 4.

In Fig. 5 there is a diagram of the prediction of the process of hourly water consumption from CWR5 calculated at the time interval k=8 proactively l=1,…, 23 for each of seven days.

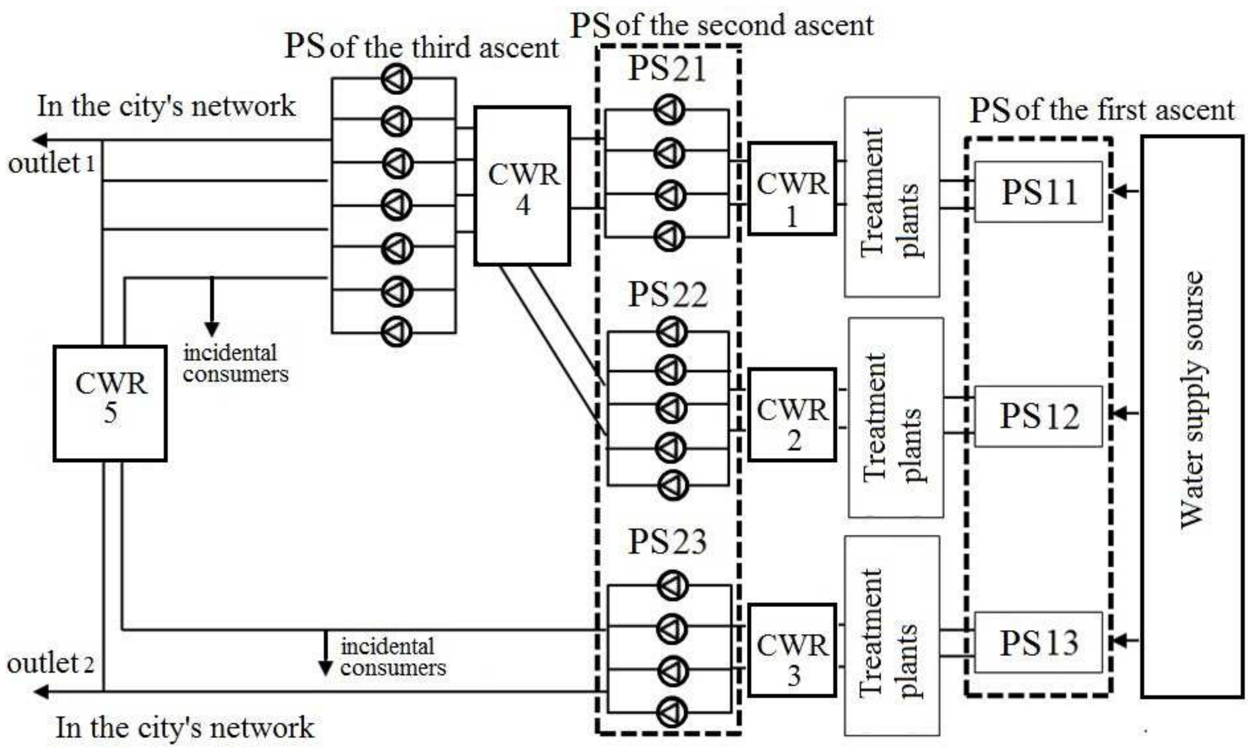

Fig.1. The structure of the water main

Table 2. The characteristics of the pumping units

Number of PU	a0	a1	a2	d0	d1	d2
PS1 – PU type 20 NDS (D3200-75)						
PU 1-4	85,0124	-0,15429	-15,7371	-0,14286	96,45429	-26,1514
PS2 – PU type 24 NDS (D6300-80)						
PU 1, 4	62,76	-1,872	-4,32	-0,14286	96,4543	-26,1514
PU 2, 3, 5	93,5006	-0,21695	-4,3193	-0,14286	96,4543	-26,1514
PS3 – PU type22 NDS (D4000-95)						
PU 1-4	109,08	-2,03524	-8,94861	0	147,0046	-61,0308
PS of the third ascent – PU type 24 NDS (D6300-80)						
PU2	87,32864	-0,21375	-4,25547	-0,14286	96,4543	-26,1514
PU3	80,14337	-0,21375	-4,25547	-0,14286	96,4543	-26,1514
PU4	90,73704	-0,21375	-4,25547	-0,14286	96,4543	-26,1514
PU5	93,5006	-0,21375	-4,25547	-0,14286	96,4543	-26,1514
PU6	83,2662	-0,21375	-4,25547	-0,14286	96,4543	-26,1514
PU7	93,5006	-0,21375	-4,25547	-0,14286	96,4543	-26,1514

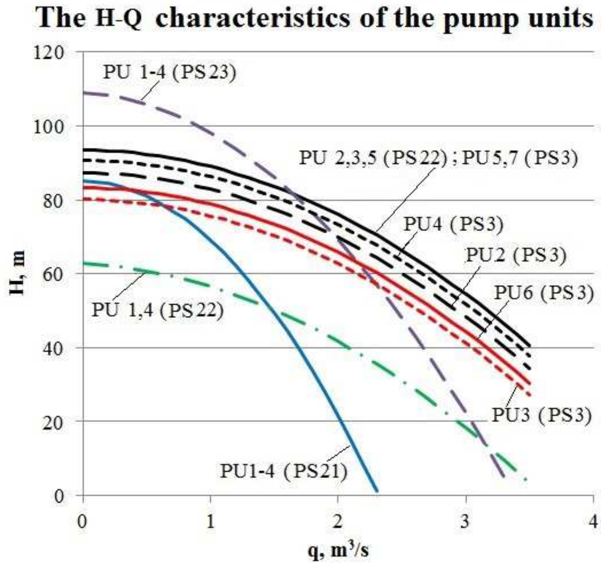

Fig. 2. The characteristics of the pump units

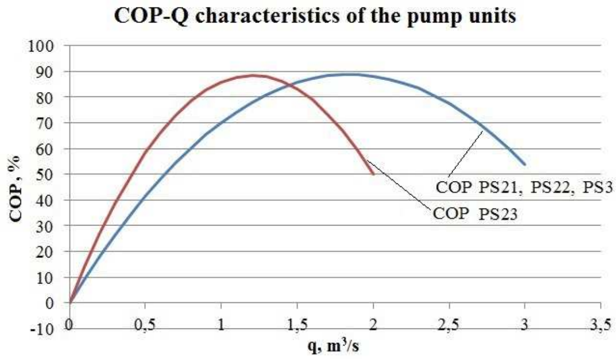

Fig. 3. COP-Q characteristics of the pump units

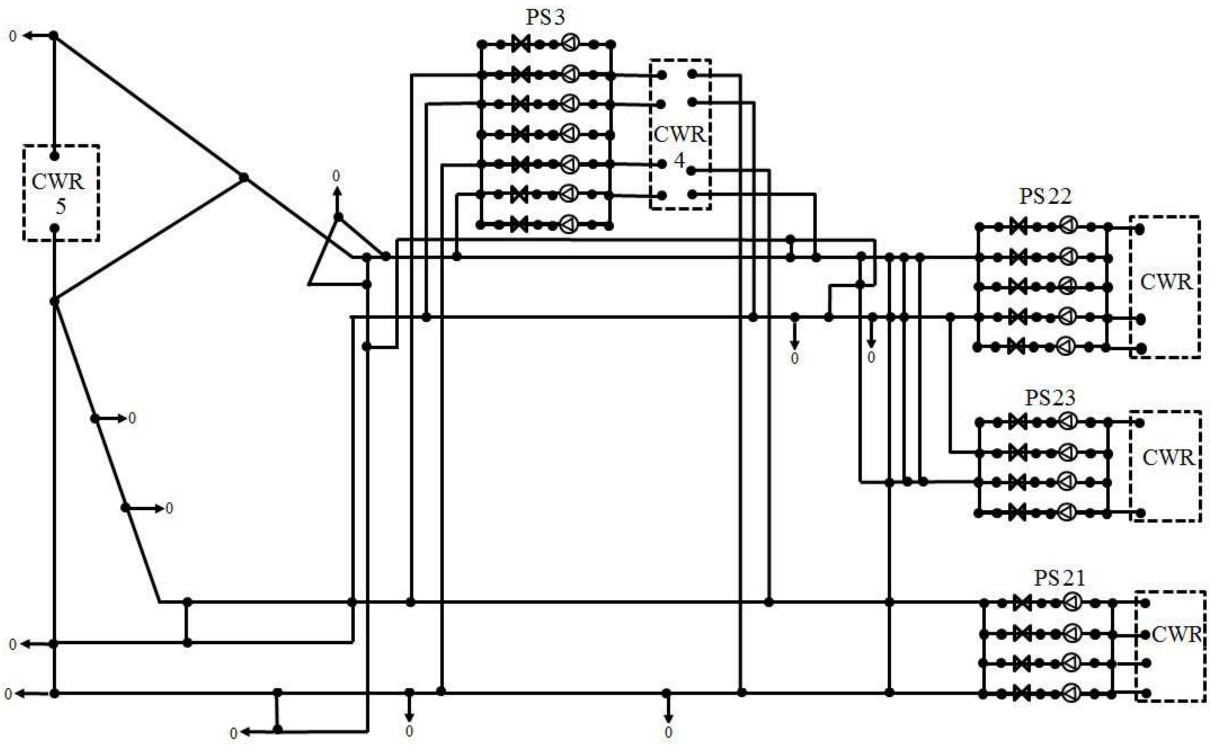

Fig.4. The net graph (● - vertex; ⊲ - pump unit; ⋈ - adjustable valve; — - arc; ↓0 - final consumer)

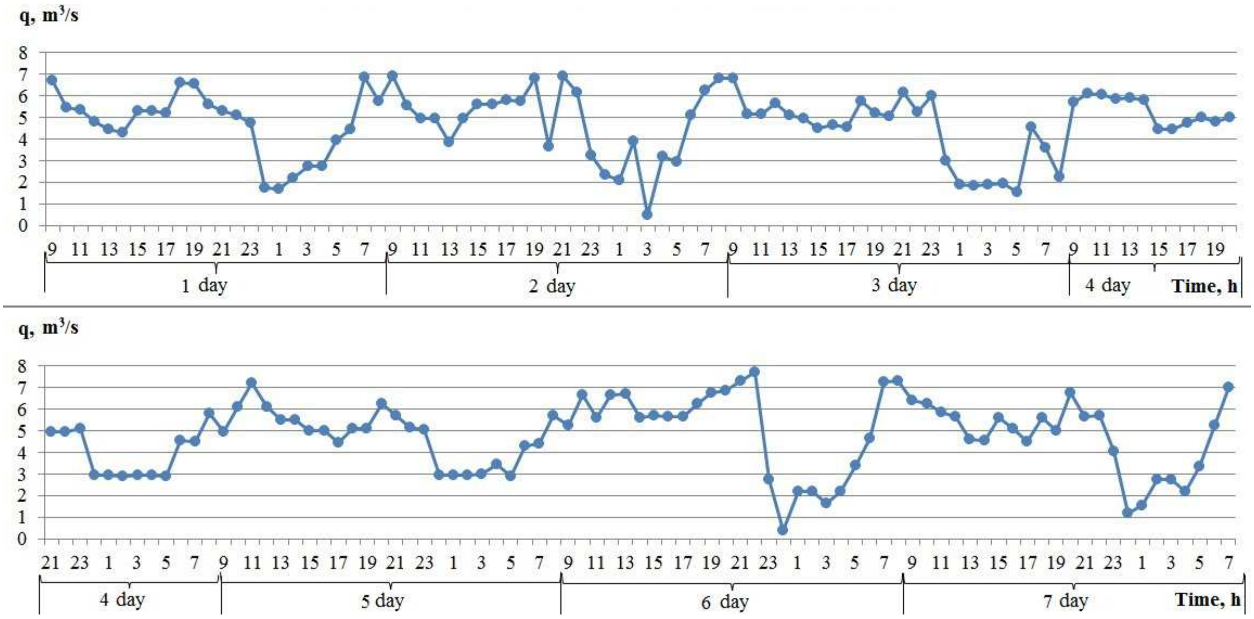

Fig. 5. The diagram of the prediction of hourly water consumption from CWR5 for seven days

At time zero k = 0 for the actual and optimal mode the same conditions have been used: mathematical expectation of water levels in CWR4 $H_{2,9} = 2,6$ m; in CWR5 $H_{1,9} = 3,9$ m; PU1 operated on PS21; PU3 and PU5 operated on PS22; PU2 operated on PS23; PU3 and PU6 operated on PS3.

The results of solving the problem of optimal stochastic control of the modes of operation of WM are shown in Table 3.

Table 3. The numbers of operating pump units for the actual (a) and optimal (o) modes of operation of the water main

Hours	Tariff	PS21			PS22						PS23			
		a	o		a		o				a			o
		Day												
		1-7	1,5	2-4, 6,7	1-5	6,7	1,5	2,3,6	4	7	1,2	3,4, 5	6,7	1-7
9	1,68	1	1	1	3,5	3,4	3,5	3	3	3	2	2	2	2
10	1,68	1	1	1	3,5	3,4	3,5	3	3	3	2	2	2	2
11	1,68	1	1	1	3,5	3,4	3,5	3	3	3	2	2	2	2
12	1,02	1	1	1	3,5	3,4	3,5	3,5	3	3	2	2	2	2
13	1,02	1	1	1	3,5	3,4	3,5	3,5	3,5	3,5	2	2	2	2
14	1,02	1	1	1	3,5	3,4	3,5	3,5	3,5	3,5	2	2	2	2
15	1,02	1	1	1	3,5	3,4	3,5	3,5	3,5	3,5	2	2	2	2
16	1,02	1	1	1	3,5	3,4	3,5	3,5	3,5	3,5	2	2	2	2
17	1,02	1	1	1	3,5	3,4	3,5	3,5	3,5	3,5	2	2	2	2
18	1,02	1	1	1	3,5	3,4	3,5	3,5	3,5	3,5	2	2	2	2
19	1,02	1	1	1	3,5	3,4	3,5	3,5	3,5	3,5	2	2	2	2
20	1,02	1	1	1	3,5	3,4	3,5	3,5	3,5	3,5	2	2	2	2
21	1,68	1	1	1	3,5	3,4	3	3	3	3,5	2	2	2	2
22	1,68	1	1	1	3,5	3,4	3	3	3	3	2	2	2	2
23	1,68	1	1	1	3,5	3,4	3	3	3	3	2	2	2	2
24	0,35	1	1,2	1,2	3,5	3,4	3,5,2	3,5,2	3,5,2	3,5,2	2	2	2,3	2,3
1	0,35	1	1,2	1,2	3,5	3,4	3,5,2	3,5,2	3,5,2	3,5,2	2	2	2,3	2,3
2	0,35	1	1,2	1,2	3,5	3,4	3,5,2	3,5,2	3,5,2	3,5,2	2,3	2	2,3	2,3
3	0,35	1	1,2	1,2	3,5	3,4	3,5,2	3,5,2	3,5,2	3,5,2	2,3	2	2,3	2,3
4	0,35	1	1,2	1,2	3,5	3,4	3,5,2	3,5,2	3,5,2	3,5,2	2,3	2	2,3	2,3
5	0,35	1	1,2	1,2	3,5	3,4	3,5,2	3,5,2	3,5,2	3,5,2	2,3	2	2,3	2,3
6	0,35	1	1,2	1,2	3,5	3,4	3,5,2	3,5,2	3,5,2	3,5,2	2,3	2	2,3	2,3
7	1,02	1	1,2	1	3,5	3,4	3,5,2	3,5	3,5	3,5	2	2	2	2
8	1,02	1	1,2	1	3,5	3,4	3,5,2	3,5	3,5	3,5	2	2	2	2

Table 3 (Continue). The numbers of operating pump units for the actual (a) and optimal (o) modes of operation of the water main

Hours	Tariff	PS3												
		a						o						
		Day												
		1	2	3	4,5	6	7	1	2	3	4	5	6	7
9	1,68	3,6	3,4	3,5	3,5	3,5	3,5	3	3	3	3	3	3	3
10	1,68	3,6	3,4	3,5	3,5	3,5	3,5	3	3	3	3	3	3	3
11	1,68	3,6	3,4	3,5	3,5	3,5	3,5	3	3	3	3	3	3	3
12	1,02	3,6	3,4	3,5	3,5	3,5	3,5	3,6	3	3	3	3	3,5	3
13	1,02	3,6	3,4	3,5	3,5	3,5	3,5	3,6	3	3	3	3	3,5	3
14	1,02	3,6	3,4	3,5	3,5	3,5	3,5	3,6	3	3	3	3	3,5	3
15	1,02	3,6	3,4	3,5	3,5	3,5	3,5	3,6	3	3	3	3	3,5	3
16	1,02	3,6	3,4	3,5	3,5	3,5	3,5	3,6	3	3	3	3	3,5	3
17	1,02	3,6	3,4	3,5	3,5	3,5	3,5	3,6	3	3	3	3	3,5	3
18	1,02	3,6	3,4	3,5	3,5	3,5	3,5	3,6	3	3	3	3	3,5	3
19	1,02	3,7	3,4	3,5	3,5	3,5	3,5	3,6	3	3	3	3	3,5	3,5
20	1,02	3,7	3,4	3,5	3,5	3,5	3,5	3,6	3	3	3	3	3,5	3,5
21	1,68	3,7	3,4	3,5	3,5	3,5	3,5	3	3	3	3	3	3	3
22	1,68	3,7	3,4	3,5	3,5	3,5	3,5	3	3	3	3	3	3	3
23	1,68	3,7	3,4	3,5	3,5	3,5	3,5	3	3	3	3	3	3	3
24	0,35	3,7	3,4	3,5	3,5	3,5,7	3,5,7	3,6,7,5,4	3,4,5,7,2	3,4,5,7	3,5,6,7	3,5,6,7,4	3,5,6,7	3,5,6,7,4
1	0,35	3,6,7	3,4,7	3,5,6	3,5	3,5,7	3,5,7	3,6,7,5,4	3,4,5,7,2	3,4,5,7	3,5,6,7	3,5,6,7,4	3,5,6,7	3,5,6,7,4
2	0,35	3,6,7	3,4,7	3,5,6	3,5	3,5,7	3,5,7	3,6,7,5,4	3,4,5,7,2	3,4,5,7	3,5,6	3,5,6,7,4	3,5,6,7	3,5,6,7,4
3	0,35	3,6,7	3,4,7	3,5,6	3,5	3,5,7	3,5,7	3,6,7,5,4	3,4,5,7,2	3,4,5	3,5,6	3,5,6,7,4	3,5,6,7	3,5,6,7,4
4	0,35	3,6,7	3,4,7	3,5,6	3,5	3,5,7	3,5,7	3,6,7,5	3,4,5,7,2	3,4,5	3,5,6	3,5,6,7,4	3,5,6,7	3,5,6,7
5	0,35	3,6,7	3,4,7	3,5,6	3,5	3,5,7	3,5,7	3,6,7,5,4	3,4,5,7,2	3,4,5	3,5,6	3,5,6,7	3,5,6,7	3,5,6,7
6	0,35	3,6,7	3,4,7	3,5,6	3,5	3,5,7	3,5,7	3,6,7,5,4	3,4,5,7,2	3,4,5	3,5,6	3,5,6,7	3,5,6,7	3,5,6,7
7	1,02	3,7	3,4	3,5	3,5	3,5	3,5,7	3,6	3	3	3	3	3,5	3
8	1,02	3,7	3,4	3,5	3,5	3,5	3,5	3,6	3	3	3	3	3,5	3

The use of the proposed strategy for solving the problem of optimal stochastic control of the modes of operation of WM has enabled to use all possible range of changes of the water level in CWR4 and CWR5 and use the technical characteristics of PU more efficiently which provides a significant (up 9%) savings of financial costs for the electricity at the time interval [0 , T] and using a three-tier electricity tariff.

Table. 4 presents the estimates of the mathematical expectation of the power and cost value for the electricity of PS of the second and third ascents during seven days for the actual and optimal modes of operation of WM.

Table 4. The comparative analysis of the estimates of the mathematical expectation of the costs of the electricity and financial costs of the operation of pumping stations of the second and third ascents for the actual (a) and optimal (o) modes

Day	N, kW (a)	N, kW (o)	Cost, UAH (a)	Cost, UAH (o)
1	261725,6	259592,8	248795,2	258043,1
2	263471,0	239818,4	250998,3	216232,7
3	255218,4	241436,4	246817,1	209520,6
4	247644,9	243391,7	245269,2	209237,7
5	246623,4	238565,2	244069,6	219133,4
6	268072,1	265745,9	252127,2	254190,9
7	268385,5	266095,8	252291,3	220425,2
Amount	1811140,9	1754646,0	1740367,9	1586783,7

From Table 4 it can be seen that as a result of the transition of the mode of operation of WM from the actual to the optimal one during seven days, we managed to save 153584 UAH., which is 8,82% of the previous amount.

Fig. 6 shows the change of the estimate of the mathematical expectation of the cost value for the electrical energy while the transition from the actual to optimal mode.

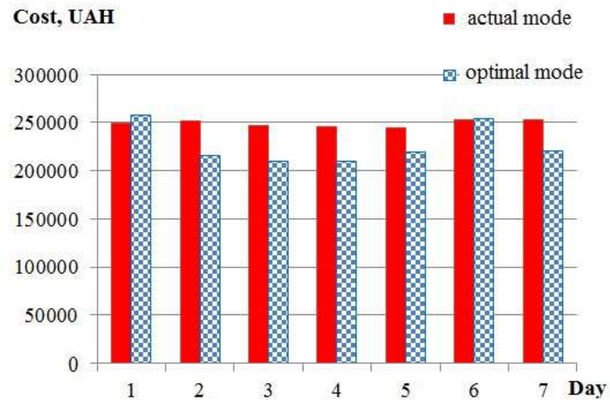

Fig. 6 The change of the estimate of the mathematical expectation of the value cost for the electrical energy consumed by the pumping station of the second and third ascents while the transition from the actual to the optimal mode.

In Tab. 5 the estimates of the target values of upper and lower bounds of water levels in CWR4 and CWR5 and also the bounds of the ranges of water level changes for the actual and optimal modes at the examined interval of seven days are shown.

Table 5. The change of water levels in CWR4 and CWR5

	Water level in CWR4, m		Water level in CWR5, m	
	min	max	min	max
Limitations	2,00	4,9	1,45	4,9
Actual mode	2,38	3,84	1,45	4,5
Optimal mode	2,6	4,83	1,81	4,89

Fig. 7, Fig. 8 show the change of the estimate of the mathematical expectation of water levels in CWR4 and CWR5 as a result of actual and optimal mode of operation during seven days of the planned period.

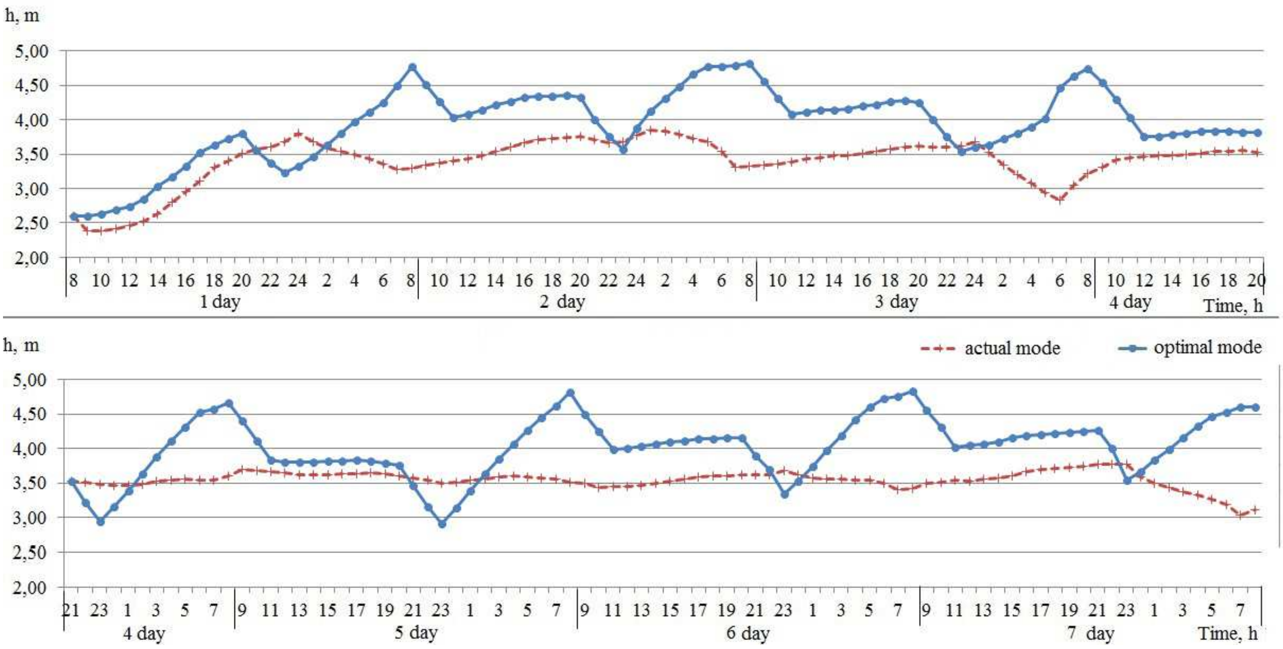

Fig. 7. The change of the estimate of the mathematical expectation of water level in CWR4

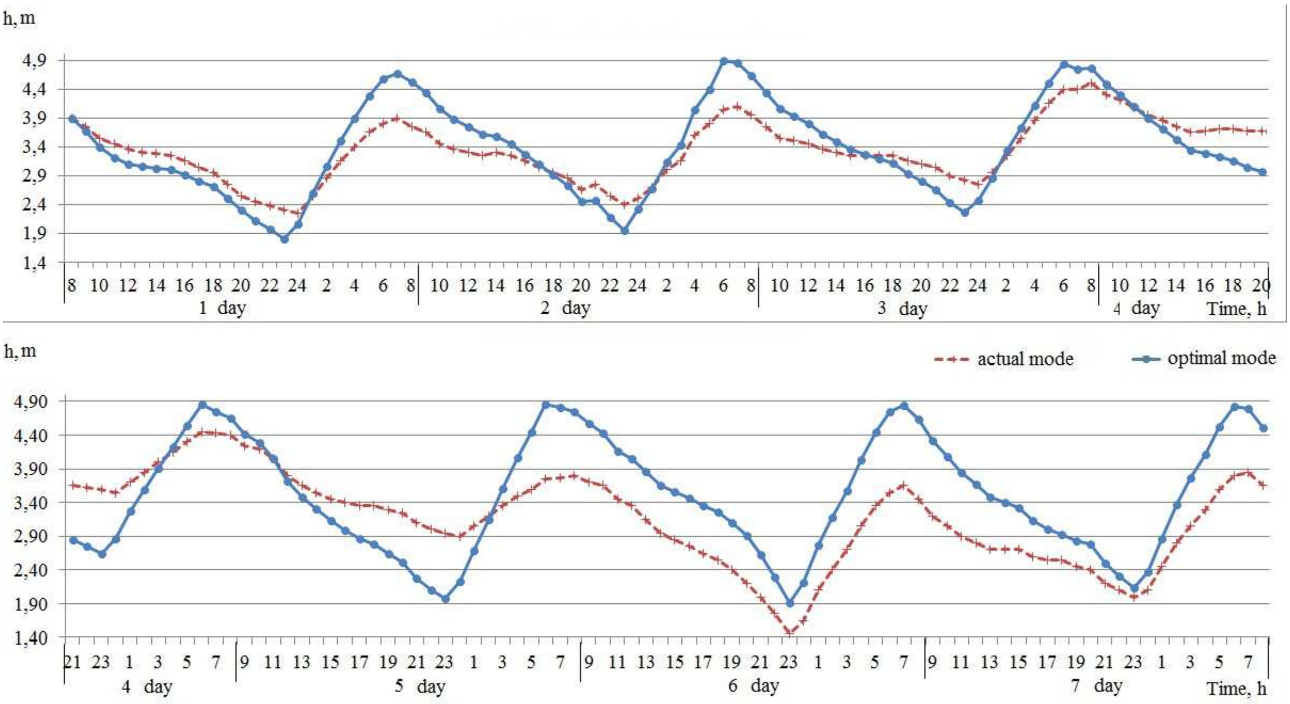

Fig. 8. The change of the estimate of the mathematical expectation of water level in CWR5

From Table. 5, Fig. 7, Fig. 8 it is seen that the capacities CWR4 and CWR5 under optimal mode of operation of WM are used more efficiently, i.e. the water level in the reservoirs varies in a wider range.

CONCLUSIONS

Scientific novelty:

1. a new class of the problems of optimal stochastic control of the operation with discrete-time of the complex dynamic objects, different from well-known by the introduction of additional extreme and probabilistic constraints on the phase variables has been developed;

2. the mathematical formulation of the problems of optimal stochastic control of the modes of operation of WM with extreme and probabilistic constraints on the phase variables has been presented;

3. to obtain an approximate solution of the examined problem a new strategy of optimal stochastic control of the modes of operation of WM has been offered, it takes into account the specific features of WM as a stochastic object of control operating in the stochastic environment, the use of which has permitted to simplify the solution of the examined problem significantly and provided a significant reduction of the financial expenses for the electricity while the transition to a three-tier tariff.

Practical value: the estimates of the effectiveness of the proposed method compared to the current one are given on the example of one of the largest WM of Ukraine. It is shown that the use of the proposed method has allowed to obtain the economic benefit for the cost of the electricity up to 8,82%, which in absolute terms for the examined sample has figured up to the savings of 658 thousand UAH per month.

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ECONTECHMOD. AN INTERNATIONAL QUARTERLY JOURNAL – 2015, Vol.4, No.3, 13-18

REENGINEERING THE TOPOLOGICAL STRUCTURES OF LARGE-SCALE MONITORING SYSTEMS

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Received July 02.2015: accepted August 07.2015

Abstract. As part of the solution of problem optimization of large-scale facilities carried out formalization of the system description of large-scale monitoring, defined the composition and the relationship subsets of elements, relationships, topologies and properties. Formulated the mathematical model and the task of reengineering topological structures of centralized three-tier system of large-scale monitoring based on indices of cost and efficiency. The proposed mathematical model explicitly set relation between costs for the reengineering and time processing messages in the system from its structure and topology. The analysis of the objective function revealed that envelopes their local extrema are one-extreme (relative to the number of nodes in the system). Considering this, proposed a method of directed inspection of local extrema, which allow to find best solutions in terms of the minimum additional cost. Selection of the single solution from a set of effective proposed to carry out the method of hierarchy analysis or cardinalist approach aided by the additive function of general utility. The values of the weighting coefficients of the utility functions is carried out by an expert or based on comparator identification.

Practical application these results allows reduce the time of obtaining solutions and more accurate solving of large dimension problem.

Key words: large-scale monitoring system (LSMS), structure, topology, reengineering.

INTRODUCTION

In modern conditions, a lot of scientific and research, social and economic, as well as technical decisions are based on the data provided by large-scale monitoring systems (LSMSs). This is exemplified by the systems of astronomic, ecological, radiation, geological and hydrometeorological, economic and medical monitoring.

Changes of the monitoring conditions (emerging new objects of observation, stricter requirements to the operativeness and accuracy of observations) and (or) new tools (appliances and technologies) lead to inefficiency of the current variant of the system construction. Any attempts to adapt the system do not secure the best outcome.

The most effective variant of the system construction can be obtained through its reengineering, which suggests a fundamental reconsideration of the current state of the observed objects, the entire system, tools and technologies of monitoring, as well as through its radical redesign.

The notion “reengineering” was suggested and originally interpreted in the study [1] that revealed reengineering principles for business processes of companies. Most contemporary publications on various aspects of reengineering problem also refer to reengineering business processes or software structures, and use the notion of “reengineering” alongside such notions as “redesign”, “evolution”, “migration”, “modernization”, and “restructuring” [2–5].

In LSMSs, operativeness and cost indices largely depend on the applied technology, structure, and parameters of the elements and links, as well as on their topology (site implementation). This peculiarity predetermines the need to solve the problem of technological, structural, topological and parametric optimization in the process of reengineering LSMSs.

Since the monitoring practice applies a relatively small set of technologies, types of elements, nodes and links, the most difficult task is optimization of the LSMS structure and topology.

The analysis of contemporary publications on the design of monitoring systems has revealed that the main objective of monitoring systems is collection of the necessary information at minimum cost [6–8].

Minimized additional costs [7] (alongside minimized regular costs), the required or maximized control owing to a multiple coverage of the monitoring zone [8], a maximum coverage of the monitored objects (with regular and irregular coverage radii) [9–11] and a minimized average time of information receipt (optimal operativeness) [12] are used as criteria in the tasks of optimization of monitoring systems. Restrictions on probabilistic supply of information to a specified number of consumers [13] and the location of the monitoring points [14] serve as additional limitations.

Mathematical models and methods for solving the problems of the analysis and synthesis of other large-scale objects in the fields of transportation, communication and logistics can be applied in reengineering LSMSs [7, 15–16].

The analysis has revealed that the most common are monitoring systems with radial nodal structures that contain a single center, one level of nodes and a plurality of elements distributed between the nodes of the system (each node covering its subset of the monitored objects). Design and (or) operation costs as well as operativeness (time of information receipt) costs serve as indicators of the monitoring system efficiency. Therefore, a topical problem lies devising a method that would solve a two-criteria task of reengineering topological structures of LSMSs in terms of the costs and operativeness.

FORMALIZATION OBJECTIVE OF REENGINEERING TOPOLOGICAL STRUCTURES OF LSMSs

Formalization of the generalized LSMS description is based on the suggested in the study [15] scheme for large-scale objects. The LSMS is viewed as a system $S =< E,R,G >$, where: E is a set of elements in the system, R is a set of relations (links) between the elements, and G is a topological implementation of the monitoring system structure $<E, R>$.

Topological implementation of the LSMS is based on the topological complex of elements G_E, relations G_R, and data transmission trajectories G_A. The process of reengineering must distinguish between the subsets of intrinsic and the required properties of the system – P' and P'', respectively. The sets of properties P' and P'' are subsets of the universal set of properties P^U that can be obtained on universal sets of elements E^U, relations R^U, and topologies G^U [15]:

$$P^U = \varphi(E^U, R^U, G^U),$$

where φ is a mapping.

The E^U set consists of various types of elements that can be applied in reengineering LSMS. The R^U set is determined by the E^U set composition, whereas the latter is determined by composition of the E^U and R^U sets. Meanwhile, the difference between the sets of elements in the new E'' and the existing E' structures determines the set of elements that ought to be included in the new structure:

$$E^+ = E'' \setminus E'.$$

Accordingly, it is possible to identify a subset of elements in the existing LSMS structure that can be excluded from further consideration in the process of reengineering LSMS:

$$E^- = E' \setminus E''.$$

The set of elements E^S, that can be reapplied in reengineering, presented as an intersection of the sets E' and E'':

$$E^S = E' \cap E'', E' = E^S \cup E^-, E'' = E^+ \cup E^S. \qquad (1)$$

Since composition of the sets of relations between the elements R', R'' and the topologies G', G'' is determined by composition of the sets E' and E'', we can identify the corresponding subsets of relations that ought to be included in LSMSs during their reengineering, either reused or not used at all:

$$R^+ = R'' \setminus R', E^- = R' \setminus R'',$$

$$R^S = R' \cap R'', R' = R^S \cup R^-, R'' = R^+ \cup R^S, \qquad (2)$$

$$G^+ = G'' \setminus G', G^- = G' \setminus G'',$$

$$G^S = G' \cap G'', G' = G^S \cup G^-, G'' = G^+ \cup G^S.$$

The scheme of interconnections between such categories as “element”, “relation”, “topology” and “property” in reengineered LSMSs allows introduction of sets of new properties $P^+ = P'' \setminus P'$ and properties that are or can be excluded from consideration $P^- = P' \setminus P''$.

At the first stage, a set of feasible solutions during reengineering LSMS $S^* = \{ s \} \subseteq S''$ is determined by subsets of elements $E^* \subseteq E'' \subseteq E^U$, their relations $R^* \subseteq R'' \subseteq R^U$ and topologies $G^* \subseteq G'' \subseteq G^U$. Further stages of reengineering the topological structure of LSMSs allow selection of subsets of elements $E^o \in E^*$, relations $R^o \in R^*$ and topologies $G^o \subseteq G^*$ from a feasible area $S^* = \{ s \}$. Using the above subsets we obtain a set of the required properties $P'' \subseteq P^U$ that are specified as objective functions, either cost and (or) functional limitations.

The set of tasks (stages) of the structural and topological reengineering LSMS largely coincides with the set of problems of synthesis the initial version LSMS, but will be different by productions, input data and limitations.

According to the suggested in [6] general decomposition scheme for reengineering LSMSs, the meta-level task can be presented as follows:

$$\begin{aligned} &MetaTask = Task_1^0 : \{ Objs, s, Q^*, C^*, S' \} \to \\ &\to \{ s^o, K(s^o) \}, \end{aligned} \qquad (3)$$

where: $Objs$ – a set of quantitative and qualitative characteristics of the LSMS objects; s – the existing realization LSMS; Q^* – the required set of the system functional qualities; C^* – marginal values of the system cost; S' – the area of reengineering (feasible patterns), s^o – a new LSMS pattern obtained during its reengineering; $K(s^o)$ – criterial assessment of the selected pattern and topology of the LSMS.

The objective of reengineering the topological structure of a three-tier LSMS that is based on the same-type elements, nodes and links and regards reengineering costs as well as operativeness requirements is considered in the following formulation.

Specified:

– a set of the system elements $I = \{ i \}, i = \overline{1,n}$ that cover the entire set of the monitored objects;

– the existing pattern of the topological structure $a \in S$ (where S is a set of feasible topological patterns) determined by the sites of elements $I = \{ i \}, i = \overline{1,n}$, nodes $y' = [y'_i], i = \overline{1,n}$ (where y' is a Boolean variable; if there is an i-element based node, $y' = 1;$ otherwise $y' = 0$), the center (the system center is sited on the base of the element $i = 1$), as well as links between the elements, nodes and the center $x' = [x'_{ij}], i, j = \overline{1,n}$ (where x'_{ij} is a Boolean variable; if the elements i and j are linked directly, $x'_{ij} = 1$; otherwise $x'_{ij} = 0$);

– the cost of setting up (operation of) nodes $[c_{ii}]$, $i = \overline{1,n}$ and links $[c_{ij}]$, $i, j = \overline{1,n}$.

It is necessary to identify the optimum in terms of efficiency and cost topological structure $s^o \in S$ (where S is a set of feasible patterns) that is determined by the number of nodes u their sites $y = [y_i], i = \overline{1,n}$ (the central node is sited on the base of the first element, i.e. $y_1 = 1$) and the scheme of links between the elements, nodes and the center $x = [x_{ij}], i, j = \overline{1,n}$ in view of the specified constraints of costs and operativeness.

In order to simplify the model and taking into account the symmetry a square matrix of links (between system elements, nodes and center) and the cost will replace the triangular upper diagonal matrix.

Whereas the initial set of feasible solutions is determined by the following [5]:

$$S = \{s\} = \begin{cases} x = [x_{ij}], x_{ij} \in \{0,1\}, i, j = \overline{1,n}, x_{11} = 1; \\ \sum_{j=i}^{n} x_{ij} \ge 1, \forall j = \overline{1,n}; \\ \sum_{i=1}^{n} \sum_{j=i}^{n} x_{ij} = n + \sum_{i}^{n} x_{ii}; \\ x_{ii} = 1 \to x_{i1} = 1 \; \forall i = \overline{1,n}; \\ x_{ii} = 1 \wedge x_{ij} = 1 \to ij = \\ = arg\ min\{ \min_{1<i'\le j} c_{i'j}, \min_{j<i'\le n} c_{ji'} \} \forall i \le n, i, j = \overline{1,n}, \end{cases} \quad (4)$$

where S – a set of feasible patterns of topological structures of LSMSs; s – a pattern of the topological structure; $x = [x_{ij}], i, j = \overline{1,n}$ – a matrix of links (where x_{ij} is a Boolean variable; if the elements i and j are linked directly, $x_{ij} = 1$; otherwise $x_{ij} = 0$; if the system node is i-element based, $x_{ii} = 1$; otherwise $x_{ii} = 0$; $i = \overline{1,n}$), n – a number of the system elements, and $[c_{i'j}]$, $i', j = \overline{1,n}$ is the cost of links between the elements i' and j.

The cost of the existing LSMS pattern $C(a), a \in S$ consists of the costs of the center $C_C(a)$, nodes $C_U(a)$, elements $C_E(a)$, and links between the nodes and the center $C_{UC}(a)$ as well as the elements and the nodes $C_{EU}(a)$ [7]:

$$C(a) = C_C(a) + C_U(a) + C_{UC}(a) + C_E(a) + C_{EU}(a). \quad (5)$$

By analogy, estimate the cost $C(b)$ of the optimal pattern LSMS for new conditions of functioning, (excluding the current topological structure $a \in S$) can be represented as:

$$C(b) = C_C(b) + C_U(b) + C_{UC}(b) + C_E(b) + C_{EU}(b). \quad (6)$$

A desirable goal consists in minimizing the additional costs $\Delta C(a,b)$. Meanwhile, the difference in the costs (5) and (6)

$$\Delta C(a,b) = C(a) - C(b), \quad (7)$$

fails to account for the possible use of parts of the existing topological structure $a \in S$.

In view of the above equation (7), a particular criterion of the minimum additional costs:

$$k_1(a,s) \to \min_{s \in S},$$

(with the possible use of a part of the existing topological structure $a \in S$) can be presented as follows:

$$k_1(a,s) = \Delta C(a,s) = \sum_{i=1}^{n} [(c_i + e_i)(1 - x'_{ii})x_{ii} + (d_i - g_i)x'_{ii}x_{ii}] + $$
$$+ \sum_{i=1}^{n} \sum_{j=1}^{n} [(c_{ij} + e_{ij})(1 - x'_{ij})x_{ij} + (d_{ij} - g_{ij})x'_{ij}x_{ij}] \to \min_{s \in S}, \quad (8)$$

where c_i – the cost of the elements, nodes and the center in the new structure, $i = \overline{1,n}$; x'_{ij} and x_{ij} – respectively, elements of the matrices of adjacency (links) between the elements, nodes and the center in the existing structure $x' = [x'_{ij}]$ and in the reengineered structure $x = [x_{ij}]$ (if the elements i and j are linked directly, $x'_{ij} = 1$ or $x_{ij} = 1$; otherwise $x'_{ij} = 0$ or $x_{ij} = 0$); d_i – the cost of modernizing an element, a node, or the center in the new structure $i = \overline{1,n}$; e_i – the cost of dismantling the nodes in the existing structure $i = \overline{1,n}$; g_i – the cost of resources that can be reused after dismantling the nodal equipment $i = \overline{1,n}$; $[c_{ij}], i, j = \overline{1,n}$ – the cost of links between the elements i and j; and S – a set of feasible patterns of the topological structures of LSMSs.

The second desirable objective is minimizing the maximum time for receipt of the information on the monitored objects. The task under consideration allows use of the deterministic operativeness model that takes into account the dependence of information time on the system's topological structure. The model would facilitate assessment of the strictly specified operation technology that determines the intensity of the same-type flows of information from and to the center:

$$\alpha_i = [\alpha_i], \alpha_i = const, \beta_i = [\beta_i], \beta_i = const, i = \overline{1,n}$$

in the channels and nodes of the system.

The entire time of information receipt from each element of the system $I = \{i\}, i = \overline{1,n}$ can be presented as consisting of the following time intervals: (1) receipt of a request from the center τ_i^C, (2) transmission of the request via the center-node channel τ_i^{CU}, (3) processing of the request in the node τ_i^{U1}, (4) transmission of the request via the node-element channel τ_i^{UE}, (5) receipt of the information by the system element τ_i^{E}, (6) transmission of the response via the element-node channel τ_i^{EU}, (7) processing of the response in the node τ_i^{U2}, and (8) transmission of the response via the node-center channel τ_i^{UC}:

$$k_2(s) = \tau_i(s) = \tau_i^{C} + \tau_i^{CU}(s) + \tau_i^{U1}(s) + \tau_i^{UE} + \\ + \tau_i^{E} + \tau_i^{EU} + \tau_i^{U2}(s) + \tau_i^{UC}(s), i = \overline{1,n}. \tag{9}$$

The time intervals for transmission of requests and responses via the channels center-node $\tau_i^{CU}(s)$, element-node $\tau_i^{EU}(s)$ as well as processing of requests and responses in the nodes $\tau_i^{U1}(s)$, $\tau_i^{U2}(s), i = \overline{1,n}$ depend on the amount of elements connected to each of the nodes (of the LSMS topological structure). Meanwhile, time intervals for receipt of a request from the center τ_i^{C}, receipt of the information by the system element τ_i^{E} and transmission of the response via the element-node channel τ_i^{EU} are independent from the system's topological structure.

Since a desirable goal is minimizing the maximum time for receipt of the information on the monitored objects, the efficiency criterion (based on the above equation (9) can be presented as follows:

$$k_2(s) = \max_{1 \le i \le n} \left[\begin{array}{l} \tau_i^{C} + \dfrac{\alpha_i}{q_{ij}} + \tau_i^{E} + \dfrac{\beta_i}{q_{ij}} + \\ + \left(\dfrac{\alpha_i}{q_i} + \dfrac{\alpha_i}{h_i^1} + \dfrac{\beta_i}{h_i^2} + \dfrac{\beta_i}{q_i} \right) \sum_{i=1}^{n} \sum_{j=i}^{n} x_{ij} x_{ii} \end{array} \right] \to \min_{s \in S}, \tag{10}$$

where: q_i and q_{ij} – bandwidths of the center-node and node-element channels; h_1 and h_2 – velocities of processing the request and the response in the system nodes.

When the monitoring system uses a not strictly deterministic data collection technology that causes heterogeneous flows in the network, the correlations (9) – (10) are used for preliminary assessment of the operativeness. Imitation models would secure a reliable assessment of the time for information receipt in LSMSs [17–18].

A METHOD FOR REENGINEERING THE TOPOLOGICAL STRUCTURES

A mathematical model of a two-criteria task of reengineering the LSMS topological structures includes formalized criteria of costs (8) and operativeness (10):

$$\begin{cases} k_1(a,s) \to \min\limits_{s \in S}, k_1(a,s) \le k_1^*; \\ k_2(s) \to \{\max\limits_{1 \le i \le n} \tau_i\} \to \min\limits_{s \in S}, k_2(s) \le k_2^* \end{cases}, \tag{11}$$

where: k_1^* and k_2^* – marginal values of costs on reengineering $k_1(a,s)$ and operativeness $k_2(s)$, respectively.

A set of feasible solutions (4) generally consists of two subsets $S = S^S \bigcup S^K$, where S^S is a subset of agreement, in which particular criteria of costs $k_1(a,s)$ and efficiency $k_2(s)$ can change concertedly, while S^K is a subset of compromise (effective options), in which particular criteria of costs $k_1(a,s)$ and efficiency $k_2(s)$ are strictly contradictory.

An optimal solution of any multi-criteria objective belongs to the area of compromise [21]. In a solvable discrete two-criteria objective (11), an optimal solution $s^o \in S$ belongs to a subset of compromise $s^o \in S^K \subseteq S$. None of solutions of the S^K subset can be improved by all particular criteria simultaneously. In view of the latter, selection of the best option of topological structures $s^o \in S$ for LSMSs consisting of relatively few elements ought to be accompanied by formation of a set of alternatives S and a subset of compromise S^K. The approach is as follows [22].

The first of generated options s is integrated in the set S^K. Each of further alternatives $s' \in S$ is compared to each option belonging to the set of compromise $s \in S^K$. If a generated option $s' \in S$ is the best of all subset S^K options in terms of costs and efficiency, it is integrated in the subset of effective options S^K. If an option $s' \in S^K$ is worse than the new one $s' \in S$, it is excluded from the subset S^K.

When the generation of alternative options $s \in S$ (4) is completed, the subset of effective options S^K is formed. In general, $Card\ S^K << Card\ S$ which allows a considerable reduction of the memory capacity to store alternative options and save time for their further analysis.

The method of hierarchy analysis [23] is suggested for selecting the only solution from the subset of effective options $s^o \in S$.

Given the volumes of the existing LSMS and the initial set of feasible solutions (4), the set of effective solutions (11) can be quite potent. Therefore, the best compromise solution $s^o \in S$. ought to be found with the cardinalist approach aided by the additive function of general utility:

$$P(s) = \eta_1 \xi_1(s) + \eta_2 \xi_2(s) \to \max_{s \in S}, \tag{12}$$

where: η_i – coefficients of significance of particular criteria

$$k_i(s), 0 \le \eta_i \le 1, i = \overline{1,2}, \eta_1 + \eta_2 = 1; \\ \xi_i(s) = [(k_i(s) - k_i^-)/(k_i^+(s) - k_i^-)]^{\mu i}, \tag{13}$$

where: $k_i(s)$, k_i^-, $k_i^+(s)$, $i = \overline{1,2}$ – the current (for an option $s \in S$), the worst and the best values of a particular criterion i ; $\eta_i, i=\overline{1,2}$ – a weight coefficient of a particular criterion i , and $\mu_i, i=\overline{1,2}$ is a parameter that determines the type of the utility function of a particular criterion i .

The analysis of the objective functions (8) and (10) revealed that the envelopes of their local extrema are single-extreme dependences on the number of nodes in the system. Therefore, the maximum point of the general utility function (12) is between the minima of the cost function (8) and the efficiency function (10) by the number of nodes in the system u .

Therefore we suggest that the task of reengineering of the LSMS topological structures should be solved with the method of a directed enumeration of local extrema of the objective function (12).

The method can be applied via preliminary assessment of weight coefficients $\eta_i, i=\overline{1,n}$ as well as parameters $\mu_i, i=\overline{1,n}$ of the utility functions of particular criteria (12) – (13). They can be found by means of the methods of expert assessment or comparatory identification [19–20].

The method of comparatory identification of the pattern of multi-factor assessment (12) consists in the following. A decision-maker or an expert determines the qualitative utility on the set of options $s \in S^K$ going by the values of particular criteria of cost (8) and operativeness (10). The qualitative utility can be expressed by a set of binary relations of equivalence, of lax and strict preferences:

$$R_E(S^K)=\{(y,z): y,z \in S^K, y \succ z\},$$
$$R_{NS}(S^K)=\{(y,z): y,z \in S^K, y \succ z\},$$
$$R_S(S^K)=\{(y,z): y,z \in S^K, y \succ z\}$$

and generally represented by the order of one of the following functions:

$$R_E^O(S^K): s^o \approx s_i \approx s_j \approx \ldots \approx s_m,$$
$$R_{NS}^O(S^K): s^o \geq s_i \geq s_j \geq \ldots \geq s_m, \qquad (14)$$
$$R_S^O(S^K): x^o \succ x_i \succ x_j \succ \ldots \succ s_m,$$

where: m – capacity of the subset of options used in selection of the pattern parameters (12) – (13).

Systems of equations and (or) inequalities are based on the set order of alternatives (14) and complemented by the following ratios:

$$0 \leq \eta_i \leq 1, \mu_i > 0, i=\overline{1,2} \text{ и } \eta_1+\eta_2=1 .$$

The best values of parameters can be selected by the criterion of the minimum error in the recovery of the decision-maker’s (expert’s) preferences.

However such formulation of the task is not correct (by Hadamard). In general, such task may have no solution at all (if the decision-maker mistakenly has specified preferences $R^O(s)$), or have more than one solution. The only solution can be found by means of a regularized original task, i.e. an additional criterion. Preferences based on the relationship of strict preference $R_S(S^K)$ are found due to such criteria as the maximized minimum difference of the general utility function (12) of adjacent options $s_j, s_{j+1} \in R_S^O(S^K)$ or the maximum sum of their differences.

Preferences that can be expressed as a ratio of equivalence $R_E(S^K)$ are provided with such criterion as the minimum sum of the modules of values difference in the general utility function (12). A lax preference $R_{NS}(S^K)$, requires pre-selection of binary relations of the strict preference $R_S(S^K)$ and the equivalence $R_T(S^K)$.

The method of a directed enumaration of local extrema of the objective function (12) is as follows. Presumably the system lacks nodes, i.e. $u=0$. The general utility function’s (12) value is calculated for the known values of the weight coefficients $\eta_i, i=\overline{1,n}$ and parameters $\mu_i, i=\overline{1,n}$ of the utility functions of particular criteria. If the selected topological structure satisfies the constraints of the objective (11), the obtained value of the generalized criterion is viewed as record $P^*(s^o)=P(s,u=0)$, and the obtained option – as locally optimal s^o .

Let us increase the number of nodes: $u=1$. Analyzing the options for the topological structure with a single node we find the best option among those which meet the objective constraints: $P^*(s,u=1)$.

If $P^*(s,u=1)<P^*(s^o)$, the best option is s^o , where the number of nodes is $u=0$. Otherwise, we increase the number of nodes in the system ($u:=u+1$) and distinguish best option of the topological structure among those which satisfy the objective constraints until the value of $P*(s,u)$ decreases $P*(s^o)$.

CONCLUSION

1. The study formulates the task and presents a new mathematical model for reengineering the topological structures of centralized three-tier large-scale monitoring systems (LSMSs) in view of the indices of efficiency and cost, which is aimed at optimization of large-scale objects.

2. The analysis of objective functions of the task has revealed that such functions are one-extreme (relative to the number of nodes in the system). On this basis, we have suggested the method of a directed inspection of local extrema of the objective function to solve the problem of reengineering the topological structures in terms of their efficiency and cost. In contrast to the methods of exhaustive search, the suggested approach considerably narrows the search area and facilitates the search of effective solutions.

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SYNTHESIS SYSTEM MODELS OF CHOICE THE PRIORITIES AT REALIZATION OF NATIONAL FORESIGHT-RESEARCHES

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Received July 09.2015: accepted August 14.2015

Abstract. The analysis of implementation technology foresight in various countries is carried out which showed that for today foresight is used as the system instrument of formation the future allowing to consider changes in all spheres of public life: science and technologies, economy, social, public relations, culture. Types and structural elements of technology foresight are separated. The necessity of further research the problem associated with increasing the efficiency of foresight-projects through its informatization is shown. The *aim of the article* is to describe process of synthesis the model of informatization as technologies foresight in general, and its specific variants (foresight-project). Informative and formal statements of problems synthesis system model (SM) choice of priorities in the implementation of national foresight-researches are given. Approach to construction of SM technology foresight in the form of the two-level hierarchical system consisting of the functional and methodical levels is offered. At that the functional level includes a set of types and purposes of technology foresight, and methodical - reflects a transition way from input elements to output. For a further concretization of SM, taking into account the selected properties of discrecity and determinancy, the mathematical apparatus of the automata theory is used. In this case the system is represented in the form of automaton which processes the discrete information and changes its internal states only in admissible timepoints. For computer implementation of model technology foresight is supposed to use network models which, in general, provide adequacy of the formal representation of foresight-researches. Reasonability of use the apparatus of Joiner-networks (JN) defines a connectivity and directivity of transmission of output results as input alphabets is shown.

Keywords: technology foresight, scientific and technical development, system model, national foresight-researches, types of foresight, structural elements of foresight.

INTRODUCTION

During a globalization era support of world leadership in the sphere of hi-tech productions and innovative technologies belongs to number of fundamental priorities scientifically - technical and innovative policies of the majority countries of the world. At that efforts of the states are directed both at stimulation of research and development works in the advanced areas of science and technologies, and on definition of national priorities of scientific and technical development [1, 2]. Practically in all developed countries the special programs of defining priority areas of development science and technique are periodically created. The methods used in development process of these programs received the generalized name foresight, from English - "foresight", and until now proved themselves as the most effective tool of a choice the priorities in the sphere of science and technologies.

The concept foresight arose in the 1950th years in the american corporation "Rand" where solves the problems definition of perspective military technologies. Having faced with insufficiency of traditional predictive methods (quantitative models, extrapolation of the existing tendencies, etc.), experts of "Rand" developed a method Delphi [3], which became a basis of many foresight-researches. In the 60th years large-scale operations on prediction were carried out Naval and air-force by departments of the USA. From 1980th years foresight has become used in the European countries [4]. Foresight reached the heyday as an analysis method in the mid-nineties within national programs of technological prediction which still remain the main scope of application foresights. For today foresight is used as the system instrument of formation of the future which allows considering changes in all spheres of public life: science and technologies, economy, social, public relations, culture.

THE ANALYSIS OF RECENT RESEARCHES AND PUBLICATIONS

Recently is observed the increase of number the publications devoted to research of theoretical and practical aspects application of foresight – technology of designing the future is [4 – 15]. Foresight started using actively since the beginning of the 90th years by the governments of the U.S., United Kingdom, Germany, Japan and Australia, and to 2000 years number of such countries exceeded 30. At the present time this technology has been adopted not only in Western Europe, U.S. and Japan, but also in a number of developing countries and countries with economies in transition (Poland, Czech Republic, Russia, Belarus, Ukraine, etc.) [16-26].

Under *foresight* understood the process of systematically identifying new strategic directions of scientific and technological achievements, which in the long run will have a serious impact on the economic and social development of the country [27 - 29]. Technology foresight has the following main characteristics:

– foresight is a systematic process;

– central place in this process, is taken by the scientific and technological directions;

– priorities are considered from the point of view of their influence on social and economic development of the country;

– time horizon considered in the average and long term.

In the context of foresight there is a question about an assessment of the possible prospects of innovative development connected with progress in science and technologies, outlines the possible technological horizons which can be reached in case of investment of certain funds and the organization of systematic work, and also probable effects for economy and society.

In practice, there are various types of the foresight [8, 27, 29] as each foresight-project differs from others in various parameters: to the contents, depth of analysis, scales, time frames, the territory of coverage, to number of participants, the available resources, etc. Types of foresight are shown in fig. 1.

On the basis of the carried-out analysis of realization the foresight in the different countries of the world it is possible to allocate its basic structural elements (fig. 2).

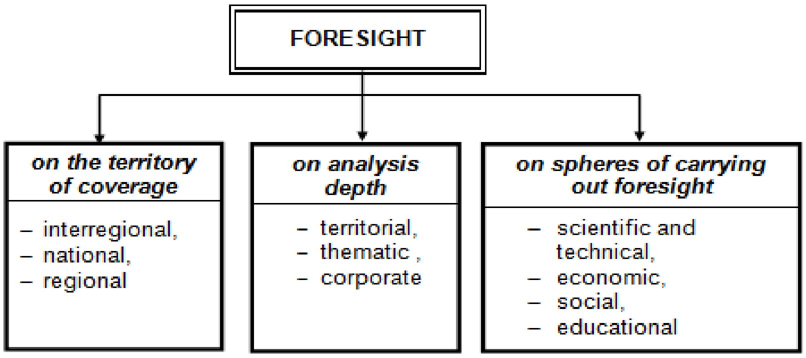

Fig. 1. Types of technology foresight

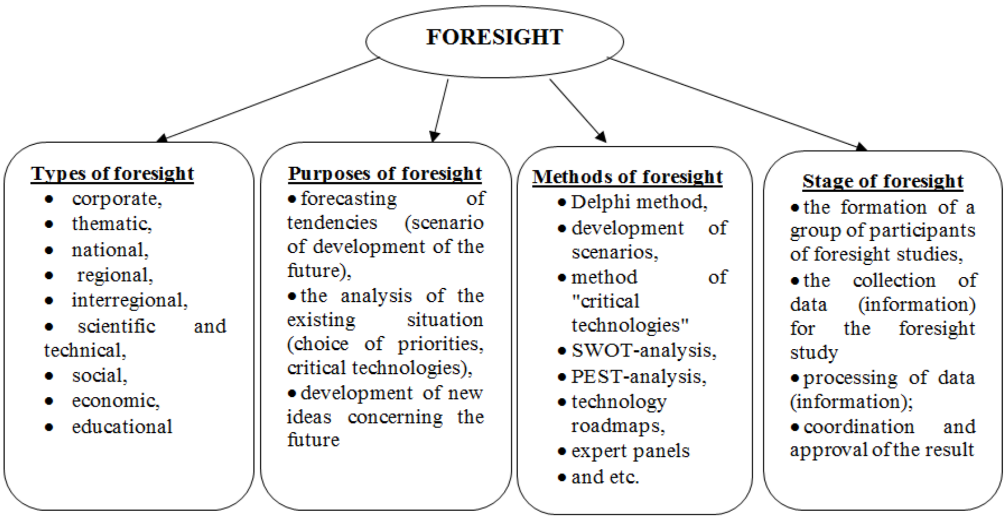

Fig. 2. Structural elements of technology foresight

Considering experience of various countries it is possible to claim that for today there is no uniform model of foresight, each country adapts this technology under their specific goals and requirements, and methods of its realization are badly formalized and mostly are expert, therefore, there is a need of further research of the problem connected with increase of efficiency of foresight-projects.

OBJECTIVES

The *aim of the article* is to describe process of synthesis the model of informatization as technologies foresight in general, and its specific variants (foresight-project).

STATEMENT OF THE PROBLEM

As initial data for informatization of technology foresight its mandatory constituent elements appear (a set of stages and methods of technology foresight).

To solve the problem it is necessary to develop a formal means by representation of decision-making process in the implementation of technology foresight, by use of adequate mathematical means.

As a result of the solution of the task the model of computer implementation of technology foresight in the form of a set of stages and collection methods of their computer implementation will be created. Implementation of the specified model will allow to increase efficiency of foresight-researches due to transition from heuristic procedures to their formal description, and also to informatization of technology foresight.

RESEARCH OF STRUCTURE OF TECHNOLOGY FORESIGHT, AS A DIFFICULT SYSTEM

For computer implementation of technology foresight it is necessary to formalize it, by development of the model, with a known level of adequacy reflecting all stages of the foresight-research. The technology foresight consists of a set of interacting components - subprocesses (foresight-research stages) and possesses the following row of the main properties:

– hierarchies - actions of subsystems of the top level depend on the actual execution by the bottom levels of their functions;

– discretizations - correlation between elements of system (subprocesses) is carried out sequentially;

– determinancies – all transitions between elements of system are strictly defined, i.e. transition to the next happens on condition of successful execution of the previous subprocess.

To select a special mathematical apparatus which would consider the selected main characteristics of foresight-researches, it is appropriate to conduct modelling which will allow to receive an holistic, systemic view model, allowing to reveal correlations of elements technology foresight, possible states of each element and the relation between them.

Technology foresight representable in the form multilevel structure described from positions of systems theory [30]. This structure should reflect the most important characteristics of the simulated system, namely:

- that the technology foresight consists of interrelated subsystems, which have a right to make decisions;
- that these subsystems form a hierarchy.

On the assumption of that, theoretical-system model of technology foresight represented in terms of functional-method relations [31], in which a function is understood as subject needs for receiving some result, and a method - some process by which this result is obtained. In this case, the upper level of technology foresight is set by the functional part and the lower - the methodical.

On the functional level displayed the main purpose of the technology foresight (analysis of the existing situation (the choice of priorities, the search for critical technologies), prediction of tendencies (described of development scenarios), etc.), which in turn can be decomposed into sub-goals (stages), depending on the type of foresight (national, corporate, scientific and technical, social, etc.). The methodical level reflects the transition way from the input to the output elements and contains as methods of achieving the purpose (set of methods for technology foresight), and conversion technology from input to output elements (certain methods and order for their implementation).

The provided description of technology foresight is initial for its formalized description on the set-theoretic level, at that the general problem statement of synthesis the models of computer implementation of technology foresight, given on the set-theoretic level of description, is similar in its structure and content to the general problems statement of decision-making problems in the conditions of a multicriteriality. A formal set-theoretic description is carried out using the following model:

$$\Phi = \langle \Theta, G, \Lambda, \Omega \rangle, \qquad (1)$$

where: $\Phi = \{ \varphi_g \},\ g = \overline{1,m}$ - the set of types technology foresight;

$\Theta = \{ \theta_i \}, i = \overline{1,k}$ - set of goals technology foresight that indicate a given state of technology foresight;

$G \subset G_0 \cup G_1$ - set of initial G_0 and final G_1 states of foresight technology, at that $G_0 \cap G_1 \neq \varnothing$;

$\Lambda = \{ \lambda_q \}, q = \overline{1,z}$ - set of stage of technology foresight;

$\Omega = \{ \omega_j \},\ j = \overline{1,n}$ - plural sets of methods technology foresight.

For the description of dynamic properties by means of system model, we will enter the following concepts:

1) Time T is a linear ordered by the relation "$\leq$" a set of timepoints t:

$$T = < T^O = \{ t \},\ \leq >: t \in [t_0, t], \qquad (2)$$

where: t_0 - initial timepoint in the interval $[t_0, t]$;

2) the instantaneous state of technology foresight Φ for a period of time T:

$$\Phi^T \subset \Phi \times T : \Phi^T = \{ \Phi^t \} \wedge \Pi_T(\Phi^T) = \{ t \} \subseteq T, \qquad (3)$$

where: $\Pi_T(\Phi^T)$ - projection of a set of the instantaneous statuses Φ^T to a set of timepoints T.

$\Pi_T(\Phi^T)$ is understood as a set of those elements from T which are projections of elements from (Φ^T)on *T*. For a couples $\Phi^t = (\Phi, t)$ projection element Φ^T on the set *T* serves the element t. Instant state of stage technology foresight $\Phi \in \Phi^T$ - making in a timepoint t some event (e.g. appearance of data at the input or output of stage technology foresight), relating to this stage.

The initial G_0^T and final G_1^T states of technology foresight represent the sets, including prehistory of its instantaneous states for the period of time *T* to some initial and final timepoints.

Using the introduced concepts, build the functional part $\Phi^{\Phi T}$ of a system model technology foresight as follows:

$$\Phi^{\Phi} \subset P(G_0^T \times \theta_i^T \times G_1^T) \quad (4)$$

In the particular case Φ^{Φ} it can be given mapping

$$\Phi^{\Phi} : (G_0^T \times \Theta^T) \to G_1^T, \quad (5)$$

where: G_0^T, G_1^T - initial and final states of technology foresight for the time period T;

Θ^T - set of goals technology foresight for the time period T.

Mapping (5) shows, that the final status of any of the stages of foresight - a function of its initial state and specified goal of this stage, specifying these states.

Methodical part of the model Φ^M is intended to describe the possibilities on any stage technology foresight to reach certain values of the output value for the fixed initial state and a specified goal, i.e. reflects a transition way from input elements to output:

$$\Phi^M : (\Theta \times \Lambda) \to \Omega, \quad (6)$$

where: $\Theta = \{\theta_i\}, i = \overline{1,k}$ - set of goals technology foresight that indicate a given state of technology foresight;

$\Lambda = \{\lambda_q\}, q = \overline{1,z}$ - set of stage of technology foresight;

$\Omega = \{\omega_j\}, j = \overline{1,n}$ - plural sets of methods technology foresight.

As a result, the system model (SM) of technology foresight will be the following:

$$\Phi = (\Phi^{\Phi} \times \Phi^M),$$
$$\Phi^{\Phi} : (G_0^T \times \Theta^T) \to G_1^T, \quad (7)$$
$$\Phi^M : (\Theta \times \Lambda) \to \Omega$$

where: Φ^{Φ}, Φ^M - functional and methodical parts of SM of technology foresight;

G_0^T, G_1^T - initial and final states of technology foresight for the time period *T*;

Θ^T - set of goals technology foresight for the time period T.

SM of technology foresight is shown in fig. 3. On the input of stage technology foresight when he is in some initial state, incoming input action in the form of given purpose, which upon reaching of it this stage should go to the desired finite state.

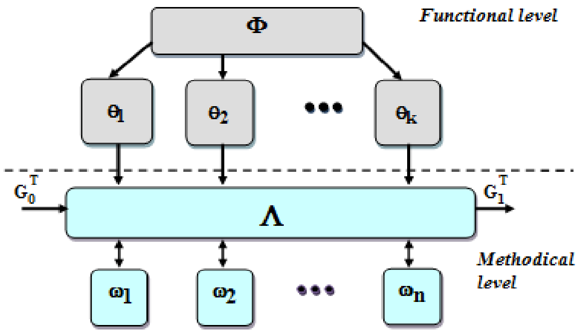

Fig. 3. Structural diagram the system model of technology foresight

For a further concretization of SM, taking into account the selected properties of discrecity and determinancy, the mathematical apparatus of the automata theory is used. In this case the system is represented in the form of automaton which processes the discrete information and changes its internal states only in admissible timepoints [32]. For computer implementation of model technology foresight is supposed to use network models, namely, the apparatus of Joiner-networks (JN) defines a connectivity and directivity of transmission of output results as input alphabets. JN is extension of Petri nets and differs in existence of special starting and flag functions which are formed by arbitrary boolean functions and allow to describe logic of network functioning [33, 34]. Each transition in JN (technology foresight stage) with a set of input and output positions compared automaton:

$$A = \langle \psi, \varphi, P, R \rangle, \quad (8)$$

where: $P(p_1,...,p_n)$ - a set of input and output positions;

$\psi(p_1,...,p_n)$ - starting function, defining conditions of start transition and the corresponding subprocess (a stage of a foresight-research). $\psi(p_1,...,p_n)=1$, where value of position $p_i=1$ - the appropriate event arose, $p_i=0$ - the event didn't arise, or was "erased" from memory of a position;

$\varphi(p_1,...,p_n)$ - the flag function giving new values to all positions (input and output) after the end of process;

$R(r_1,...,r_n)$ - a register memory of positions where are remembered the values $\{0, 1\}$ signaling about emergence (not emergence) of the appropriate events.

Operation of the elementary automaton is gives by the boolean equations for each transition *S*:

$$S:\psi(p_1(t),...,p_n(t))\rightarrow\varphi(p_1(t+1):= \\ =\{0,1\},...,p_n(t+1):=\{0,1\}) \quad (9)$$

The system of the logical equations compared to each transition $S_i\ (i=\overline{1,k})$ between stages of a foresight-research sets a network of automata which is obtained by identification of the appropriate positions of these automata:

$$\begin{cases} S_1:\psi_1(P_1(t))\rightarrow\varphi_1(P_1(t+1)) \\ S_2:\psi_2(P_2(t))\rightarrow\varphi_2(P_2(t+1)) \\ ... \\ S_k:\psi_k(P_k(t))\rightarrow\varphi_k(P_k(t+1)) \end{cases}. \quad (10)$$

The automaton launches subprocess if the vector of positions *P(t)* corresponds $\psi=1$, and by finishing of its operation change of a vector *P(t+1)* happens according to flag function.

Each stage of a foresight-research presents itself separate subprocess, representable in the form of a network, which controls "switching on" of own process and delivering of the synchronizing events to other elements of a network. Fig. 4 shows the internal structure of any of foresight-research stages in the form of JN. The beginning of a stage - S_0, and an event $\psi=1$ controls the beginning of the stage S_0. The termination of a stage *S* - S_P, and event $P=1$ controls its termination. Formally transition in JN will respond the elementary finite state machine, with the states: S_0 - process in a standby mode; S_p - process in an operation mode.

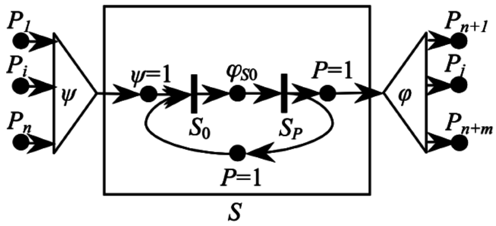

Fig. 4. The internal structure of a typical stage foresight-research in the form of JN

CONCLUSION

1. Shows the informative and the formal statement of the problem of synthesis the model of computer implementation of technology foresight.
2. Create the system model of implementation the foresight-researches based on event approach to decision making that unlike the existing allows to display the difficult nature of foresight and provides transition from heuristic procedures to their formal description for further informatization of technology foresight.
3. It is shown that network models, generally, provide adequate formal representation of foresight-researches and the most appropriate instrument of representation foresight-researches is the JN.

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ECONTECHMOD. AN INTERNATIONAL QUARTERLY JOURNAL – 2015, Vol.4, No.3, 25-32

A MATHEMATICAL MODEL FOR EVALUATION THE EFFICIENCY OF GAS-MAIN PIPELINES IN TRANSIENT OPERATIONAL MODES

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Received July 15.2015: accepted August 16.2015

Abstract. A mathematical model for control by transient modes of gas flows in the long-distance gas pipeline is considered in the paper. The long-distance pipeline is considered in the model as the system of line segments serially connected via compressor stations. Gas motion in such system is described by the non-linear system of equations of gas dynamics. In the frame of this model the integral parameters which determine the expenditure of energy and durations of the transient mode are introduced. These parameters can be used for formulation the problems for optimal control steady-state and transient modes of operation of main-gas pipelines.

Key words: gas-main pipeline, transient modes of operation, models of gas dynamics, control by transient process, efficiency of gas transportation, duration of transient process.

INTRODUCTION

Long-distance gas pipelines are used in many countries for natural gas delivery from the producing areas to market areas. The gas transmission system (GTS) of Ukraine resolves two main functions: supplies the internal customers by natural gas and transits it to Central and Eastern European's countries [1]. The length of the Ukrainian gas-main pipelines is over 37 thousands km. They are provided by 71 compressor stations, the overall power of which exceeds 5400 MW. High power of the compressor stations, high pipeline's capacity, which substantially exceeds the average annual gas flow through it, and availability of underground gas storage facilities of capacity $31\cdot10^9$ m^3 make it possible to deliver big amounts of gas on long distances in short time periods [1].

The expenditures of energy for gas transportation are dependent on mode of GTS operation. Steady-state operate modes are the most effective ones if the maximal pressure in the pipeline is close to maximum allowable pressure and the compressor stations work with the highest efficiency. But in practice the necessity to use transient modes under which the inlet and outlet pressures and flow density in the pipelines vary in time. In the transient modes the expenditures of energy can be considerably higher in comparison with the stationary modes. In this connection the problem of minimization of energy costs of gas transportation in the transient modes of operation of gas-main pipelines becomes actual.

A mathematical model for control by transient modes of gas flows in the long-distance gas pipeline is considered in the paper. In the frame of this model the integral parameters which determine the expenditure of energy and durations of the transient mode are introduced. These parameters can be used for formulation the problems for optimal control by steady-state and transient modes of operation of main-gas pipelines.

THE PROBLEM STATEMENT

We consider a long-distance pipeline as the system of line pipelines (segments) serially connected via compressor stations. Each segment is long pipeline. Gas motion in such system is described by the non-linear system of equations of gas dynamics. The equations of this system bound the parameters of gas state (pressure P, mass density ρ, and temperature T) and the parameters of gas motion (velocity V and mass flux J) in each segments. The system should be complemented by the conditions, which take into account the effect of the compressor stations on the gas flow. These conditions couple the gas-dynamics parameters of adjoining segments.

In stationary modes the state and flow parameters in each segment are dependent just on the spatial coordinate along he tube's axis whereas the interface conditions are constant. In transient modes the interface conditions change with time whereas the state and flow parameters are functions of the spatial coordinate x and time t:

$$P = P(x,t),\ \rho = \rho(x,t),\ T = T(x,t)\ \ V = V(x,t),$$
$$J = J(x,t).$$

These functions can be determined by solving the boundary-initial value problem, formulated within the mathematical model describing the mass, momentum and energy transfer in each segment. With the use of the obtained solution one can calculate integral parameters of the transient flow – the mass of the gas containing in each segment, the duration of the transient process, the expenditure of energy spent on its realization etc.

We suppose that inlet and outlet pressures can be measured with sufficient precision as functions of time:

$$P_\lambda^{in} = P_\lambda^{in}(t),\ P_\lambda^{out} = P_\lambda^{out}(t).$$

We can use these functions as the boundary conditions for each segment. In such way we define two functionals, which for any pair of functions:

$$\{P_\lambda^{in}(t), P_\lambda^{out}(t)\}$$

determine two positive numbers: τ – the duration of the transient process, and W – the expenditure of energy spent on this process realization.

Similarly, if to suppose that inlet and outlet mass fluxes can be measured:

$$J_\lambda^{in} = J_\lambda^{in}(t),\ J_\lambda^{out} = J_\lambda^{out}(t),$$

we can consider another three pair of boundary conditions:

$$\{P_\lambda^{in}(t), J_\lambda^{out}(t)\},\ \{J_\lambda^{in}(t), P_\lambda^{out}(t)\} \text{ and } \{J_\lambda^{in}(t), J_\lambda^{out}(t)\}.$$

The boundary-value problems, formulated with the use of these conditions, define the functionals for determination τ and W for corresponding transient process, controlled by given pair of the parameters.

THE MODEL FOR GAS-DYNAMIC IN A LONG PIPELINE

We will conduct the study within the one-dimensional model of gas-dynamics, describing non-stationary motion of natural gas in a cylindrical pipe of constant diameter. Such models were considered by many authors [2-12]. Here we restrict ourselves by the isothermal case, supposing the temperature T as the given parameter, independent on coordinate x and time t. In this case the flows in the segment are described by two partial differential equations – the equation for mass balance (equation of continuity):

$$\frac{\partial\rho}{\partial t} + \frac{\partial\rho V}{\partial x} = 0 \qquad (1)$$

and equation for balance of momentum:

$$\frac{\partial\rho V}{\partial t} + \frac{\partial}{\partial x}\left(\rho V^2 + P\right) + \rho g\frac{\partial h}{\partial x} + f_R = 0 \qquad (2)$$

where: g stands for acceleration of gravity; $h = h(x)$ is the function, determining the elevation of the pipeline's axis; f_R stands for the density of average frictional force [4].

Density ρ of the gas is depended on its pressure P and temperature T. The dependence is defined by the equation of state:

$$P = R/\mu_g\ z\rho T = c_0{}^2 z\rho, \quad c_0^2 \equiv RT/\mu_g, \qquad (3)$$

where: R - stands for the universal gas constant, μ_g - is molar mass of the gas, z - compressibility factor of the gas, c_0 - stands for sound velocity in the gas with molar mass μ_g at temperature T.

The compressibility factor z takes into account departure of thermodynamic properties of real gas from the properties of ideal gas. The are different empirical formulas representing this thermodynamic parameter as function of pressure P and temperature T. Among them the formula of American Gas Association (AGA), which is valid for pressures up to 7 MPa:

$$z(P,T) = 1 + 0,257\cdot(P/P_c) - 0,533\cdot(P/P_c)\cdot(T_c/T), \qquad (4)$$

where: T_c and P_c stand for critical temperature and pressure

The force f_R in formula (2) takes into account the viscous friction in gas volume, in the boundary layer and on the inside surface of the pipe's wall. For sufficiently high flow's velocity (turbulent flow mode) f_R can be determined by formula:

$$f_R = \frac{\lambda|V|}{2D}\rho V, \qquad (5)$$

where: λ - stands for the coefficient of hydraulic resistance, D - is pipe's inner diameter.

The Haaland explicit equation [6] enables to express parameter λ through the height ε of roughness on the inner surface of the pipe's wall and Reynolds number Re of the flow:

$$\frac{1}{\sqrt{\lambda}} = -1.8\lg\left(\frac{6.9}{Re} + \left(\frac{\varepsilon D}{3.7}\right)^{1.11}\right).$$

Using formulas (3)-(5) one can reduce mathematical model for motion of the gas in the pipeline to non-linear system of two partial differential equations. Any pair of the parameters (ρ, V), (ρ, J), (P, V) or (P, Q) can be used as key functions for this system. Here:

$$J = \rho V \quad \text{and} \quad Q = V\pi D^2/4$$

are the mass and volumetric flow rates. Though the systems of equations formulated for different pairs of parameters are mathematically equivalent, the chosen key functions can be significant for algorithms for numerical solving of the corresponding problems. With this in view we chose the parameters $\rho = \rho(x,t)$ and $J = J(x,t)$ as the key functions for mathematical model. So, we obtain

$$\frac{\partial\rho}{\partial t}+\frac{\partial J}{\partial x}=0 \tag{6}$$

$$\frac{\partial J}{\partial t}+\frac{\partial P}{\partial\rho}\frac{\partial\rho}{\partial x}+\frac{\partial}{\partial x}\left(\frac{J^2}{\rho}\right)+\frac{\lambda}{2D}\frac{|J|J}{\rho}+g\frac{dH}{dx}\rho=0\,. \tag{7}$$

As we can see the equation (6) of the system (6), (7) is a linear one in this case.

Without restriction of generality we can treat the compressibility factor z as a function of the state parameters ρ and T. Hence of the base of (3) we have

$$\frac{\partial P}{\partial\rho}=c_0^2 Z(\rho,T),\quad Z(\rho,T)\equiv z(\rho,T)+\rho\frac{\partial z(\rho,T)}{\partial\rho}\,. \tag{8}$$

In particular, for compressibility factor in the form (4) relations (8) look like

$$\begin{gathered} z(\rho,T)=\frac{1}{1-\dfrac{\rho}{\rho_c}\left(0,257-0,533\dfrac{T_c}{T}\right)},\\ Z(\rho,T)=\frac{1}{\left[1-\dfrac{\rho}{\rho_c}\left(0,257-0,533\dfrac{T_c}{T}\right)\right]^2}, \end{gathered} \tag{9}$$

where: $\rho_c\equiv P_c/c_0^2$.

If functions $\rho(x,t)$ and $J(x,t)$ are known one can easily calculate the pressure $P(x,t)$ and velocity $V(x,t)$ as functions of coordinate x and time t:

$$P=c_0^2 z(\rho)\rho\,,\qquad V=J/\rho\,. \tag{10}$$

Let P_0 and J_0 be some characteristic values of pressure and mass flux. We introduce the normalized dimensionless coordinate, time and dependent variables:

$$\begin{gathered} \xi=2\frac{x}{L}-1,\ \tau=\frac{t}{t_0},\ \tilde\rho=\frac{\rho}{\rho_0},\\ j=\frac{J}{J_0},\ p=\frac{P}{P_0},\ v=\frac{V}{V_0}, \end{gathered} \tag{11}$$

where: L - is the section's length, $t_0=L/c_0$ - is the characteristic time, ρ_0 - stands for characteristic mass density, which corresponds to characteristic pressure:

$$P_0=c_0^2 z(\rho_0)\rho_0\,,$$

and characteristic velocity:

$$V_0=J_0/\rho_0\,.$$

In the dimensionless variables the system (6), (7) takes the form:

$$\frac{\partial\tilde\rho}{\partial\tau}+Ma\frac{\partial j}{\partial\xi}=0\,, \tag{12}$$

$$\begin{gathered} \frac{\partial j}{\partial t}+\frac{1}{Ma}Z(\tilde\rho,T)\frac{\partial\tilde\rho}{\partial\xi}+Ma\frac{\partial}{\partial\xi}\left(\frac{j^2}{\tilde\rho}\right)+\\ +Ma\beta\left(\frac{j^2}{\tilde\rho}\right)+\frac{d\gamma}{d\xi}\tilde\rho=0. \end{gathered} \tag{13}$$

Here the denotations are used:

$$Ma=\frac{J_0}{\rho_0 c_0}=\frac{V_0}{c_0},\ \beta=\frac{\lambda L}{2D},\ \gamma=\frac{H}{H_0},\ H_0=\frac{c_0 V_0}{g}\,.$$

In the stationary case:

$$\partial\tilde\rho/\partial\tau=\partial j/\partial\tau=0\,.$$

So, it follows from equation (12), that $j(\xi)=const$. With this, the equation (13) can be reduced to the form:

$$\frac{d\tilde\rho}{d\xi}=-\frac{Ma^2\beta j^2\tilde\rho+Ma\dfrac{d\gamma}{d\xi}\tilde\rho^3}{Z(\tilde\rho)\tilde\rho^2-Ma^2 j^2}\,. \tag{14}$$

Obtaining ordinary differential equation describes the steady-state distribution of the mass density in a pipeline in stationary mode. This non-linear equation can be solved numerically with the use a Runge-Kutta method. When the density ρ of the gas is known one can calculate its pressure with the use of the state equation (3).

THE MODEL FOR CONTROLLING OF THE TRANSIENT PIPELINE'S OPERATIONAL MODES

The equations (12), (13) describe a wide class of non-stationary (dynamic) motion of the gas in pipelines. We chose from this class so-called transient motions. So, each time we will consider a dynamic motion, which has been started from some known steady-state motion and will be finished as other steady-state motion. I.e. we will consider dynamic processes being transitions between two steady-state processes.

Let J^0 and J^1 be the mass fluxes in steady-state modes 0 (beginning mode) and 1 (finishing mode), P_-^0 and P_+^0 be static inlet and outlet pressures acting in the mode 0, P_-^1 and P_+^1 be static inlet and outlet pressures acting in the mode 1.

We can find pressure distributions in modes 0 and 1 using the steady-state model (14). To do that we put in the equation (14) $j = j^0 \equiv J^0/J_0$, solve this equation subordinating its solution $\tilde{\rho}^0 \equiv \tilde{\rho}^0(\xi)$ to one of boundary conditions (15) at $\mu = 0$:

$$\tilde{\rho}^\mu\big|_{\xi=-1} = \tilde{\rho}^\mu_-,\ \tilde{\rho}^\mu\big|_{\xi=1} = \tilde{\rho}^\mu_+,\quad \lambda = 0,1, \tag{15}$$

where:

$$\tilde{\rho}^\mu_- = \frac{P^\mu_-}{c_0^{\,2} z\left(P^\mu_-, T\right)\rho_0},\quad \tilde{\rho}^\mu_+ = \frac{P^\mu_+}{c_0^{\,2} z\left(P^\mu_+, T\right)\rho_0}. \tag{16}$$

Then we put in the equation (14) $j = j^1 \equiv J^1/J_0$, solve this equation, subordinating its solution $\tilde{\rho}^1 \equiv \tilde{\rho}^1(\xi)$ to one of boundary conditions (15) at $\mu = 1$.

We use the first of two conditions (15), when in the stationary mode μ inlet pressure is given, and we use the second condition (15), when in the stationary mode μ outlet pressure is given.

Using the obtained solution we can find the pressure distributions in stationary modes 0 and 1 $P^1(x)$ and $P^2(x)$ in the section:

$$P^\mu(x) = P_0 c_0^{\,2} \tilde{\rho}^\lambda\left(x/L_0\right) z\left(\tilde{\rho}^\lambda\left(x/L_0\right), T\right). \tag{17}$$

We can find also the value of pressure on the opposite end of the pipe for both modes. For instance, if in the mode μ the inlet pressure P^μ_- is given, then the outlet pressure P^μ_+ for this mode can be can be found as:

$$P^\lambda_+ = P_0 c_0^{\,2} \tilde{\rho}^\lambda(1) z\left(\tilde{\rho}^\lambda(1), T\right).$$

Otherwise, if the outlet pressure P^μ_+ is given, the outlet pressure will be found as:

$$P^\lambda_- = P_0 c_0^{\,2} \tilde{\rho}^\lambda(-1) z\left(\tilde{\rho}^\lambda(-1), T\right).$$

To attain the required flow parameters in the pipeline one can change the mechanical power, which the compressor stations transfer into the moving gas. That will be attended by varying of values of the gas-dynamics parameters on the both ends of the each section.

We suppose, that inlet and outlet pressure, and, in some cases, inlet and/or outlet mass fluxes can be measured with necessary precision as. It means, that for each segment we dispose functions $P_\pm(t)$, representing the time variation of inlet and outlet pressures. In some case we can dispose functions $J_\pm(t)$, representing the time variation of the inlet and outlet fluxes.

Such assumptions enables to consider independent problems for each segment and use for it four types of boundary conditions: i) on both ends pressure as functions of time are given (the conditions of the first kind); ii) on both ends flux as functions of time are given (the conditions of the second kind); iii) inlet pressure and outlet flux as functions of time are given; iv) inlet flux and outlet pressure as functions of time are given (the mixed boundary conditions). Due to this we consider for system (12), (13) the next boundary conditions:

$$\tilde{\rho}\big|_{\xi=-1} = \tilde{\rho}_-(\tau),\qquad \tilde{\rho}\big|_{\xi=1} = \tilde{\rho}_+(\tau), \tag{18}$$

$$j\big|_{\xi=-1} = j_-(\tau),\qquad j\big|_{\xi=1} = j_+(\tau), \tag{19}$$

$$\tilde{\rho}\big|_{\xi=-1} = \tilde{\rho}_-(\tau),\qquad j\big|_{\xi=1} = j_+(\tau), \tag{20}$$

$$j\big|_{\xi=-1} = j_-(\tau),\qquad \tilde{\rho}\big|_{\xi=1} = \tilde{\rho}_+(\tau). \tag{21}$$

Here:

$$\tilde{\rho}_\pm(\tau) = \frac{P_\pm(\tau t_0)}{c_0^{\,2} z\left(P_\pm(\tau t_0), T\right)\rho_0},\quad j_\pm(\tau) = \frac{J_\pm(\tau t_0)}{J_0} \tag{22}$$

As the transient mode begins from the mode 0, we have the next initial conditions for system (12), (13):

$$\tilde{\rho}\big|_{\tau=0} = \tilde{\rho}^0(\xi),\qquad j\big|_{\tau=0} = j^0. \tag{23}$$

Four initial-boundary-value problems (12), (13), (18) (23); (12), (13), (18), (23); (12), (13), (19), (23); та (12), (13), (20), (23) define corresponding four models to control the transient flow in each section.

We will restrict our consideration by control functions $P_\pm(t)$ and $J_\pm(t)$, which are monotonous in the intervals $\left[P^0_\pm, P^1_\pm\right]$ and $\left[J^0, J^1\right]$ correspondingly.

To do this let consider the function:

$$\varphi(t,\Delta) = \begin{cases} 0, & t \le 0, \\ t/\Delta, & 0 < t \le \Delta,, \quad \Delta > 0, \\ 1, & \Delta < t, \end{cases} \tag{24}$$

with the use of which we represent the control functions in the forms:

$$\begin{aligned} P_-(t) &= P^0_- + \left(P^1_- - P^0_-\right)\varphi\left(t, \Delta^P_-\right), \\ P_+(t) &= P^0_+ + \left(P^1_+ - P^0_+\right)\varphi\left(t - t^P, \Delta^P_+\right), \\ J_-(t) &= J^0 + \left(J^1 - J^0\right)\varphi\left(t, \Delta^J_-\right), \\ J_+(t) &= J^0 + \left(J^1 - J^0\right)\varphi\left(t - t^J, \Delta^J_+\right). \end{aligned} \tag{25}$$

where: t^P and t^J are real constants which define delay/lead the outlet control functions relative to inlet ones.

The boundary conditions (18)-(21) take the form:

$$\left.\tilde{\rho}\right|_{\xi=-1} = \tilde{\rho}_-^0 + \left(\tilde{\rho}_-^1 - \tilde{\rho}_-^0\right)\varphi\left(\tau, \Delta_-^\rho\right), \quad \left.\tilde{\rho}\right|_{\xi=+1} = \tilde{\rho}_+^0 + \left(\tilde{\rho}_+^1 - \tilde{\rho}_+^0\right)\varphi\left(\tau - \tau^\rho, \Delta_+^\rho\right) \quad (26)$$

$$\left.j\right|_{\xi=-1} = j^0 + \left(j^1 - j^0\right)\varphi\left(\tau, \Delta_-^j\right), \quad \left.j\right|_{\xi=+1} = j^0 + \left(j^1 - j^0\right)\varphi\left(\tau - \tau^j, \Delta_+^j\right) \quad (27)$$

$$\left.\tilde{\rho}\right|_{\xi=-1} = \tilde{\rho}_-^0 + \left(\tilde{\rho}_-^1 - \tilde{\rho}_-^0\right)\varphi\left(\tau, \Delta_-^\rho\right), \quad \left.j\right|_{\xi=+1} = j^0 + \left(j^1 - j^0\right)\varphi\left(\tau - \tau^j, \Delta_+^j\right), \quad (28)$$

$$\left.j\right|_{\xi=-1} = j^0 + \left(j^1 - j^0\right)\varphi\left(\tau, \Delta_-^j\right), \quad \left.\tilde{\rho}\right|_{\xi=+1} = \tilde{\rho}_+^0 + \left(\tilde{\rho}_+^1 - \tilde{\rho}_+^0\right)\varphi\left(\tau - \tau^\rho, \Delta_+^\rho\right). \quad (29)$$

where:

$$\tilde{\rho}_\pm^\lambda = \frac{P_\pm^\lambda}{c_0{}^2\rho_0 z\left(P_\pm^\lambda, T\right)}, \quad j^\lambda = \frac{J^\lambda}{J_0}, \quad \Delta_\pm^{\rho,j} = \frac{\Delta_\pm^{P,J}}{t_o}, \quad \tau^{\rho,j} = \frac{t^{P,J}}{t_0}.$$

Thereby due the suggested approach any of the control model (18) – (21) is defined by 7 scalar parameters. For instance for model defined by boundary conditions (28) they are $P_-^0, P_-^1, \Delta_-^P, J_-^0, J_-^1, \Delta_-^J$ and t^J.

Solving the initial-boundary-value problem, corresponding to any of control model (18) – (21), we obtain two functions $\tilde{\rho}(\xi,\tau)$ and $j(\xi,\tau)$. With the use of these functions we can introduce integral measures which determine the duration of the transient process and the expenditure of energy for its realization.

EVALUATION THE DURATION OF TRANSIENT MODE

The gas containing in the pipeline is an inertial system. Transient processes in this system can still go on even after the compressor stations have gained the steady-state modes. To evaluate the transient mode's duration we introduce measures for deviation of the current state of the gas accumulated in the pipeline from its state in the stationary mode 1, to which the system tends.

We consider two kinds of such measures. The measures of the first kind determine the deviations of the current values of gas-dynamic parameters on the ends of the section from their corresponding values in the stationary mode 1. Depending on the chosen control model (18)-(21), we will consider four such measure:

$$\begin{aligned} \delta^j(\tau) &= \max\left(\delta_-^j(\tau), \delta_+^j(\tau)\right), \\ \delta^\rho(\tau) &= \max\left(\delta_-^\rho(\tau), \delta_+^\rho(\tau)\right), \\ \delta^{j\rho}(\tau) &= \max\left(\delta_-^j(\tau), \delta_+^\rho(\tau)\right), \\ \delta^{\rho j}(\tau) &= \max\left(\delta_-^\rho(\tau), \delta_+^j(\tau)\right), \end{aligned} \quad (30)$$

where:

$$\delta_-^j(\tau) = \left|\frac{j(-1,\tau) - j^1}{j^1}\right|, \ \delta_+^j(\tau) = \left|\frac{j(1,\tau) - j^1}{j^1}\right|, \quad \delta_-^\rho(\tau) = \left|\frac{\tilde{\rho}(-1,\tau) - \tilde{\rho}_-^1}{\tilde{\rho}_-^1}\right|, \ \delta_+^\rho(\tau) = \left|\frac{\tilde{\rho}(1,\tau) - \tilde{\rho}_+^1}{\tilde{\rho}_1^1}\right|. \quad (31)$$

The measures of second kind determine deviations of the current values of integral characteristic in pipeline's volume. We will consider two kinds of such measures, which corresponds two equations of gas dynamics (6) and (7).

The first measure $\delta^M(\tau)$ defines deviation of the mass containing in the pipeline at the current moment τ from its value in the stationary state 1. The second one determines the current deviation the value of the momentum of gas containing in the pipelines:

$$\delta^M(\tau) = \frac{\int_{-1}^{1}\left|\tilde{\rho}(\xi,\tau) - \tilde{\rho}^1(\xi)\right| d\xi}{\int_{-1}^{1}\tilde{\rho}^1(\xi)\, d\xi}, \quad \delta^J(\tau) = \frac{\int_{-1}^{1}\left|j(\xi,\tau) - j^1\right| d\xi}{j^1}. \quad (32)$$

Let ε a given positive real number:

$$\tau_\varepsilon^\omega : \delta^\omega\left(\tau_\varepsilon^\omega\right) = \varepsilon \ \ \forall\omega \in \left\{j, \rho, i\rho, \rho j, M, J\right\}.$$

Then we define the real number:

$$\tau_\varepsilon = \mathrm{Inf}\left\{\tau_\varepsilon^\omega, \omega = j, \rho, i\rho, \rho j, M, J\right\}$$

as dimensionless duration of the transient process from stationary state 0 to stationary state 1.

Introduced measures (30) and (31) of nonstationarity enable to evaluate quantitatively the duration of the transient process for any chosen control model (18) – (21).

EVALUATION THE POWER EFFICIENCY OF TRANSIENT MODES

Using the solution of the initial-boundary-value problems corresponding to any chosen control model (18) – (21), we can calculate the power of friction force f_R at any moment τ:

$$W_R(\tau) = \beta\frac{\pi D^2 J_0{}^3}{8\rho_0{}^2}\int_{-1}^{1}\frac{j^3(\xi,\tau)}{\tilde{\rho}^2(\xi,\tau)}d\xi. \quad (33)$$

Due to this the energy efficiency of the transient mode can be evaluated as:

$$\eta_\varepsilon = \beta \frac{J_0^{\,2}}{2\rho_0^{\,2}} \int_0^{\tau_\varepsilon} \int_{-1}^{1} \frac{j^3(\xi,\tau)}{\tilde\rho^2(\xi,\tau)} d\xi d\tau \Big/ \int_0^{\tau_\varepsilon^\omega} j(1,\tau) d\tau \qquad (34)$$

Then we can compare parameter η_ε to corresponding parameters η^0 and η^1, defining the expenditures of energy for the modes 0 and 1 correspondingly:

$$\eta^0 = \beta \frac{(J^0)^2}{2\rho_0^{\,2}} \int_{-1}^{1} \frac{d\xi}{(\tilde\rho^0(\xi))^2}, \ \eta^1 = \beta \frac{(J^1)^2}{2\rho_0^{\,2}} \int_{-1}^{1} \frac{d\xi}{(\tilde\rho^1(\xi))^2}. \qquad (35)$$

Using introduced parameter η_ε we can compare quantitatively different transient modes and different control models.

NUMERICAL STUDY

Consider an example of application the developed mathematical tools to study the control model (20).

To numerical solving the initial-boundary-value problem (12), (13), (23), (28) we represent the sought-for functions $\tilde\rho(\xi,\tau)$ and $j(\xi,\tau)$ as Fourier-Legendre series expansions:

$$\tilde\rho(\xi,\tau) = \sum_{k=0}^{N} A_k(\tau) P_k(\xi), \ j(\xi,\tau) = \sum_{k=0}^{N} B_k(\tau) P_k(\xi) \ .(36)$$

With the use of the spectral Galerkin method [13–16], we reduce equations (12), (13) to the system of ordinary differential equations:

$$\begin{array}{l} \dfrac{d\mathbf{A}}{dt} + \mathbf{C}_{12}\cdot\mathbf{B} + \mathbf{K}_1 = 0 \\ \dfrac{d\mathbf{B}}{dt} + \mathbf{C}_{21}\cdot\mathbf{A} + \mathbf{C}_{22}\cdot\mathbf{B} + \mathbf{K}_2 = 0 \end{array}, \qquad (37)$$

where:

$$\begin{array}{l} \mathbf{A} = (A_1(\tau), A_2(\tau), \dots, A_N(\tau))^{\mathrm{T}}, \\ \mathbf{B} = (B_0(\tau), B_1(\tau), \dots, B_{N-1}(\tau))^{\mathrm{T}} \end{array}.$$

The (**37**) is nonlinear one as elements of matrixes $\mathbf{C}_{21}$, $\mathbf{C}_{22}$ are functionals of sought-for solution (36). Elements of vectors $\mathbf{K}_1$ and $\mathbf{K}_2$ are functionals of the given control functions of boundary conditions (28).

System (37) was discretized on the uniform time grid with the use of the Crank–Nicolson's difference scheme [13]. To solve the obtained nonlinear algebraic system of equations an iterative algorithm was developed.

On fig.1,2 some results obtained by solving the problem (12), (13), (23), (28) are shown (arrows on the plots show time increasing). The numerical solution was obtained for the case, when mass flow rate in the pipeline is increased for 15 % under constant inlet pressure.

The calculations were made for $N = 15$, time discretization was made with time step $\delta\tau = 0,05$.

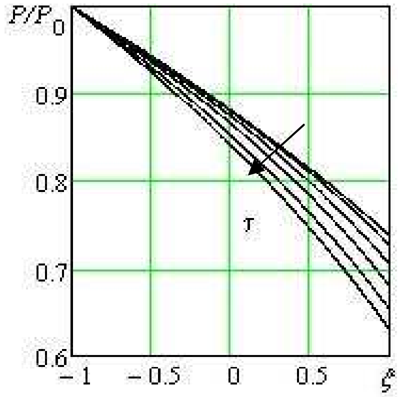

Fig.1. Pressure distributions along the pipeline at the moments τ = 0; 4; 8; 12; 20 and 40

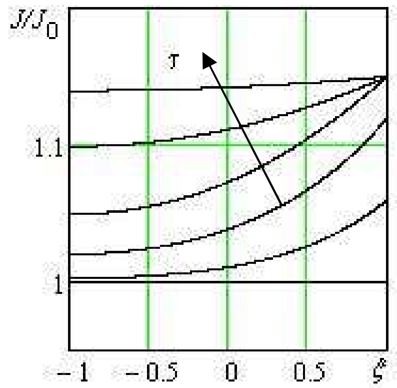

Fig.2. Flux distributions along the pipeline at moments τ = 0; 4; 8; 12; 20 and 40

The gas mixture in proportion: methane – 98.6 %, ethane – 0.15 %, carbon dioxide – 0.31 %, nitrogen – 1.24 %. was considered. The next values for the task's parameters were taken: the pipeline's length L = 120 km, the pipeline's inner diameter D = 1.338 m, the characteristic pressure P_0 = 6.65 MPa, the characteristic temperature T = 300 K, the characteristic mass flux J_0 = 468 kg / m^{2}s, the friction factor $\lambda = 9.22\cdot 10^{-3}$. Calculated characteristic time and Mach number are: $t_0 = 302.58\ s$, $Ma = 0.024$, dimensionless friction factor $\beta = 413.46$.

On the fig. 3 the time dependences for the measures of nonstationarity are shown: the solid, dashed, chain and dotted lines correspond:

$$\delta_-^J(\tau),\ \delta_+^P(\tau),\ \delta^M(\tau) \text{ and } \delta^J(\tau),$$

respectively.

We obtained the values:

$$\delta_-^J(\tau) = 4.79\cdot 10^{-3}, \quad \delta_+^P(\tau) = 3.24\cdot 10^{-3},$$

$$\delta^M(\tau) = 1,28\cdot 10^{-3} \text{ and } \delta^J(\tau) = 6,42\cdot 10^{-3} \text{ at } \tau = 48.$$

On this basis we can conclude, that with precision $6,42\cdot 10^{-3}$ the transient process's duration, determined due to measure δ^J equals $48 t_0 \approx 1,452\cdot 10^4$ s, i.e. is more the four hours.

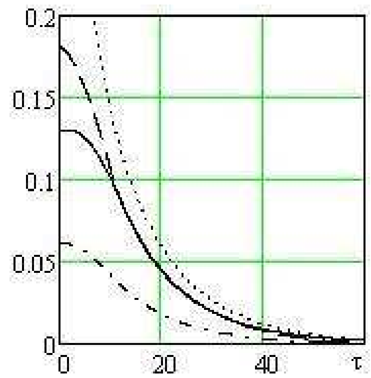

Fig. 3. Dependences of the measures of nonstationarity on time τ

The expenditure of energy referred to the constant $\left(\beta J_0^{\,2}\right)/\left(2\rho_0^{\,2}\right)=8.143\ \mathrm{J/kg}$ equal: $\eta_\varepsilon^J=3,689$ (for transient mode), $\eta^0=2.744$ (for stationary mode 0) and $\eta^1=3,207$ (for stationary mode 1).

CONCLUSIONS

1. The nonstationary one-dimensional initial-boundary-value problems for gas dynamics in long-distance pipeline have been considered. The problems describe transient processes arising in the pipeline under transition of the pipeline from one stationary operational mode to another. Several models to control the transient operational modes have been considered. They differ by the control functions, which determine time variations of the inlet and outlet control parameters (pressures and/or fluxes). The approach for parameterization of the control functions has been proposed. Due to it the control functions can be parameterized by several scalar parameters, among them – mean rates of inlet and outlet control parameters' variations, and time shift between the output and input control actions.

2. The approach to evaluation the duration and expenditure of energy of the transient operational mode has been proposed. The approach is based on the functionals which have been introduced to determine the measures for deviation of the current state of the gas accumulated in the pipeline from its state in the stationary mode, to which the system tends. The measures enable to compare quantitatively different transient modes which realized according to different control models with different control functions. The defined functionals can be used to formulate the problems for optimal control the steady-state and transient modes of operation of main-gas pipelines.

3. The iterative algorithm for numerical solving of the nonlinear initial-boundary-value problems, which correspond to the proposed models for controlling the transient modes, has been developed. The approach is based on representation the solutions as Fourie-Legendre series expansion and time discretization of the sought-for functions with the use of the Crank–Nicolson's difference scheme.

4. The numerical experiments, which have been conducted for different control models, corroborated the high efficiency of the developed approaches and possibility of their application to model the transient processes in long-distance pipelines. The developed approaches and mathematical tools can be used to formulate the problems for optimal control the pipeline's transient operational modes and to solve these problems by their reducing consequences of corresponding direct problems.

5. Considered in the paper model of isothermal flow do not includes the expenditure of energy caused be heat exchange with environment. To raise the practical value of the developed approach it should be improved by taking into consideration the process of energy transfer.

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ECONTECHMOD. AN INTERNATIONAL QUARTERLY JOURNAL – 2015, Vol.4, No.3, 33-38

ELEMENTS TRANSPOSITIONS AND THEIR IMPACT ON THE CYCLIC STRUCTURE OF PERMUTATIONS

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Received June 25.2015: accepted August 24.2015

Abstract**.** The objective of this paper is the investigation of the cyclic structure and permutation properties based on neighbor elements transposition properties and the properties of the permutation polyhedron. In this paper we consider special type of transpositions of elements in a permutation. A feature of these transpositions is that they corresponding to the adjacency criterion in a permutation polyhedron. We will investigate permutation properties with the help of the permutation polyhedron by using the immersing in the Euclidian space. Six permutation types are considered in correspondence with the location of arbitrary components. We consider the impact of the corresponding components on the cyclic structure of permutations depending on the type of a permutation. In this paper we formulate the assertion about the features of the impact of transpositions corresponding to the adjacency criterion on the permutations consisting of the one cycle. During the proof of statement all six types of permutations are considered and clearly demonstrated that only two types arrangement of the elements in the cycle contribute to the persistence a single cycle in the permutation after the impact of two transpositions. Research conducted in the given work, will be further employed in mathematical modeling and computational methods. Especially for solving combinatorial optimization problems and for the generation of combinatorial objects with a predetermined cyclic structure.

Key words. Permutations set, permutation polyhedron, adjacency criterion, permutation properties, transposition, combinatorics.

INTRODUCTION

This research is devoted to the investigation of two consecutive transpositions of neighboring by value generative elements of a permutation and their impact on the cyclic structure of the permutation being considered, and also their relative location on the permutation polyhedron.

In this paper we introduce a classification of permutations in dependence of some components relative location and the impact of these components transpositions on the permutation structure.

The aim of this paper is the investigation of the cyclic structure and permutation properties based on neighbor elements transposition properties and the properties of the permutation polyhedron.

THE ANALYSIS OF RECENT RESEARCHES AND PUBLICATIONS

Permutations sets are very often considered in theoretical and applied research in the field of combinatorics and combinatorial optimization [1–18]. By now many properties of permutations have been investigated, in particular those associated with the cyclic structure of permutations. Some methods and algorithms allowing the representation of permutations as the product of cycles and the generation of permutations having a predefined cyclic structure are known [1, 4, 6-9, 10-14].

A well-known way for investigating combinatorial sets is their immersion into the Euclidian space, which allows using tools of continuous mathematics when analyzing combinatorial problems [2, 5]. The convex hull of a permutations set immersed into the Euclidian space is a permutation polyhedron [3, 16]. One of the basic properties of this polyhedron is the fact that the adjacency criterion for its vertexes is satisfied [1-3].

The geometric and analytic interpretations of one transposition corresponding to the permutation adjacency criterion are well known and were investigated earlier [2, 3, 18, 19]. The same issues discussed in this paper are used in the mathematical modeling and computational methods to describe and solve many economic, social and applied problems [20-23].

BASIC DEFINITIONS

Let P_n^C be the set of cyclic permutations without repetition from n real numbers [4, 9]:

$$a_1 < a_2 < ... < a_n : \ \alpha = (\alpha_1, \alpha_2, ..., \alpha_n) \in P_n^C ,$$

where:

$$c_i \in R , \ i \in J_n = \{1, 2, ..., n\} .$$

Consider the notion of permutation in detail [9].

Definition 1. A linear ordering of the elements from a certain generating set $A = \{a_1, a_2, ..., a_n\}$ is called a permutation:

$$\pi = \pi(a_1, a_2, ..., a_n) = (\pi(a_1), \pi(a_2), ..., \pi(a_n)) = (a_{i_1}, a_{i_2}, ..., a_{i_n})$$

or, if it is necessary to stress the fact that it contains n elements, n-permutation.

We denote as P_n the set of permutations generated by the elements $a_1 < a_2 < ... < a_n$.

Consider a certain permutation $\pi = (\pi(a_1), \pi(a_2), ..., \pi(a_n)) \in P_n$ and its element $\pi(a_i) = a_j$, $\forall i, j \in J_n$. Then we can write down:

$$\pi(a_j) = \pi(\pi(a_i)) = \pi^2(a_i) .$$

Generally, this formula can be represented in the following form:

$$\pi^{k-1}(a_j) = \pi(\pi^{k-1}(a_i)) = \pi^k(a_i) ,$$
$$\forall i, j \in J_n ,\ k \le n .$$

Thus if for some $l \ge 1$ we have:

$$\pi^l(a_i) = a_i ,\ i \in J_n$$

and all the elements

$$a_i, \pi(a_i), \pi^2(a_i), ..., \pi^{l-1}(a_i)$$

are different, the sequence:

$$(a_i, \pi(a_i), \pi^2(a_i), ..., \pi^{l-1}(a_i))$$

is called [2] an l length cycle.

Definition 2. A cyclic permutation is such a permutation π from n elements that contains a single n length cycle [2], i.e.:

$$\pi^n(a_i) = a_i ,\ \forall i \in J_n .$$

We denote such permutations as π_C. Note that, according to [4]:

$$Card\ P_n^C = (n-1)! .$$

Let us consider a cyclic permutation example. In this work we will use the following notation way. We record two rows so that the generating elements are written not in the increasing order but in the order of their appearance in the cycle:

$$\begin{pmatrix} 1 & & 4 & & 6 & & 2 & & 5 & & 8 & & 3 & & 7 \\ \downarrow & \nearrow & \downarrow & \nearrow & \downarrow & \nearrow & \downarrow & \nearrow & \downarrow & \nearrow & \downarrow & \nearrow & \downarrow & \nearrow & \downarrow \\ 4 & & 6 & & 2 & & 5 & & 8 & & 3 & & 7 & & 1 \end{pmatrix} = \begin{pmatrix} 1 & 4 & 6 & 2 & 5 & 8 & 3 & 7 \\ 4 & 6 & 2 & 5 & 8 & 3 & 7 & 1 \end{pmatrix}.$$

One of the widespread directions of combinatorial research is the immersion (enclosure mapping) of a combinatorial set into the Euclidian space [5].

The immersion of combinatorial sets in the Euclidian space allows constructing combinatorial polyhedrons [1] with the help of which it is possible to investigate the properties of permutations sets classes in the Euclidian space.

Let us fulfill the enclosure mapping of the permutations set P_n and cyclic permutations P_n^C to the arithmetic Euclidian space R^n. According to [2, 5] the given mapping (which is called immersion) can be represented in the following form:

$$f : P \to R^n ,\ \forall p = (p_1, p_2, ..., p_n) \in P ,$$
$$x = f(p) = (x_1, x_2, ..., x_n) \in E \subset R^n ,$$
$$x_i = p_i ,\ i \in J_n .$$

As a result of the immersion f we have one-to-one correspondence between each set:

$$P_n ,\ P_n^C \text{ and } E \subset R^n :$$
$$E_n = f(P_n) ,\ E_n^C = f(P_n^C) .$$

Because of the above operations it becomes possible to investigate properties of the elements of the subset $P_n^C \subset P_n$ with the help of the polyhedron Π_n.

OBJECTIVES

To formulate goals consider relative location of some permutation components.

Consider a permutation polyhedron Π_n generated by a set:

$$a_1 < a_2 < ... < a_n ,\quad vert\ \Pi_n = E_n$$

is the set of its vertexes.

Since any cyclic permutation belongs to the set of permutations P_n:

$$\pi_C = (\pi(a_1), \pi(a_2), ..., \pi(a_n)) \in P_n$$

all cyclic permutations are vertexes of the permutation polyhedron Π_n.

Let us introduce:

$$\Pi_n^C \subset vert\ \Pi_n ,$$

which is the subset of permutation polyhedron vertexes corresponding to all possible cyclic permutations with the cycle of n elements generated by the set:

$$a_1 < a_2 < ... < a_n ,\quad \Pi_n^C = E_n^C .$$

Let us denote v^C the vertex $v \in vert\, \Pi_n$ corresponding to a certain cyclic permutation $p \in P_n^C$ i.e. $v^C \in \Pi_n^C \subset vert\, \Pi_n$.

The adjacency criterion for the vertexes of the permutation polyhedron deals with the elements of the generating set $A = \{a_1, a_2, ..., a_n\}$ and their location in the permutation, i. e.: a vertex adjacent to the vertex $v = (a_{v_1}, a_{v_2}, a_{v_3}, ..., a_{v_n})$ that corresponds to the permutation $p \in P_n^C$ is any vertex corresponding to the permutation p_k obtained from p by the transposition of components equal to k and $k+1$, $\forall k \in J_{n-1}$. And the two permutations $p_1, p_2 \in P_n$, corresponding to the vertexes $v_1, v_2 \in \Pi_n$ are called adjacent permutations if the vertexes v_1, v_2 are adjacent vertexes of the polyhedron Π_n [19].

Further in this paper, without losing generality we suppose:

$$A = \{a_1, a_2, ..., a_n\} = \{1, 2, \ldots, n\}.$$

Let us consider the location of the components equal to $i, i+1$ and $j, j+1$, $i, j \in J_{n-1}, j \neq i$ in an arbitrary cyclic permutation $p \in P_n^C$ and write them down in the form of chains. The components can be located in a chain in six ways that we call types. Let us fix the first two elements of the chain. This is a certain component $x \in A = \{a_1, a_2, ..., a_n\}$ the value of which is arbitrary and the component i such that $\pi(x) = i$. Thus the beginning of a chain always looks as follows:

$$(x, i, \_, \_, \_),$$

and further there are three positions in which the components $i+1, j, j+1$ can be located in a different order. It is this order that sets the type of a cyclic permutation for components i, j. The number of ordering ways for 3 components is equal to $3! = 6$, which is the number of permutations from 3 elements.

Let us write down all the six permutations from the elements $i+1, j, j+1$:

1) $j, i+1, j+1$;
2) $j+1, i+1, j$;
3) $i+1, j, j+1$;
4) $j+1, j, i+1$;
5) $i+1, j+1, j$;
6) $j, j+1, i+1$.

Consider the elements chains corresponding to the given sequences.

Since we consider the location of components in an arbitrary cyclic permutation $p \in P_n^C$ it is not important which component will be the beginning of a chain because in a cyclic permutation any component can be obtained from any other component by the number of steps $\leq n-1$. Further, in this paper, without losing generality, we will always start chains with a fixed component i and an arbitrary component x the value of which is inessential but the component i is a mapping of x.

Thus using the above considerations let us show all the six location types for the components

$$i, i+1 \text{ and } j, j+1,\ i, j \in J_{n-1}, j \neq i$$

in an arbitrary cyclic permutation $p \in P_n^C$ (for all types $a, b, c \in \{0, ..., n-2\}$):

Type I:
$$\begin{pmatrix} x & \pi^a(i) & \pi^b(j) & \pi^c(i+1) \\ \downarrow\nearrow & \downarrow\ \nearrow & \downarrow\ \nearrow & \downarrow \\ i & j & i+1 & j+1 \end{pmatrix},$$

Type II:
$$\begin{pmatrix} x & \pi^a(i) & \pi^b(j+1) & \pi^c(i+1) \\ \downarrow\nearrow & \downarrow\ \nearrow & \downarrow\ \nearrow & \downarrow \\ i & j+1 & i+1 & j \end{pmatrix},$$

Type III:
$$\begin{pmatrix} x & \pi^a(i) & \pi^b(i+1) & \pi^c(j) \\ \downarrow\nearrow & \downarrow\ \nearrow & \downarrow\ \nearrow & \downarrow \\ i & i+1 & j & j+1 \end{pmatrix},$$

Type IV:
$$\begin{pmatrix} x & \pi^a(i) & \pi^b(j+1) & \pi^c(j) \\ \downarrow\nearrow & \downarrow\ \nearrow & \downarrow\ \nearrow & \downarrow \\ i & j+1 & j & i+1 \end{pmatrix},$$

Type V:
$$\begin{pmatrix} x & \pi^a(i) & \pi^b(i+1) & \pi^c(j+1) \\ \downarrow\nearrow & \downarrow\ \nearrow & \downarrow\ \nearrow & \downarrow \\ i & i+1 & j+1 & j \end{pmatrix},$$

Type VI:
$$\begin{pmatrix} x & \pi^a(i) & \pi^b(j) & \pi^c(j+1) \\ \downarrow\nearrow & \downarrow\ \nearrow & \downarrow\ \nearrow & \downarrow \\ i & j & j+1 & i+1 \end{pmatrix},$$

We will use the introduced definitions and types of cyclic permutations for the formalization and investigation of the adjacency properties for elements from the set Π_n^C.

THE MAIN RESULTS OF THE RESEARCH

In correspondence with the criterion of vertexes adjacency in the permutation polyhedron Π_n [1] for any vertex $v \in vert\, \Pi_n$ there are $(n-1)$ adjacent vertexes obtained from the v transposition of the components equal to i and $i+1$ correspondingly, $i \in J_{n-1}$. Note that this is true also for any vertex $v \in \Pi_n^C$.

For any vertex $v \in vert\,\Pi_n$ we will call the transposition of components equal to i and $i+1, i \in J_{n-1}$ belonging to the same k length cycle of the corresponding permutation $p \in P_n$ a "break" transposition, since as a result of this operation the vertex $v_1 \in vert\,\Pi_n$ adjacent to the original one will be obtained and the permutation $p_1 \in P_n$ corresponding to the obtained vertex contains at least two cycles of length k_1 and k_2, $k_1 + k_2 = k$.

Therefore for the vertexes $v \in vert\,\Pi_n$ one transposition of components equal to i and $i+1$, $i \in J_{n-1}$ can be either "break" or "conjunction" of cycles to which these components belong. If the original vertex $v \in vert\,\Pi_n$ corresponds to the permutation $p \in P_n^C$ belonging to the set of cyclic permutations and has a single cycle of length n, any transposition of the components i and $i+1$, $i \in J_{n-1}$ will be a "break" [18, 19].

Next let us consider if it is possible to keep the cyclicity of a permutation when we have two transpositions of components equal to

$$i, i+1 \text{ and } j, j+1,\ i, j \in J_{n-1}, j \neq i.$$

Consider the case where there are four components involved in two transpositions of components.

Statement 1. If in a certain permutation $p \in P_n^C$ 2 consecutive transpositions of the elements

$$i, i+1 \quad \text{and } j, j+1,\ i, j \in J_{n-1}, j \neq i, i+1$$

have been fulfilled then the obtained permutation $p_{i,j} \in P_n$ will be cyclic if the original permutation $p \in P_n^C$ for the given components i, j belongs to the type I or II.

Proof. Let us consider the fulfillment of transpositions for all the six types of permutations for some components $i, i+1$ and $j, j+1$, $i, j \in J_{n-1}, j \neq i, i+1$ and demonstrate which types keep the property of cyclicity. For all the six types: $a, b, c \in \{0, ..., n-2\}$.

Type I: $j, i+1, j+1$. The original chain looks as follows:

$$\begin{pmatrix} x & \pi^a(i) & \pi^b(j) & \pi^c(i+1) \\ \downarrow\nearrow & \downarrow\ \nearrow & \downarrow\ \nearrow & \downarrow \\ i & j & i+1 & j+1 \end{pmatrix}.$$

Fulfill consecutively two transpositions: $i \leftrightarrow i+1$, $j \leftrightarrow j+1$ and represent the chain elements without changing the links to facilitate visual perception. As a result, we get:

$$\begin{pmatrix} x & \pi^a(i) & \pi^b(j) & \pi^c(i+1) \\ \downarrow\nearrow & \downarrow\ \nearrow & \downarrow\ \nearrow & \downarrow \\ i & j & i+1 & j+1 \end{pmatrix} \underset{\substack{i \leftrightarrow i+1 \\ j \leftrightarrow j+1}}{\Longrightarrow}$$

$$\begin{pmatrix} x & \pi^c(i+1) & \pi^b(j) & \pi^a(i) \\ \downarrow\ \nearrow & \downarrow\ \nearrow & \downarrow\ \nearrow & \downarrow \\ i+1 & j & i & j+1 \end{pmatrix}.$$

Type II: $j+1, i+1, j$. The original chain looks as follows:

$$\begin{pmatrix} x & \pi^a(i) & \pi^b(j+1) & \pi^c(i+1) \\ \downarrow\nearrow & \downarrow\ \nearrow & \downarrow\ \nearrow & \downarrow \\ i & j+1 & i+1 & j \end{pmatrix}.$$

Fulfill consecutively two transpositions: $i \leftrightarrow i+1$, $j \leftrightarrow j+1$ and change places of chain elements without changing the links. We will get:

$$\begin{pmatrix} x & \pi^a(i) & \pi^b(j+1) & \pi^c(i+1) \\ \downarrow\nearrow & \downarrow\ \nearrow & \downarrow\ \nearrow & \downarrow \\ i & j+1 & i+1 & j \end{pmatrix} \underset{\substack{i \leftrightarrow i+1 \\ j \leftrightarrow j+1}}{\Longrightarrow}$$

$$\begin{pmatrix} x & \pi^c(i+1) & \pi^b(j+1) & \pi^a(i) \\ \downarrow\ \nearrow & \downarrow\ \nearrow & \downarrow\ \nearrow & \downarrow \\ i+1 & j+1 & i & j \end{pmatrix}.$$

Type III: $i+1, j, j+1$. The original chain looks as follows:

$$\begin{pmatrix} x & \pi^a(i) & \pi^b(i+1) & \pi^c(j) \\ \downarrow\nearrow & \downarrow\ \nearrow & \downarrow\ \nearrow & \downarrow \\ i & i+1 & j & j+1 \end{pmatrix}.$$

Let us fulfill consecutively two transpositions: $i \leftrightarrow i+1$, $j \leftrightarrow j+1$ and change places for the chain elements without changing the links. We will get:

$$\begin{pmatrix} x & \pi^a(i) & \pi^b(i+1) & \pi^c(j) \\ \downarrow\nearrow & \downarrow\ \nearrow & \downarrow\ \nearrow & \downarrow \\ i & i+1 & j & j+1 \end{pmatrix} \underset{\substack{i \leftrightarrow i+1 \\ j \leftrightarrow j+1}}{\Longrightarrow}$$

$$\begin{pmatrix} x & \pi^b(i+1) & \pi^a(i) & \pi^c(j) \\ \downarrow\ \nearrow & \downarrow & \updownarrow & \updownarrow \\ i+1 & j+1 & i & j \end{pmatrix}.$$

Type IV: $j+1, j, i+1$. The original chain looks as follows:

$$\begin{pmatrix} x & \pi^a(i) & \pi^b(j+1) & \pi^c(j) \\ \downarrow\nearrow & \downarrow\ \nearrow & \downarrow\ \nearrow & \downarrow \\ i & j+1 & j & i+1 \end{pmatrix}.$$

Fulfill consecutively two transpositions: $i \leftrightarrow i+1$, $j \leftrightarrow j+1$. We will get:

$$\begin{pmatrix} x & \pi^a(i) & \pi^b(j+1) & \pi^c(j) \\ \downarrow\nearrow & \downarrow\ \nearrow & \downarrow\ \ \nearrow & \downarrow \\ i & j+1 & j & i+1 \end{pmatrix} \underset{\substack{i\leftrightarrow i+1 \\ j\leftrightarrow j+1}}{\Longrightarrow} \begin{pmatrix} x & \pi^a(i) & \pi^c(j)\pi^b(j+1) & \\ \downarrow & \downarrow\ \nearrow\nwarrow & \downarrow & \updownarrow \\ i+1 & j & i & j+1 \end{pmatrix}.$$

Type V: $i+1, j+1, j$. The original chain looks as follows:

$$\begin{pmatrix} x & \pi^a(i) & \pi^b(i+1) & \pi^c(j+1) \\ \downarrow\nearrow & \downarrow\ \nearrow & \downarrow\ \ \nearrow & \downarrow \\ i & i+1 & j+1 & j \end{pmatrix}.$$

Fulfill consecutively two transpositions: $i \leftrightarrow i+1$, $j \leftrightarrow j+1$. We will get:

$$\begin{pmatrix} x & \pi^a(i) & \pi^b(i+1) & \pi^c(j+1) \\ \downarrow\nearrow & \downarrow\ \nearrow & \downarrow\ \ \nearrow & \downarrow \\ i & i+1 & j+1 & j \end{pmatrix} \underset{\substack{i\leftrightarrow i+1 \\ j\leftrightarrow j+1}}{\Longrightarrow} \begin{pmatrix} x & \pi^b(i+1)\pi^a(i)\pi^c(j+1) & & \\ \downarrow\ \nearrow & \downarrow & \updownarrow & \updownarrow \\ i+1 & j & i & j+1 \end{pmatrix}.$$

Type VI: $j, j+1, i+1$. The original chain looks as follows:

$$\begin{pmatrix} x & \pi^a(i) & \pi^b(j) & \pi^c(j+1) \\ \downarrow\nearrow & \downarrow\ \nearrow & \downarrow\ \nearrow & \downarrow \\ i & j & j+1 & i+1 \end{pmatrix}.$$

Fulfill consecutively two transpositions: $i \leftrightarrow i+1$, $j \leftrightarrow j+1$. We will get:

$$\begin{pmatrix} x & \pi^a(i) & \pi^b(j) & \pi^c(j+1) \\ \downarrow\nearrow & \downarrow\ \nearrow & \downarrow\ \nearrow & \downarrow \\ i & j & j+1 & i+1 \end{pmatrix} \underset{\substack{i\leftrightarrow i+1 \\ j\leftrightarrow j+1}}{\Longrightarrow} \begin{pmatrix} x\ \ \pi^a(i) & \pi^c(j+1)\pi^b(j) & & \\ \downarrow\ \ \downarrow\ \nearrow\nwarrow & \downarrow & \updownarrow & \\ i+1\ \ j+1 & i & j & \end{pmatrix}.$$

Thus, after fulfilling two transpositions of components $i, i+1$ and $j, j+1$, $i, j \in J_{n-1}, j \neq i$, in the permutation $p \in P_n^C$ only two types of the components original location in the chain correspond to keeping the cyclicity property. The other four types do not keep cyclicity after component transpositions and lead to appearing cycles of a length less than n:

$$\pi^k(z) = z,\ k < n,\ z \in \{i, i+1, j, j+1\}.$$

The statement is proven.

CONCLUSIONS

1. The given work has been devoted to the investigation of adjacent permutations and their cyclic properties. We have investigated permutation properties with the help of the permutation polyhedron by using the immersing in the Euclidian space.
2. Based on the known adjacency criterion for the vertexes of the permutation polyhedron Π_n, similar transpositions of components in permutations have been investigated.
3. Depending on the location of arbitrary components $i, i+1$ and $j, j+1$, $i, j \in J_{n-1}, j \neq i, i+1$ six types of permutations have been introduced.
4. For these types the changes in the cyclic structure of a permutation that appear after fulfilling two consecutive transpositions of the corresponding components have been investigated.

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ECONTECHMOD. AN INTERNATIONAL QUARTERLY JOURNAL – 2015, Vol.4, No.3, 39-46

MULTY-CRITERIA FUZZY ANALYSIS OF REGIONAL DEVELOPMENT

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Received July 19.2015: accepted August 25.2015

Abstract. The article presents the possibility of using multi-criteria fuzzy analysis for assessing the regional competitiveness. This estimation can be used for place marketing strategy development and based on results of socio-economic development. The proposed approach is characterized by comparative estimation, when the level of development of one region is determined by the development of other areas. The final evaluation is the level of the cluster which the object being analyzed belongs. This allows ignoring minor fluctuations in total indexes. The results of robust and fuzzy groups of regions are analyzed. This grouping is characterized by similar levels of development and helps to define the directions of further development of the regions.

Keywords: membership function, classification, fuzzy clusters, Grodno counties, regional economy, sustainable development, regional competitiveness, place marketing.

INTRODUCTION

Economic objects and processes are very difficult nowadays. Most of them we can describe as a system which includes different elements. The properties of the system are determined by the relationships between these elements and the nature of its interdependence. The characteristic of object includes not only criteria for the whole system but for its elements as well. As a result most of economic problems become multi-criteria. And the special methods of analysis are used for solving these problems. In this article the fuzzy methods of multi-criteria analysis will be described.

The proposed methodology is universal and it can be adapted to different objects. The test area in this chapter is regional socio-economic development evaluation. The results of this analysis are useful for place marketing strategy development. In this case the region's position is a base for subsequent economic growth. The comparative analysis of regional competitiveness lets to receive the position of estimated region between others and the degree of similarity of current situation with others. Based on this information we can work out place marketing strategy for the region including the result of previous development and the leaders of economic growth experience.

The purpose of this article is to show the benefits of fuzzy methods for analysis of economic objects and to determine the circumstances of its using. For this purpose we'll make multi-criteria analysis by different methods (robust and fuzzy) and compare results. The methods will be applied to regional socio-economic strategic decision-making. We'll take into analysis the results of economic growth and life quality of lower level of counties. The experimental calculations were carried out on the example of counties of Grodno region (Belarus) in 2008-2014.

The multi-criteria fuzzy sets are useful for region's marketing strategy development. It was found that multi-criteria fuzzy clusters can describe the comparative competitiveness. In this paper the estimation of the competitiveness is based on the values of the membership functions to a particular cluster. It's possible to use this result for identifying of membership function value and forecasting the future positions. Single fuzzy clustering (based on one integral criterion) is easier for interpretation and visualization, but it cannot make multi-faced analysis.

The article is structured as follows. In beginning the basic definition like local region, socio-economic development evaluation and regional competitiveness are clarified. Then the methodology of research is presented. Then the experimental part of the chapter is considered. It includes data collection based on system of indexes of regional evaluation and it analysis, single and multi-dimensional fuzzy clustering of Grodno counties in dynamic and as a whole over the period. At the end the conclusions are made.

THE ANALYSIS OF RECENT RESEARCHES AND PUBLICATIONS

The problem of regional competitiveness, its investment attraction and place marketing attracts more attention nowadays. Moreover the modern conditions require revising existing concepts and methods of its evaluations. Globalization and high-tech industry development lead to the regional competitive grows. It means that regions become active participants in the struggle for resources (labor, technological, investment) and markets (tourism, investors, products). The distinctive feature of this process is that regions act as goods and as producers simultaneously. Dijkstra [11] notes that it's impossible to apply the firm's competitiveness concept to the regions level:

The framework describing a firm's capacity to compete, grow and be profitable is relatively uncontested, but applying the same concept to countries or regions has been subject to much debate.

Golovikhin S. [12] notes that the concept of regional competitiveness shouldn't lead to increase of regional separatism. There're different approaches to the regional competitiveness definition: based on productivity [26], rising income and improving livelihood [19], as an environment for firms [7]. Moreover Nasser [20] and Chukhray [33] claims that regional competitiveness on national or global level is not the end in itself:

Maintaining a high level of competitiveness is not a goal by itself, it is a goal within another: development and growth for the present and future generations [20].

This approach is close to the concept of sustainable development [30] which considers regional competitiveness not only from economic position but also take into account ecological (natural) and social (human) components. Serebryakov L. [27] noted that regional competitiveness can't be evaluated without taking into account system on regional infrastructure.

The second growth point of economic development is region's (or place) marketing. Arzhenovskij [4] make a conclusion that region's marketing is an important part of regional economy and that it's based on the regional competitiveness. The region in this meaning is the territory limited by the existing administrative-territorial segmentation. And region's marketing can be seen in following Kotler's view:

Place development means to develop for a place a systematic and long-term marketing strategy directed towards nurturing and developing the natural and potential attributes of an area or region.

One of the mistakes of regional governance in post-soviet countries [8] is strategy development based on allocable budget without taking into account territorial potential. It means that the first step in marketing strategy development should be analysis of current position and tendencies of economic growth. The level of socio-economic development is the result of previous economic growth and the factor of ensuing development. It's an important criterion for region's marketing strategy development that's why this topic is actual and important.

The relevance of this topic in Belarus can be revealed by Program of Socio-Economic development [23] and National Strategy of Sustainable development [21]. They confirm that sustainable development of regions and increasing their competitiveness is a priority of socio-economic growth.

The feature of approach to the assessing of socio-economic development proposed in article is the object of study, which are local regions. The increase of interest to local regional analyzes can be proof by a lot of research on this topic. L. Servillo and others [28] explores territorial attractiveness for migration and it impact to the socio-economic development. J. Mawson [18] presents the UK experience in local governance. B. Blazevic and A. Jelusic [6] developed a model of regional economic and tourism development. All of the researchers confirm that local regional development as a system consists of complex and multidiscipline problems and needs special methods for evaluation.

Marquardt [17] used Analytical Hierarchy Process (AHP) by Saaty [25] for evaluating regional development concept elaboration process. Distinct disadvantages of this method are expert estimation and a large number of pairwise comparisons. Aivazyan [2] and Lialikova [16] applied the principal component method for evaluating regions by life-quality. This method aimed at decreasing of number of criteria through combining in principal components which preserve variation of benchmarks. But most of time it's difficult to interpret these components in its economic sense. Zhelezko [32] presents some elements of multi-criteria fuzzy ranking, which can be adopted to the regional estimation. Alves and others [3] offer a fuzzy decision approach for location selection among potential available areas based on some criteria. It allows include in analysis not only quantitative but also qualitative criteria.

This chapter presents the fuzzy clustering application for object evaluation. In this case the fuzzy clustering performs as a classification tool. Diaz B. and others [10] applied it to the economy sectors and received the key sectors of Spanish economy. The groups with similar level of development can be received when fuzzy clustering applied to regional evaluation.

THE MAIN RESULTS OF THE RESEARCH

In the beginning, we'll clarify the concept of local region and socio-economic development evaluation.

Kuznecova [15] noted that region can be present in two meanings. By one meaning, region is the territory limited by the existing administrative-territorial segmentation. By other, region is territory limited by any signs of interrelating (population, geographical conditions and others). In this paper region is considered in first meaning because only administrative segmentation has authorities and opportunities to manage of socio-economic development.

Most of countries have a multitier system of regions. And the facilities of evaluating of high regional development are always much bigger than at local level. There're more statistical data and indexes value at high level. Some of important criteria of economic development (like gross regional product) are not calculating in local level. That's why specific methods and technics should be developed.

From the previous analysis we can distinguish that region can be seen in two aspects [28]. In one side region is seen as an independent system with its own resources and goal to increase the life's quality of the local population. In other side the region is considered as a subsystem of the state (or the high regional formation). The aim of region's functioning in this aspect is to find out resources for national economic growth. These two aspects relate and condition each other. So, when we are talking about competitiveness of region we should take into account that they are not only fighters for each other because they are elements of one system. But they are interesting in individual results of the local and high region the same time.

The system of local government includes departments and agencies with dual subordination to the ministry and to the local executive committee. Therefore, the inter-departmental barriers may lead to a slowdown in decision-making although the linear submission to the chairman of the executive committee. Sometimes it leads to duplication of functions, data collection and absence of clear zones of control.

The most of problems and issues of socio-economic regional development is complex, complicated and multiplex. It means that in regional decision-making we should take into account a lot of factors, indexes and constrains.

The socio-economic development of the region can be evaluated by multi-criteria analysis. The term of “the socio-economic development” includes an indication of the simultaneous control of several areas. The process can be characterized by next area:

- **Economic** (result of industry, agriculture, transport, trade and paid services).
- **Financial** (profitability, debt growth, investments).
- **Demographic** (population, nature and migration growth).
- **Social** (employment, crimes, salary, life’s quality, educational level, poverty).
- **Ecological** (emissions, water saving, waste products).

The complex of these fields leads to the effective socio-economic development named sustainable. But each of these fields is characterized by set of criteria. As a result the number of analyzed parameters ups to several dozen. The regional governance is interesting in evaluation of each area and of the whole system development. More over the estimation should be made in dynamic and in comparison with other counties. For this purpose the system of indexes should base on open source data.

The benchmark data for the analysis can be received from different sources: statistical data in official statistic collections, regional legislation, information of large enterprises and so on. But there’s not a single data source of regional socio-economic development for external users.

The results of estimation of regional socio-economic development can be used by following customers:

- **National governance** for development of socio-economic polity and strategy;
- **High region governance** for evaluating local regions composed the high region;
- **Local region governance** for comparing its level with others and receiving an experience of development;
- **Businessmen and investors** for identify objects of future investments.

We can make a conclusion that this concept lets to develop the region’s marketing strategy directed to the sustainable development based on local potential. Now we’ll formulate the methodology of this evaluation.

THE METHODOLOGY OF RESEARCH

Previously noted that the analysis of socio-economic regional development present the competitiveness estimation. The analysis of enterprise estimation by [14] has 7 steps and starts with information support and developing indicators systems The methodology of this analysis includes only 5 steps:

1. **The original data collection**

a) **to form the system of indexes**. It must take into account all important parameters of competitiveness and based on those characteristics of the object, which are essential for competitiveness.

b) **to define the values of indexes for each object**. The original data are represented as a matrix in which the columns are recorded parameters and the rows - the objects (alternatives).

2. **To lead the data to comparable form.** The nominal model of object has the best results for this indicator and presents the most successful competitor in current market competition. If the prescriptive value of index is known it can be used instead of corresponding supremum. On the other hand, if the data gathering was carried out correctly and the prescriptive values weren’t received, may be they are not achievable for a given circumstances. Each alternative can be compared with this nominal model of object by different formulas [1], but we use the following:

$$z_{ij} = \frac{x_{ij}}{\max x_{ij}} \tag{1}$$

or

$$z_{ij} = \frac{\frac{1}{x_{ij}}}{\max \frac{1}{x_{ij}}} \tag{2}$$

where: z_{ij} – comparable value, x_{ij} – original value of index.

If the proposed method is using then all comparable values are led to a common scale of measurement in the interval [0; 1] and reflect the level of the object compared with the most successful competitor in this aspect of activity.

3. **To calculate integral criterion.** This step is not obligatorily. The integral criterion can be calculated by additive convolution, principal component method or by special formula. Sometimes it’s necessary to receive not only one criterion, but some criteria which reflect the result of different spheres in the object development.

4. **To make multi-dimensional fuzzy sets**. The using of fuzzy sets in socio-economic development analysis can show gradual evolution of objects. The example of its using in economic objects is presented at [13]. The construction of membership functions often base on expert opinion. This gives the share of subjectivity and requires a lot of time. There is a method [29], which offers the construction of the membership functions using fuzzy clustering results. This conclusion is based on the assumption that membership function of a fuzzy cluster correspond to the membership function of congruent fuzzy set. Mathematically multidimensional fuzzy clustering procedure can be carried out by methods of fuzzy c-means, Gustafson-Kessel, with k-ellipsoids, etc. In this paper the fuzzy c-means method was used.

5. **To analyze the results.** The values of membership functions for different sets show the level of competitiveness of object. It's interesting to look at the cluster with maximum attitude and the degree of attitude to better clusters. If it's possible (when we have enough data) then it's useful to make the analyses in dynamic.

It can be assumed that the proposed methodology for constructing fuzzy sets with similar level of development is applicable to construct rankings of any objects and not only competitive, but its testing was carried out only in the assessment of the regional socio-economic development.

Experimental research at Belarusian regions

Previously noted that the analysis of socio-economic regional development present the competitiveness estimation. The proposed methodology was applied to this evaluation. The first step of the procedure connects with data collection. There're different approaches to system of indexes for regional socio-economic development evaluation. But most of them were developed for high regional development and they don't take into account local regional particularities. It's interesting to descry the European Union experience in this sphere. The whole territory of European Union is divided into 3 levels of regions (NUTS-1, NUTS-2 and NUTS-3) [24]. The current classification characteristics are represented at the table 1.

Table 1. The NUTS characteristics

Level	Number of regions	Minimum population	Maximum population
NUTS-1	97	3 millions	7 millions
NUTS-2	270	800 000	3 millions
NUTS-3	1294	150 000	800 000

The smallest region (NUTS-3) level corresponds to the high regional level in the country (in most of cases). Moreover European commission doesn't use analyses which include data from only NUTS-3 level. For example the evaluation of coherence in Europe includes 4 groups of factors (25 criteria) and only 3 of them belong to the local level [9]. That's why the system of indexes was developed for this analysis. It includes economic evaluation, demographic indexes, social criteria and sustainable development. This system includes only quantitative criteria because the evaluation of qualitative obtains experts' measurement. The using of fuzzy theory can help to convert the qualitative estimates to the numeric but it also requires experts' participation. The structure of this system in local regional level [22] is shown in table 2.

Table 2. System of criteria of regional socio-economic development evaluation

Social	Economic	
Demographic 1) population 2) natural increase 3)migration rate	Source 1) budget 2) investments 3) direct foreign investments 4) receivables and payables 5) employment 6) unemployment rate 7) percentage of population in working age 8) import	Results 1) industrial production 2) productivity of yield and livestock capita 3) retail trade and paid services 4) goods turnover 5) value of constructions 6) profitability 7) small business production 8) export
Life quality 1) availability of housing 2) crimes 3) salary		
Sustainable development 1) emissions		

We didn't add any indexes of education [5] because in local regions (of Grodno county) there's not high education institutions and the secondary education is mandatory in Belarus. We haven't open data about population with high education in local regions and there're very small property of PhD's in region.

Some of criteria (like productivity of yield and livestock capita) include more than one index. As a result all system is based on 28 criteria.

For experimental check of our methodology we apply it to the evaluation of socio-economic development of Grodno's local region (Belarus). We received the data for 28 indexes value of 17 Grodno's local regions and city Grodno in 2008-2014. All of them were led to the comparable form. It was interesting to estimate the correlation between these indexes. The following result was received by correlation analysis: there is a strong relationship between the value of the population (one of the main demographic indicators) and the majority of economic indicators (regional budget (0.95), turnover (0.93), retail trade (0.97), paid services (0.97), the volume of industrial production (0.9), the number of employed in the economy (0.99)). It mean that population (or the number of employed in the economy) is the determining factor for economic growth in Belarus regions. The absence of indexes for evaluating information and communication technologies at local regional level doesn't let us to characterize local economy as post-industrial.

The methodology provides an opportunity of using an integral criterion for assessment and building a rating of regions by this criterion. The strong correlations between indexes allow to use the principal components analysis. Using it we received factors which have the greatest impact for general variance. In this analysis we didn't take into consideration city Grodno. We received that first principal component retains 51.99% of the variance. This is not enough for using the value of this component as a ranking value of regional development estimation [2]. This component is determined by following indexes: regional budget, investments, retail trade, paid services, receivables and payables, employment value, industrial production, goods turnover and value of constructions. All of these indexes are important factors of economic development in industrial society. It reaffirms that Belarusian economy is not at the post-industrial step yet. The second principal component retains 13.3% of the variance. This component is mostly determined by rural factors (livestock capita and productivity of yield).

Let's try to adopt the known at national level methods for calculating the integral criterion. For the national economic development this criterion is gross domestic product (GDP). By [31] GDP is the total value of goods and services (counted without duplication) that are newly produced in the economy during an accounting period, generated net incomes to the economy and are available for domestic final uses or for exports.

It can be calculated by 3 approaches: the production (or output or value added) approach, the income approach, or the expenditure approach. The analog of this criterion on regional level is gross regional product (*GRP*). But it's determined only by value-added approach and in Belarus only for high Regional County. It's possible to adopt the expenditure approach to the local regions and calculate analog of GRP at local level. In this case, the GRP will be formed as sum of household expenditure (*C*), investment (*I*), government expenditure (*G*) and net exports (*Xn*). The formula of calculating is:

$$GRP = C + G + I + Xn. \quad (3)$$

Household expenditure as a statistical measure is not published in open sources. But it's possible to find data of the value of retail sales and the cost of paid services to the population. Household expenditure spends to pay for goods and services. Therefore, we can assume that these values reflect the approximate level of household's expenditure.

The value of investments in fixed capital is a statistical measure, which is estimated at the level of high and local regions of the republic and published in statistical yearbooks.

Government expenditure can be estimated as the regional budget. The value of regional budget can be found in regional legal acts.

The value of net exports is the difference between exports and imports in goods and services. Each of these values shall be published in statistical yearbooks.

This method allows receiving the integral result of economic development. Moreover all factors (except export) which assumed in GRP were included in first principal component. So we used the most influential factors in this method.

To test this method of calculating GRP we compare results of official data of GRP and calculated by this method at high level of regional economy. We received that the degrees of each region in total GRP by official and calculated values have not a significant discrepancy between two samples. So we can use this methodology for evaluating the share of each local region in the economic reward of high region.

We should include in integral criterion that regions have different size. For this aim we calculated GRP per Capita by dividing the value of GRP to the average population.

One-dimensional Fuzzy Clusters

Let's try to evaluate the regional economic growth with this criterion by fuzzy clusters analysis. One of the important questions is how many clusters should we have. In this research we make 4 clusters: low, medium, high and top of socio-economic development. It's interesting to use fuzzy clusters because it's impossible instantaneous transition from one group to another. The membership function shows the degree of membership of each local region to each group. The calculations were made in MS Excel. The author's software was used for construction of membership functions.

The research confirms that there is a high degree of differentiation of Grodno's local regions development. The membership functions of clusters and corresponding value of GRP are presented on fig.1. The results of regions attitude to fuzzy clusters are presented on the map of region at fig.2. The darker color means the higher the level of economic development of region. Some regions refer to two clusters with different degree simultaneously. It is reflected as double color.

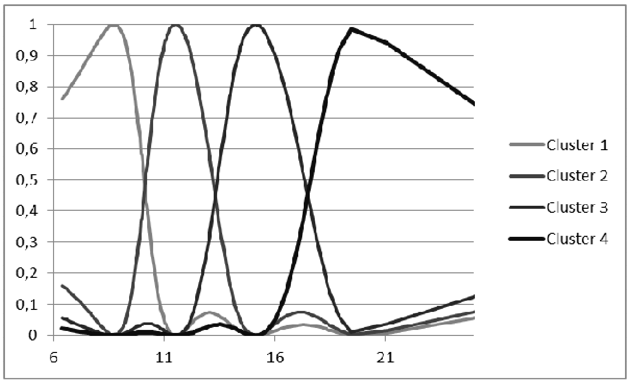

Fig.1. Membership functions and GRP

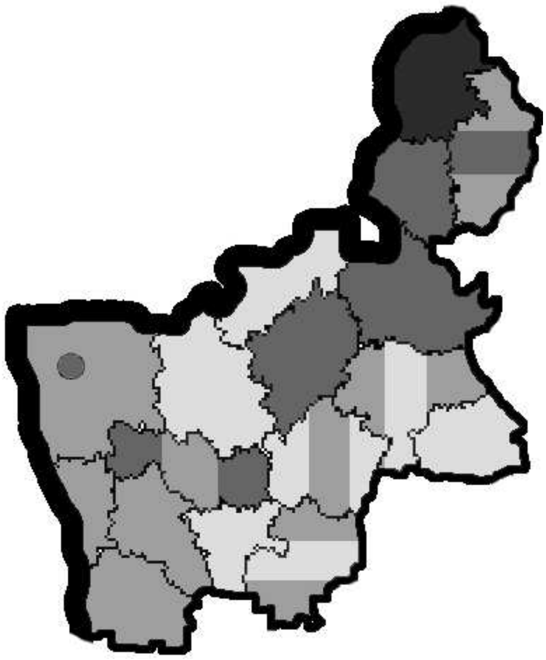

Fig.2. Regions attitude to fuzzy cluster in 2014

We can make a math model of each membership function for every year and compare its dynamics. It's possible to use this membership functions for predict results of regional socio-economic development in stable conditions. When economic conditions greatly change (for example in financial crisis) there's a shift in membership functions and changes in models of GRP.

Also this type of analysis lets us to make historical conclusions. We can see the relative magnitude of the recession or growth of real GRP (at constant prices).

Multi-dimensional Fuzzy Clusters

Often there's not possibility to calculate an integral criterion. Then we have a multi-criteria problem. The c-mean fuzzy clustering procedure lets to work with multi-dimensional spaces. Membership functions are based on the set of indexes. We can't receive an analytical form of the functions, but only a set of points in the multi-dimensional space. The graphical display of the results based on the value of input data is impossible and their interpretations become difficult. But it's possible to represent these functions based on case number.

We made this procedure and compared results of one-dimensional and multi-dimensional fuzzy clustering. For this analysis we used all the indexes presented in table 2.

The result was some different from one-dimensional clustering. At first the system of indexes doesn't contain the GRP per capita. Most of used indexes are in absolute form. It means that they were not adjusted by population, employment and so on. At second the system combines indexes from different spheres (not only economic characteristics, but also social). Moreover it includes agricultural estimation, construction volume and freight turnover. This allows making multilateral estimation of economic growth.

In this conditions city Grodno attitude to the top cluster for more than 0,99 throughout the period under review. City Grodno is one object which significant attitude to this cluster. This can be explaining by large role of city Grodno in socio-economic development of region. Its impact to the GRP is more than 33%. It's interesting that we have in our system some rural indexes, and city Grodno, which hasn't agriculture, anyway belongs to the top cluster absolutely.

The cluster with high level of development always includes Lida's region with the highest degree of attitude. Only this one region belongs to this cluster with significant degree (more than 0,2). But there're two more regions which attitude to this cluster regularly. It's Volkovysk's and Slonim regions. Volkovysk's region is two times smaller than Lida's (by population number), but has a very good indexes in rural and social spheres. The attitude to this cluster of Slonim's region can be explained by the value of regional budget.

We had also compared these results with previous researches. The analysis of competitiveness of Grodno's region was made by V. Lialikova [16]. She used principal component analysis for receiving the integral index and then made 4 robust clusters with homogeneous groups of regions. In this methodology the number of clusters is chosen as large as possible which preserves the significant differences between the groups. But the absence of gradual transitions leads to sharp jumps of regional competitiveness rating. V. Lialikova received more optimistic results. 6 regions are in the high development cluster in 2011. We received only 3 regions with more than 70% of membership and 1 with 50% membership to better cluster. So the fuzzy clusters can show the slow progressive in regional development.

One more particularities of fuzzy clusters using is that it helps to find out the most important factor in the system. We mentioned above that visualization of membership functions can be done by graphic representation based on case number. For this purpose all cases should be ranked. All possible cases were explored, but only sorting by population gave acceptable results (noises are negligible). In other cases, the trend is not visible.

The benchmark data were ranked by population. We can see on fig.3. that there's high inhomogeneity in regional socio-economic development.

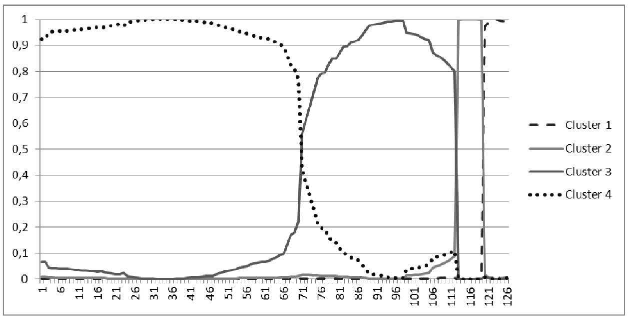

Fig.3. The membership functions of multi-criteria fuzzy clusters of Grodno local regions in 2008-2014

The top cluster includes only result of city Grodno with significant membership function value. The analysis of membership functions values of other cases of city Grodno testify that it can be used for historical research.

Solutions and recommendations.

The local regional economy can characterize by strong correlation dependence between economic and social indexes. That's why regional governance should take into account a lot of criteria for decision-making.

In Belarus there're lacks of statistical data that characterize the current stage of development of the information economy. We didn't receive the impact of services and knowledge to the result of socio-economic development. The local regional development in Belarus in these circumstances can be characterized only as industrial. National statistical committee makes sense to reconsider the system of indexes and add the evaluation of knowledge society.

There're inequalities in regional socio-economic development in Belarus. When we considered fuzzy sets based of multi-criteria we received that city Grodno has huge results with maximum values of most of indexes. The same time most local regions have a low and medium contribution to the socio-economic development. For changing this situation the government should attract investments to local regions.

It was found that economy in the Grodno region is mostly time-consuming and result of socio-economic development is mainly determined by demographic factors. Insufficient attention is paid to the development of high-tech innovation. These negative trends in the development must be overcome through the development of investment activity of both local and foreign entrepreneurs.

A significant contribution to socio-economic development of local regions is made by regional budget. It reaffirms that regions should attract private capital and develop entrepreneurships.

FUTURE RESEARCH DIRECTIONS

One of the drawbacks of this concept is that we take all indexes as equivalent. It would be interesting in future to complete the software by adding a possibility to take into account the importance of indexes.

Moreover, it makes sense to develop integrated criteria for the various areas of regional socio-economic development and to construct a multi-dimensional membership functions based on a smaller number of baseline factors.

One of the most important directions of this research is construction of analytical form of multi-criteria membership functions. It will allows to develop different scenarios of regional economic grows and predict future position of regions. It also can help to evaluate the influence of different factors to the result of socio-economic development.

It's interesting to apply this methodology to other objects. It can be used for evaluating of set of products for marketing strategy development or for comparative measure of solvency of enterprises or organizations.

CONCLUSION

1. The fuzzy logic argues that a sharp transition from one cluster to another is impossible, and there is the possibility of a piecemeal transition from one group to another. This process can be described by a membership function, which shows the degree of each region belongs to each fuzzy set.

The study was conducted comparative characteristic of the level of socio-economic development of the Grodno region, an analysis of the results robust and fuzzy multidimensional clustering and multi-dimensional and one-dimensional comparison of clustering.

2. The multidimensional fuzzy clustering is useful for group's construction based on several criteria. The goal of this analysis is to form a fuzzy group of regions with similar levels of socio-economic development based on multiple values of initial indices. The degree of membership to the fuzzy cluster will be a degree of group membership. This saves the standard rules of the group, in which the differences within groups are much smaller differences between the groups.

3. The methodology for these procedures can be easily automated. This allows carry out interregional comparisons operatively. The testing area of this method was the assessment of Grodno region in 2008-2014.

At first, a system of criteria, indicators that reflect different aspects of socio-economic development was developed. The system consists of 28 indicators combined into 5 groups.

Then, the database was collected. It includes the statistics of these indicators for the 17 counties of the Grodno region and city Grodno in 2008-2014.

In the next step the raw data were normalized, scaled and unified to the form "the more, the better."

4. Application of factor analysis and principal component analysis allowed form a single integral criterion, which retained most of the variance of initial data. On the basis of the criterion which is analog to GRP per Capita, all counties of the Grodno region were grouped into 4 clusters based on socio-economic development's level.

After that, using a multidimensional method of fuzzy c-means, the original set of counties was also grouped into 4 fuzzy clusters. So we obtained a degree of membership for each county to each cluster. It's known that the classical membership functions may be represented by a triangular, trapezoidal, etc. We tried to display the membership function on the chart with lowest noises. As a result of streamlining counties by different parameters we revealed that the most representative view of the membership functions are in the ordering by the population. This suggests the priority of this indicator in determining the level of socio-economic development.

5. Multi-dimensional fuzzy clusters better reflect the comparative level of socio-economic development. But using of very informative criterion of GDP per Capita allows receiving interesting results. The difficulty of interpretation and using of the result of multi-dimensional fuzzy clustering in future leads to the need of building and using some integral criteria.

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ECONTECHMOD. AN INTERNATIONAL QUARTERLY JOURNAL – 2015, Vol.4, No.3, 47-55

OPTIMAL STOCHASTIC CONTROL OF THE MODES OF OPERATION OF THE SEWAGE PUMPING STATION

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Received July 22.2015: accepted August 27.2015

Abstract: In this work we propose a new mathematical model and method of optimal stochastic control of the modes of operation of the sewage pumping station for three-band tariff for the electricity, the implementation of which provides a significant reduction of financial expenses of the electricity for pumping waste water. The proposed model and method take into account the stochastic properties of the object of control and environment most adequately. The mathematical formulation of the problem of optimal stochastic control with extreme and probabilistic constraints on the phase variables and efficient algorithm to solve it is presented. The proposed method of optimal stochastic control provides minimum of the mathematical expectation of the volumes of pumped waste water at the time interval with a high electricity tariff and maximum of the mathematical expectation of the volumes of pumped waste water at the time interval with a minimal tariff when all technological limitations are accomplished.

Key words: optimal stochastic control, sewage pumping station, receiving tank, three-band tariff for the electricity, efficient use of resources.

INTRODUCTION

In the urban sector of modern cities the expenses for the electricity in supply and sanitation systems occupy about 25% of total operating costs in water supply systems [1, 13, 15, 18, 26]. Significant increase of the electricity tariffs has led to the urgent need in development and implementation of energy-saving technologies of the operation of the sewage pumping station (SPS) [12, 14]. Specific features of SPS like relatively small receiving tank capacity (RT), severe restrictions on the conditions of its overflow or emptying (emergencies) and the single-band tariff for the electricity have turned to widespread of classical deterministic strategies of the operation of pump units (PU) of SPS.

The classical strategy of the operation of PU of SPS is in the following: all acceptable range of the variation of the levels of waste water (WW) in RT is divided into several levels (thresholds); if the level of WW in RT of SPS exceeds the predetermined threshold, an additional PU is switched on; if the level of WW in RT of SPS keeps rising and exceeds the following threshold, another additional PU is switched on and this process goes on until all PU of SPS are switched on. If the level of WW in RT of SPS continues to rise and exceeds the maximum allowable level then in order to avoid flooding of the room of SPS an alarm reset of WW from RT into surface water is carried out. When the level of WW reduces lower than the predetermined threshold PU on SPS is switched off. If the level of WW in RT becomes lower than minimum allowable level then all PU on SPS are switched off [3-6, 10].

Such a strategy proved to be extremely simple and quite safe and it is widely used in the practice of the operation of PU of SPS for one-band tariffs for the electricity. [9]

The problem of optimal stochastic control of the modes of operation of SPS while its transition to three-band tariff for the electricity is examined in the present work. At that SPS is considered as a stochastic object operating in the stochastic environment. The stochastic nature of the environment can be seen in the fact that the processes of inflow of WW in RT of SPS (inputs of the object of control) have pronounced random character depending on a variety of chronological, meteorological and organizational factors [8, 27]. The stochastic nature of the object of control is seen in the fact that the parameters of the technological equipment of SPS are unknown a priori, but they are estimated according to the experimental data of the final length, which are random variables [21-25, 7]. The consideration of real conditions of the functioning of SPS, the development and use of more adequate mathematical models of technological equipment of SPS and three-band tariff for the electricity make it possible to build more cost-effective methods of control of the modes of operation of SPS at a given interval of control [0, T].

THE MATHEMATICAL FORMULATION OF THE PROBLEM OF OPTIMAL STOCHASTIC CONTROL OF THE MODES OF OPERATION OF SPS

The cost of the electricity is determined by the diagram of three-band tariff, given in Fig. 1. Without loss of generality, we give the mathematical formulation of the problem of optimal stochastic control of the modes of operation of SPS for SPS, the structure of which is shown in Fig 2.

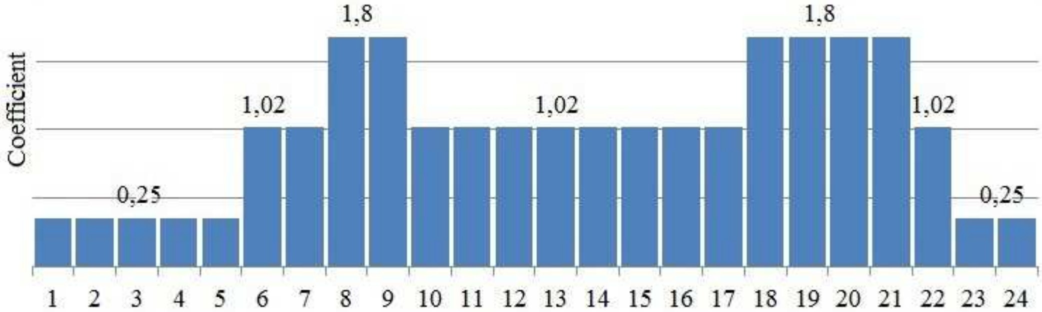

Fig. 1. The diagram of three-band tariff for the electricity

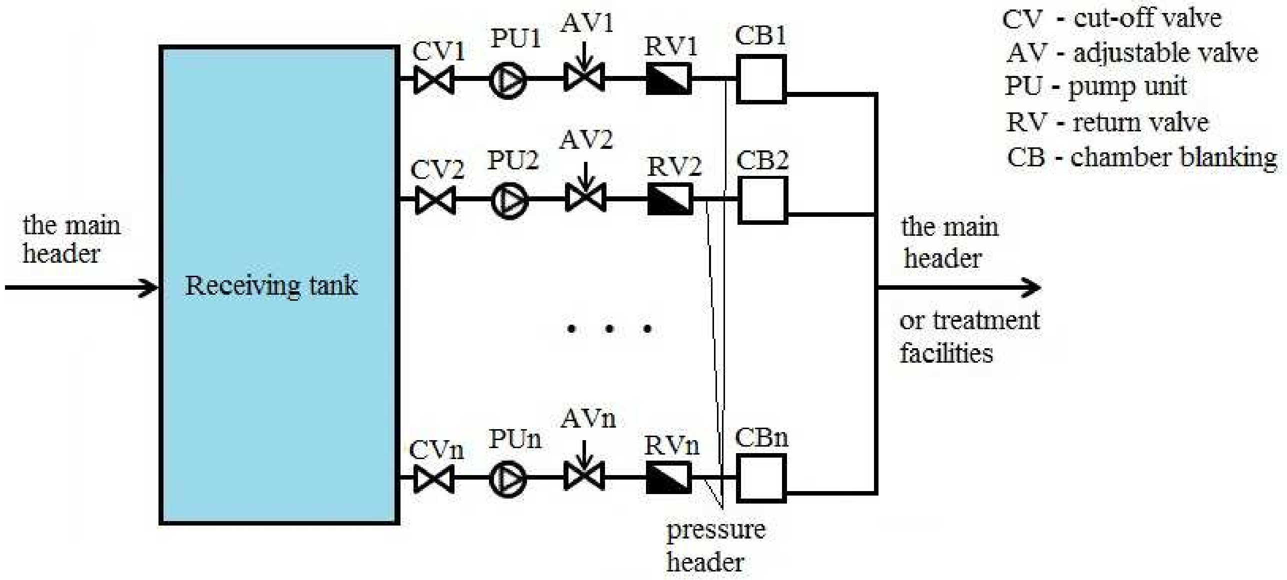

Fig. 2. Typical structure of SPS

The interval of control [0, T] (a day) is divided into 24 subintervals corresponding to each hour k=0, ..., 23. We assume that at k=0 the predictions of inflows of WW into RT $\bar{q}_{vh0}$ are known in the form of conditional mathematical expectations (ME) of future volumes of the inflow of WW, calculated at the time interval k=0, proactively l=1,2, ..., 23; ME of the level of WW in RT of SPS- $\bar{H}_0$; ME of the number of operating PU - $\bar{m}_0$. The static data are also known: the structure of SPS, lengths, diameters, geodetic marks of the sections of pressure header, the types of PU, the evaluations of the parameters of PU models, physical dimensions of RT, the evaluations of the parameters of AV, cut-off valves and return valves.

The objective function of the problem of optimal stochastic control of the modes of operation of SPS at the time interval [0, T] is ME of the sum of the electricity costs by all operating PU at the time interval [0, T]:

$$\underset{\omega}{M} \sum_{k=0}^{23} \sum_{i=1}^{m} N_{ik}(q_{ik}(\omega)) \cdot s_k \to \min_{u(k)\in\Omega}, \quad (1)$$

the area of restrictions Ω is determined by the stochastic model of quasi-stationary modes of operation of the pumping station (PS) [21-25]:

$$\underset{\omega}{\mathrm{M}}\Big(h_{KNSk}(\omega) - H_k(\omega) - h_{NArk}(q_{rk}(\omega)) + h_{RZrk}(q_{rk}(\omega)) + \\ + \sum_{i\in M} b_{1ri}(h_{ik}(q_{ik}(\omega)) + h_i^{(g)})\Big) = 0, \quad (r = 1,\dots, \mathrm{m}), \quad (2)$$

$$q_{vihk}(\omega) = \sum_{r=1}^{m} q_{rk}(\omega), \qquad q_{rk}(\omega) > 0, \quad (3)$$

$$h_{ik}(q_{ik}(\omega)) = sgn\, q_{ik}(\omega) S_i(\omega) q_{ik}^2(\omega), \quad i \in M, \quad (4)$$

$$h_{NAik}(q_{ik}(\omega)) = a_{0i}(\omega) + a_{1i}(\omega) q_{ik}(\omega) + a_{2i}(\omega) q_{ik}^2(\omega), \\ i \in L, \quad (5)$$

$$\eta_{NAik}(q_{ik}(\omega)) = d_{0i}(\omega) + d_{1i}(\omega) q_{ik}(\omega) + d_{2i}(\omega) q_{ik}{}^2(\omega), \\ i \in L, \quad (6)$$

$$N_{NAik}(q_{ik}(\omega)) = \frac{9{,}81 \cdot h_{NAik}(q_{ik}(\omega)) \cdot q_{ik}(\omega)}{0{,}9 \cdot \eta_{NAik}(q_{ik}(\omega))}, \quad i \in L, \quad (7)$$

$$h_{RZik}(\mathrm{q}_{ik}(\omega)) = \frac{\mathrm{q}_{ik}(\omega) \mathrm{C}_i(\omega)}{\mathrm{E}_{ik}^2}, \quad \mathrm{i} \in \mathrm{R}, \quad (8)$$

the stochastic model of RT:

$$\underset{\omega}{M}\left\{H_k(\omega) - H_{k-1}(\omega) - c_k(q_{vhk}(\omega) - q_{vihk}(\omega))\right\} = 0, \quad (9)$$

probabilistic and extreme constraints on the phase variables fixed at the time interval $k = 6,\ k = 23$:

$$P\left(H_k(\omega) \le H^{\max}\right) \ge \alpha, \quad \alpha \approx 0{,}97, \quad (10)$$

$$P\left(H_k(\omega) \ge H^{\min}\right) \ge \alpha, \quad \alpha \approx 0{,}97, \quad (11)$$

$$\underset{\omega}{M}\{H_6(\omega)\} \to \min_{q_{vhk}\in\Omega}, \quad (12)$$

$$\underset{\omega}{M}\{H_{23}(\omega)\} \to \max_{q_{vhk}\in\Omega}, \quad (13)$$

where: $u(k)$ - vector of control which determines the amount of operating PU, the position of AV; $H_k(\omega)$ - level of WW in RT of SPS at a given k time interval; $H^{\min}$ - minimum allowable level of WW in RT of SPS; $H^{\max}$ - maximum allowable water level in RT of SPS under certain initial conditions $\bar{m}_0, \bar{H}_0$.

Random variables characterize: $q_{ik}(\omega)$ – WW consumption on i section of the pressure header at k time interval; $h_{ik}\ (q_{ik}(\omega))$ - evaluation of the head fall on *i* section of the pressure header at k time interval; $h_{KNSk}(\omega)$ – water head at the output of SPS, $h_{NAik}(q_{ik}(\omega))$ – water head of i PU; $q_{vhk}(\omega), q_{vihk}(\omega)$ - WW consumption at the input and output of RT at k time interval. $S_i(\omega)$ – evaluation of the hydraulic resistance on i section of the pressure header ($i \in M$); $h_{RZik}(q_{ik}(\omega))$ – evaluation of the head fall on i AV; $\eta_{NAik}(q_{ik}(\omega))$ – evaluation of the coefficient of efficiency of i PU;

$$a_{0i}(\omega), a_{1i}(\omega), a_{2i}(\omega), d_{0i}(\omega), d_{1i}(\omega), d_{2i}(\omega) \; –$$

evaluations of the parameters of PU ($i \in L$); $C_i(\omega)$ – evaluations of the parameters of AV ($i \in R$); E_{ik} – rate of the opening of AV (E ϵ (0,1]); c - coefficient inversely related to the area of RT; $h_i^{(g)}$ – geodesic mark of i section of the pressure header ($i \in M$); $N_{NAik}(q_{ik}(\omega))$ - evaluation of the power by i PU at k time interval; m - number of PU on SPS; s_k - electricity tariff at k time interval; $\underset{\omega}{M}\{\cdot\}$ - ME of corresponding random variables, enclosed in brackets {.}.

The problem of optimal stochastic control of the modes of operation of SPS (1) - (13) belongs to the class of nonlinear problems of optimal stochastic control with discrete time, probabilistic and extreme constraints on the phase variables [2, 11, 19, 20]. There aren't any exact solutions of the problems of such a class nowadays. The approximate method of solving the examined problem by the transition from stochastic problem (1) - (13) to its deterministic equivalent the decision of which is carried out by the modified method of branches and bounds is given in the present work.

THE DETERMINISTIC EQUIVALENT OF THE PROBLEM OF OPTIMAL STOCHASTIC CONTROL OF THE MODES OF OPERATION OF SPS

The deterministic equivalent [8, 9] of the problem of optimal stochastic control of the modes of operation of SPS per day (1) - (13) can be represented as:

$$\sum_{k=0}^{23}\sum_{i=1}^{m} \bar{N}_{ik}(\bar{q}_{ik}) \cdot s_k \to \min_{u(k)\in\Omega}, \quad k = 0,...,23, \tag{14}$$

$$\bar{h}_{NSjk} - \bar{H}_k - \bar{h}_{NAjrk}(\bar{q}_{rk}) + \bar{h}_{RZjrk}(\bar{q}_{rk}) + \sum_{i\in M} b_{1ri}(\bar{h}_{ik}(\bar{q}_{ik}) + h_i^{(g)}) = 0,$$
$$(r = 1,\ldots, \text{m}), \tag{15}$$

$$\bar{q}_{vihk} = \sum_{r=1}^{m} \bar{q}_{rk}, \qquad \bar{q}_{rk} > 0, \tag{16}$$

$$\bar{h}_{NAik}(\bar{q}_{ik}) = \bar{a}_{0i} + \bar{a}_{1i}\bar{q}_{ik} + \bar{a}_{2i}\bar{q}_{ik}^2, \quad i \in L, \tag{17}$$

$$\bar{\eta}_{NAik}(\bar{q}_{ik}) = \bar{d}_{0i} + \bar{d}_{1i}\bar{q}_{ik} + \bar{d}_{2i}\bar{q}_{ik}^{\,2}, \quad i \in L, \tag{18}$$

$$\bar{N}_{NAik}(\bar{q}_{ik}) = \frac{9{,}81 \cdot \bar{h}_{NAik}(\bar{q}_{ik}) \cdot \bar{q}_{ik}}{0{,}9 \cdot \bar{\eta}_{NAik}(\bar{q}_{ik})}, \quad i \in L, \tag{19}$$

$$\bar{h}_{RZik}(\bar{q}_{ik}) = \frac{\bar{q}_{ik}\bar{C}_i}{E_{ik}^2}, \quad i \in R, \tag{20}$$

$$\bar{h}_{ik}(\bar{q}_{ik}) = sgn\,\bar{q}_{ik}\,\bar{S}_i\bar{q}_{ik}^2, \quad i \in M, \tag{21}$$

$$\bar{H}_k = \bar{H}_{k-1} + c_k(\bar{q}_{vhk} - \bar{q}_{vihk}), \tag{22}$$

$$H^{-*} \le \bar{H}_k \le H^{+*}, (k=1,2,...,23), \tag{23}$$

$$\bar{H}_6 \to \min_{q_{vhk}\in\Omega}, \tag{24}$$

$$\bar{H}_{23} \to \max_{q_{vhk}\in\Omega}, \tag{25}$$

where: H^{-*}, H^{+*} - calculated values of the minimum and maximum levels of WW in RT of SPS where for $\forall\omega \in \Omega$ probabilistic constraints (10) – (11) will be fulfilled under certain initial conditions $\bar{m}_0, \bar{H}_0$.

THE METHOD OF SOLVING THE DETERMINISTIC EQUIVALENT OF THE PROBLEM OF OPTIMAL STOCHASTIC CONTROL OF THE MODES OF OPERATION OF SPS.

To solve the deterministic equivalent of the problem of optimal stochastic control of the modes of operation of SPS (14) - (25) we will use the modified method of branches and bounds.

Initial data:

P - vector of dimension [24x1] defining the predicted values for the inflow of WW at the planning interval.

n - maximum quantity of similar PU which can be switched on SPS (n = 5).

T - vector of dimension [24x1] defining the three-band tariff for the electricity, T_i - electricity tariff at the time interval [i-1, i] (i = 1, ..., 24).

$\bar{H}_0$ - ME of the level of WW in RT of SPS at the beginning of the interval of control.

Allowable limits of the change of the level of WW in RT of SPS $[H_{\min}, H_{\max}] = [3,2; 5,9]$.

Physical dimensions of RT of SPS: $V = 4727m^3$; $H = 6m$.

ME of the WW flow in the operating point of PU: $q0 = 4180\ m^3/s$

The planning interval [0, T] (one day) is divided into three subintervals k_1, k_2, k_3 (k_j, $j = 1,2,3$) according to the three-band tariff. We will consider the planning interval one day as a set of time subintervals $S = \{1, 2, ..., 24\}$, then in accordance with the three-band tariff the set $S_1 = \{1, 2, ..., 5, 23, 24\}$ corresponds to the time interval with minimal tariff, with medium tariff – the set $S_2 = \{6, 7, 10, 11, ..., 17, 22\}$, with maximal tariff – the set $S_3 = \{8, 9, 18, 19, ..., 21\}$. S_1, S_2, S_3 - noncrossing sets $S_1 \cap S_2 \cap S_3 = \varnothing$ and $S = S_1 \cup S_2 \cup S_3$.

OptStoim - a large number.

Conventional signs of intermediate data:

q - vector of dimension [24x1] determining ME of the total flow rate of WW on SPS of all subintervals of the set S (m^3/s);

U - vector of dimension [24x1] defining ME of the level of WW in RT of SPS of all subintervals of the set S, U_i - level of WW in RT of SPS by the end of i time interval (m);

$$uroven = \begin{cases} 1, & if\ \forall U_i \in U : U_i \in [H_{\min}, H_{\max}], \\ -6, & if\ \exists \text{ at least one } U_i \in U : U_i < H_{\min}, \\ 6, & if\ \exists \text{ at least one } U_i \in U : U_i > H_{\max}. \end{cases} \tag{26}$$

m, $m*$ - values equal to the sum of the products of the number of operating PU and the time (h) spent on the operation at the planning interval for certain modes of operation of SPS.

Stoim – ME of the sum of the cost value for the electricity consumed by all operating PU at the interval of control.

The algorithm for finding the optimal mode of operation of SPS:

1. Preset T, P, n, $\bar{H}_0$, OptStoim, $H_{\min}, H_{\max}$, $j = 0$.

Knowing P and $q0$ determine ME of the number of operating PU m.

2. $j := j+1$. For the subinterval k_j: set the R mode of operation of SPS (the number of operating PU for each hour of the day) $R_i = n, \quad (i \in S_j)$.

3. Expect q, U, uroven.

If uroven = -6, then come back to the point 2.

4. Set the new mode of operation of SPS R by the way of search of all possible combinations of switching PU: $R_i = 0,1,\ldots,n$, $(i \in S_j)$.

5. If for the new mode R the conditions $\sum_{i \in S_t} R_i > m \quad or \quad \sum_{i \in S_t} R_i < m-1$ are met, then we come back to the point 4.

6. We expect q, U, uroven.

If uroven=1, then we calculate Stoim.

If uroven≠1, then come back to the point 4.

7. If Stoim<OptStoim, then OptStoim:=Stoim.

8. For the mode R mode calculating m*; if m*<m, then m:=m*.

9. Conclusion Stoim; R; U. Come back to the point 4.

10. Selection of the optimal values Stoim*; R*; U*.

Fig. 3 shows a flowchart of the algorithm of searching of the optimal mode of operation of SPS at the interval of control [0, T].

As a result of the solution of the problem (14) - (25) of optimal stochastic control of the modes of operation of SPS for each time interval k, we obtain:

1. ME of the vector of control $u(k)$, including: the number of operating PU, the position of the operating point of each PU;

2. estimates of ME of the levels of WW in RT of SPS;

3. estimates of the pressure-flow rate and pressure drop for all technological elements of SPS;

4. estimates of ME of the expenses for the electricity and its value in accordance with the three-band tariff by all operating PU.

At the time interval k = 23, we obtain the evaluation of ME of the total cost of the electricity consumed by SPS at the interval of control [0, T].

RESULTS AND DISCUSSION

The evaluation of the effectiveness of the proposed method was carried out for SPS shown in Fig. 2. equipped with five PU type FLYGT CT 3531 and four PU type SDV 9000/45, whose passport characteristics are shown in Fig. 4, the approximated parameters in Table 1.

The initial data for the problem of optimal stochastic control of the modes of operation of SPS at the interval of control [0, T] are:

• statistical data, including the structure of SPS; lengths; diameters; geodetic marks of the sections of the pressure header; evaluations of the parameters of mathematical models of all PU; evaluations of hydraulic resistances of all AV; physical dimensions of RT;

• dynamic data, including the prediction of inflow of WW into RT of SPS per day.

RT has the following physical dimensions: height - 6 m, capacity - 4728 m^3. The minimum allowable level of WW in RT - 3,2 m, the maximum allowable level of WW in RT – 5,9 m. Lengths, diameters and geodetic marks of pressure headers, respectively: : $l = 350$ m, $d = 1{,}1$ m, $h^g = -31{,}65$ m. The diagram of prediction of the inflow of WW in RT per day is shown in Fig. 5.

At time zero k = 0 for the actual and optimal mode the same conditions have been used: ME of the level of WW in RT $H_0 = 5{,}1$ м; three PU type Flygt operated on SPS. For the actual mode the single-band tariff 1,238 has been used; for the optimal mode - the three-band tariff.

The results of solving the problem of optimal stochastic control of the modes of operation of SPS are shown in Table 2 and Fig. 6.

Table 1. Estimates of ME of the parameters of the approximating functions H-Q and COP-Q

Type of PU	$\bar{a}_0$	$\bar{a}_1$	$\bar{a}_2$	$\bar{d}_0$	$\bar{d}_1$	$\bar{d}_2$
FLYGT CT 3531	67,55976	-22,2469	-2,54534	18,33433	116,416	-54,1789
SDV 9000/45	57,22619	0,82143	-2,40476	1,428571	77,2857	-17,4286

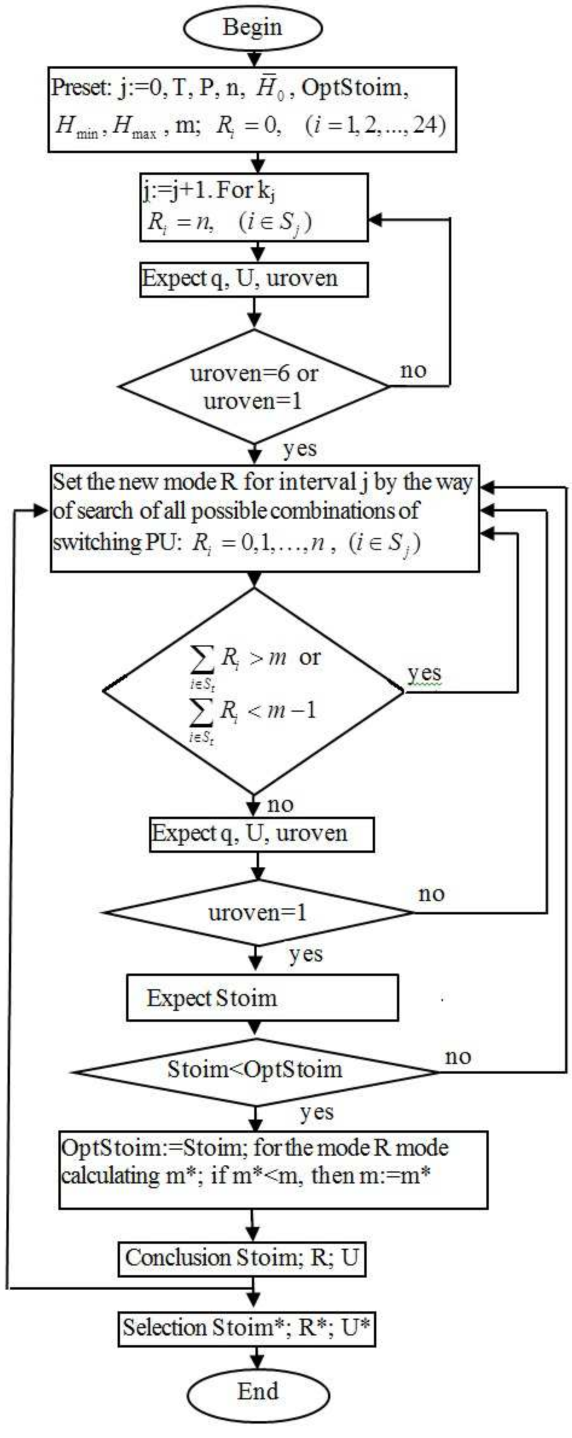

Fig. 3. Flow chart of the algorithm of searching of the optimal mode of operation of SPS at the interval of control [0, T]

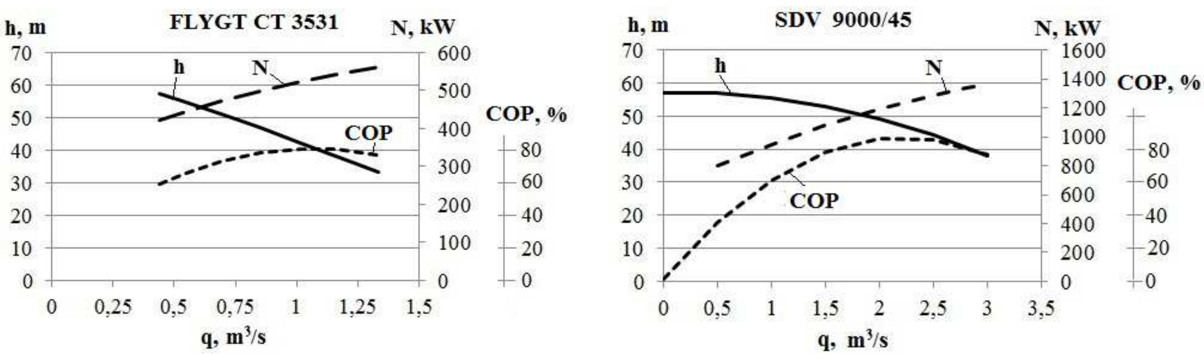

Fig.4. The characteristics of the pump units FLYGT CT 3531 and SDV 9000/45

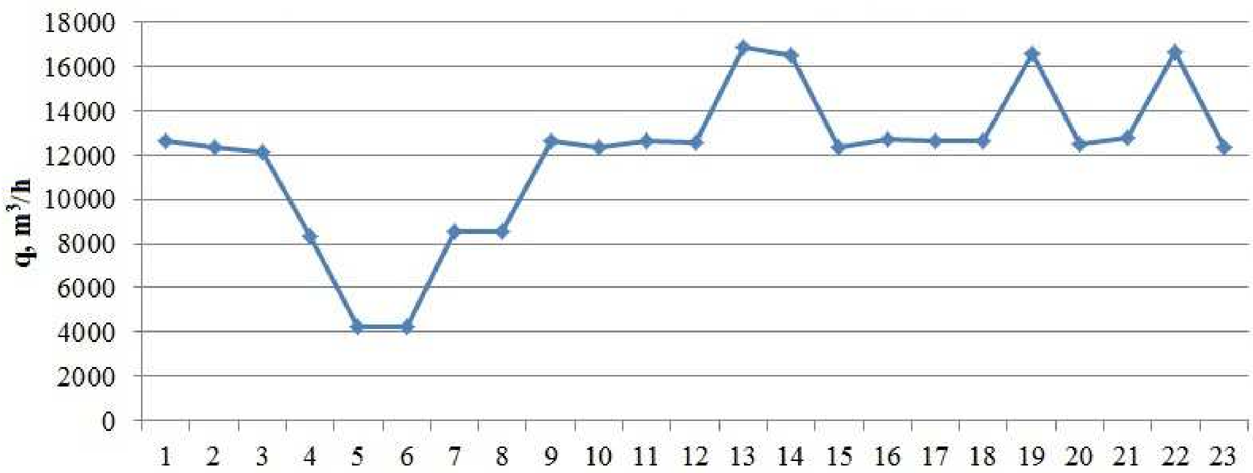

Fig. 5. The diagram of prediction of inflow of WW in RT per day

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Table 2. ME of the number of operating PU at the interval of control [0.23] for the actual and optimal modes of operation of SPS

Hours	Tariff	Actual mode		Optimal mode	
		ME of the number of operating PU type FLYGT	ME of the levels of WW in RT, m	ME of the number of operating PU type FLYGT	ME of the levels of WW in RT, m
1	0,25	3 PU	5,2	5 PU	4,78
2	0,25	3 PU	5,3	5 PU	4,47
3	0,25	3 PU	5,1	5 PU	4,15
4	0,25	3 PU	4,6	5 PU	3,83
5	0,25	2 PU	4,6	5 PU	3,39
6	1,02	1 PU	4,7	1 PU	3,39
7	1,02	1 PU	4,8	-	3,54
8	1,8	2 PU	5	-	3,84
9	1,8	2 PU	5,2	-	4,14
10	1,02	3 PU	5,3	2 PU	4,29
11	1,02	3 PU	5,1	5 PU	3,98
12	1,02	3 PU	5,2	5 PU	3,68
13	1,02	3 PU	5,2	5 PU	3,39
14	1,02	4 PU	5,4	4 PU	3,40
15	1,02	4 PU	5,1	5 PU	3,25
16	1,02	3 PU	4,9	1 PU	3,54
17	1,02	3 PU	5,1	2 PU	3,69
18	1,8	3 PU	5,2	-	4,14
19	1,8	3 PU	5,3	-	4,58
20	1,8	4 PU	5,1	-	5,17
21	1,8	3 PU	5	-	5,60
22	1,02	3 PU	5,3	1 PU	5,90
23	0,25	4 PU	5,2	5 PU	5,71
24	0,25	3 PU	5	5 PU	5,37

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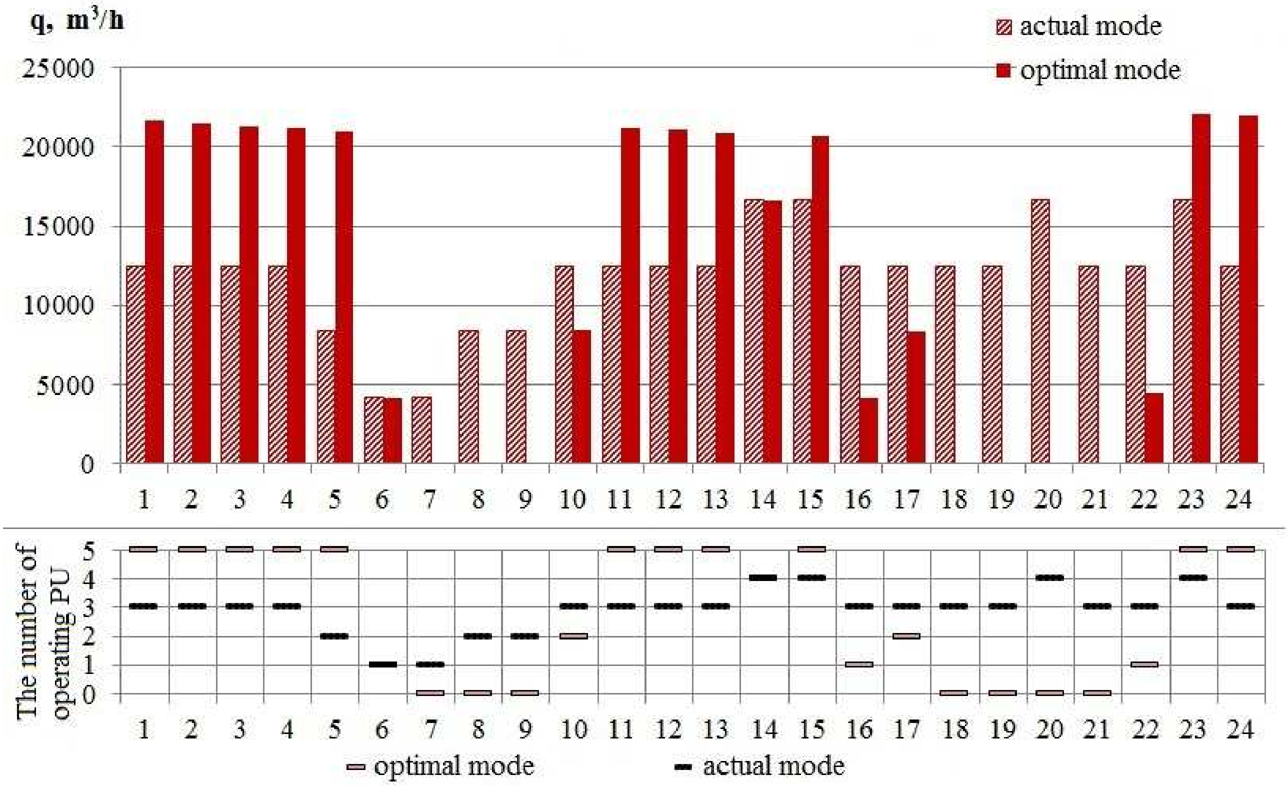

Fig. 6. ME of the volume of WW pumped by SPS at the interval of control [0.23] and ME of the number of operating PU for the actual and optimal modes of operation

Table. 3 presents the estimates of ME of power and cost value for the electricity at the interval of control [0.23] for the actual and optimal modes of operation of SPS.

Table 3. The comparative analysis of ME of the parameters of actual and optimal modes of operation of SPS

Parameters	Actual mode	Optimal mode
N, kW	38154,21	36061,73
Cost, UAH	47234,91	22009,45

The analysis of the results in Table 3 leads to the conclusion that while the transition to the three-band tariff for the electricity and use of the proposed algorithm of optimal stochastic control significant savings in the cost for the electricity from 47234,91 UAH to 22009.45 UAH can be provided, which is 53,4% less than the previous amount.

Fig. 7 presents the change of the estimate of ME of the cost value for the electrical energy while the transition from the actual to the optimal mode.

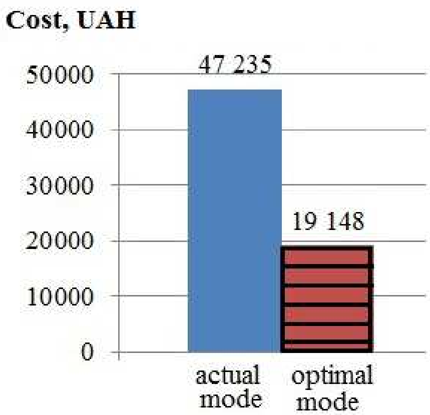

Fig. 7. The estimate of ME of the cost value for the electricity consumed by SPS at the interval of control [0.23]

Fig. 8 shows that under the optimal mode of operation of SPS the capacity of RT is used more efficiently.

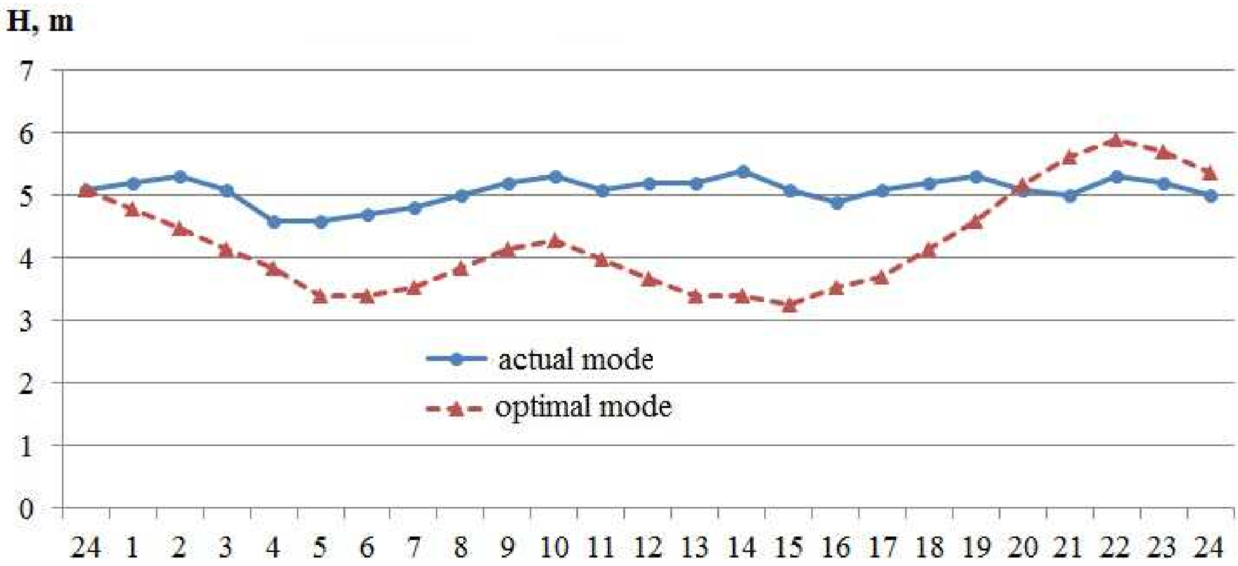

Fig. 8. ME of the changes of levels of WW in RT of SPS for the actual and optimal modes of operation of SPS

Thus, it can be seen from Fig. 8, that by 11 p.m. ME of the levels of WW in RT reaches its maximum value and by 6 a.m. its minimum value.

Practical application of the proposed mathematical model and method of optimal stochastic control of the modes of operation of SPS and the transition to the three-band tariff for the electricity provides a significant saving in financial expenses of SPS for pumping WW at the interval of control [0, T].

CONCLUSIONS

Scientific novelty:

1. for the first time SPS is represented as a stochastic object of control operating in the stochastic environment, it allowed to take into account adequately the specific characteristics of stochastic processes of the inflow of WW into RT of SPS and the stochastic properties of technological equipment of SPS which gave the possibility to present the problem of optimal control of the modes of operation of SPS as the problem of optimal stochastic control with discrete time with probabilistic and extreme constraints on the phase variables;
2. for the first time the effective method for solving the problem of optimal stochastic control of the modes of operation of SPS by the transition to its deterministic equivalent and its solutions by the modified method of branches and bounds has been proposed.

Practical value:

The estimates of the effectiveness of the proposed mathematical model and method of optimal stochastic control while the transition to the three-band tariff for the electricity was carried out using the example of the main SPS (SSPS) of one of the largest cities of Ukraine. It is shown that the use of the proposed method in comparison with the currently used method of control of the modes of SSPS allows significantly (up 53%) to reduce the cost value for the electricity, for pumping WW SSPS at the interval of control [0, T].

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ECONTECHMOD. AN INTERNATIONAL QUARTERLY JOURNAL – 2015, Vol.4, No.3, 57-63

MATHEMATICAL MODELLING OF DYNAMIC PROCESSES IN GAS TRANSMISSION

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Received July 27.2015: accepted August 28.2015

Abstract. The problem of finding the parameters of the gas transmission system in terms of its operation under unsteady operating modes are considered. We show mathematical models of gas flows in the basic facilities in the system with a complicated piping diagram. The solution is built to solve a system of partial differential equations with the finite element method of large dimension with boundary conditions, some of which are designed in the process of solving the system of equations. This is due to the provision of technical and technological constraints on the pressure of the controlled points of the system. On the resistance to finding a solution significantly affects a step of the time coordinate. The proposed algorithm in the editing process of flow diagrams provides an increase in stability of solving systems of equations, and significantly reduces the time for the simulation.

Key words: transmission system, compressor station, optimal operating mode, gas flow model, network model, piping diagram, finite element method.

INTRODUCTION

The calculation of the parameters of the gas pipeline system is a complex mathematical problem. Main gas pipelines with compressor stations and other facilities are a single facility, all parameters which are hydraulically interconnected. Changing the mode of operation of an individual object is to change the mode of the entire system. The gas transmission system (GTS) belongs to a class of nonlinear systems with distributed parameters, which are characterized by a network layered structure, a large space and time dimension and distribution, the presence of continuous and discrete control actions, a high level of uncertainty of objectives, structure, properties and states, as well as influences from the environment.

Transmission system, in which objects are hydro thermodynamic, filtration and other physical processes, is the subject of control. The physical nature of the gas allows a wide range to change its parameters - pressure, temperature and volume. In this regard, the gas-dynamic processes that take place in the facilities of the system are described by complex mathematical dependencies. The nonlinearity of the dynamic processes that evolve over large spatial and time dimensions, the weak predictability of input parameters, a significant influence of external factors and insufficient metrological support greatly complicate both the formulation and solution of problems of the analysis, optimization and finding control parameters of gas flows. Not yet fully solved the problem of creating modelling software for optimization of unsteady operating modes of gas transmission systems. The effectiveness solving unsteady flows of gas transmission will improve the operative dispatch control of gas flows

The work for finding solutions of the corresponding nonlinear systems of partial differential equations that describes the processes that take place in the facilities of the GTS used iterative approaches, which are based on the linearization of the original system with a further refinement of the solution by calculating the respective discrepancies.

THE ANALYSIS OF RECENT RESEARCHES AND PUBLICATIONS

In general, the simulation of the transmission of gas through pipelines is reduced to the analysis of the complete system of equations of gas dynamics, which contains the equation of continuity, change of momentum, energy, and the equation of gas state. The complete system of partial differential equations of gas dynamics is generally a non-linear, and its solution is connected with considerable difficulties. At this time, thay built a significant number of ways to solve problems of this type [1-6]. All of them can be divided into several classes: analytical, numerical, approximate and iterative. Each has its advantages and disadvantages. As practice shows, the choice of models and methods dictated mainly problems that need to be solved on the basis of the constructed mathematical model. The one of effective solution approaches have linearization of the initial equations with the following refinement of solutions based on the building of iterative procedures. Most modelling techniques that have practical use, lead to the necessity of solving systems of differential or algebraic equations of high dimensionality. This raises issues of resistance and the minimum time for solving systems with guaranteed accuracy.

Publications on the subject of the work carried out by many groups [7-11]. Attention should be given only to those works that have been tested on real data and can be used for the development of modern systems of dispatching management. Requirements for such works are well-known - they have to work steadfastly in the entire range of gas-dynamic processes that produce results in the modeling of gas-dynamic processes in systems with complex piping diagram does not require simplification or equivalenting parts of the facilities, to be adaptable to the different characteristics of the actual operation of gas transmission systems. At this time, the models of gas flows for individual facilities are sufficiently developed. The main problems associated with the development of methods and algorithms for the implementation of models of individual and interrelated systems of facilities. This requires a minimum simplified models of systems, providing stability of simulation process in the whole range of flow parameters and meet many of the technical and technological limitations, to minimize the time of obtaining results and maximizing the automated process of formulating and solving problems. A certain part of the works that related to the development of commercial products, they are type of advertising and advertise only functional part of the developed systems, rather than mathematical apparatus implementation. This applies to software systems: Astra (Russia), SIMONE (designer SIMONE Research Group sro) and developments, which are operated by Schlumberger. The most informative conference proceedings are, in particular, conferences which are held in "Gazprom VNIIGAZ" [22-24].

MAIN RESULTS

Unsteady non-isothermal model of gas flow.

Unsteady, nonisothermal gas flow in pipelines is described by the system of equations [5,6,9]:

$$\begin{gathered}
\frac{\partial(\rho v)}{\partial t}+\frac{\partial}{\partial x}\left(p+\rho v^2\right)=-\rho\left(\frac{\lambda v|v|}{2D}+g\frac{dh}{dx}\right),\\
\frac{\partial\rho}{\partial t}+\frac{\partial}{\partial x}(\rho v)=0,\\
\frac{\partial}{\partial t}(\rho E)+\frac{\partial}{\partial x}\rho v\left(E+\frac{P}{\rho}\right)=\frac{4k(T_{гр}-T)}{D}-\rho vg\frac{dh}{dx}.
\end{gathered} \quad (1)$$

where: ρ - the density of the gas; p - gas pressure; υ - gas velocity; λ - coefficient of hydraulic resistance; k - coefficient of heat transfer from the pipeline to the ground; T and $T_{гр}$ - the gas temperature and the soil temperature, respectively; h - the depth of the pipeline; E - total energy per unit of gas mass; g - acceleration of gravity; D - the diameter of the pipeline; $x,\ x\in[0,l]$ - the coordinate of the pipeline; l - the length of the pipeline.

To close this system of equations using the equation of gas state:

$$p=\rho zRT\ , \quad (2)$$

where: z - compressibility factor that characterizes the difference between a real gas from the ideal and is determined on the basis of empirical relationships built [1], R - gas constant.

Gas compressibility factor is calculated for the well-known formula [12-13]:

$$z=\frac{1}{1+f(a-bp)p}\ , \quad (3)$$

where: a and b - approximation coefficients calculated z for the known procedures - procedures for calculating gas compressibility factor, such as Hall-Yamburg, Redlich-Kwong and others $f=\left(24-0.21t^{\circ}C\right)\cdot 10^4$, here $p(x)$ - measured in atmospheres.

When steady-state conditions of gas flow the temperature depends only on the coordinates and calculated by the formula:

$$T(x)=T_{01}+T_{02}e^{-ax}\ ,$$

where:

$$T_{01}=T_{г}-T_{00},\ T_{02}=T_0-T_{г}+T_{00},\ a=\frac{k\pi D}{C_pM}\ ,$$

$$\Delta p=p_0-p_k\ ,\ T_{00}=\frac{1}{aL}\left(\Delta p\left(D_i-\frac{1}{c_p\rho_0}\right)+\frac{g\Delta h}{c_p}\right).$$

The Reynolds number is calculated by the formula:

$$\mathrm{Re}=\frac{Dvp}{\mu_0RT}\ \frac{T+C}{273+C}\ \left(\frac{273}{T}\right)^{3/2}.$$

where: $M=\rho_0Q_0$ - the mass flow rate; T_0 - temperature of the inflow gas to the pipeline; T_{gr} - temperature of the soil; D_h - Joule–Thomson coefficient; C_p - heat transfer coefficient from the gas to the soil; Δh - height difference between the end and the beginning of the pipeline; p_0 - the value of the pressure at the beginning of the pipeline; $p=p(x)$ - the distribution of the pressure along the pipeline; ρ_0 - the gas density under normal conditions; x - running coordinate. Gas constant and compressibility factor, usually taken constant. (3)

The linearized system by velocity occurs for horizontal pipelines in certain ranges of velocity change along the pipeline. The large-diameter pipes with significant volumes of gas transmission must take into account the change in its kinetic energy, to which little attention in publications for the subject. Linearization method, which allows you to specify the linearized model and iterative process to build solutions of the system is as follows.

The curve $f(v)=v^2$ will replace the chord and tangent. Since the transmission of gas velocity changes from v_1 to v_2, then the equation of the chord and the tangent that passes through the point:

$$\left(v_1, f\left(v_1\right)\right),\ \left(v_2, f\left(v_2\right)\right),$$

of view $\varphi_i\left(v\right) = a_{0i}v - b_{0i}$,

where: $i=1$ are for chord, and $i=2$ - a tangent. And wherein:

$$a_{01} = a_{02} = v_1 + v_2,\ b_{01} = v_1 v_2 \text{ та } b_{02} = 0.5\left(v_1+v_2\right)^2.$$

Given the above, the system (1) in an isothermal mode of flow can be written as:

$$\begin{cases} \dfrac{\partial\left(\rho v\right)}{\partial t} + \dfrac{\partial p}{\partial x} + \dfrac{\lambda a_{0i}}{2D}\rho v - \dfrac{\lambda b_{0i}}{2D}\rho = \dfrac{\lambda \rho}{2D}\left[v^2 - \varphi_i\left(v\right)\right] \\ -\dfrac{\partial\left(\rho v\right)}{\partial x} = \dfrac{1}{c^2}\dfrac{\partial p}{\partial t} \end{cases},$$

or

$$\begin{cases} \dfrac{\partial \omega}{\partial t} + \dfrac{\partial p}{\partial x} + a_i\,\omega - b_i\,p = \dfrac{\lambda \rho}{2D}\left[v^2 - \varphi_i\left(v\right)\right] \\ \dfrac{1}{c^2}\dfrac{\partial p}{\partial t} + \dfrac{\partial \omega}{\partial x} = 0 \end{cases}, \quad (4)$$

where indicated:

$$b_i = \frac{\lambda b_{0i}}{2DgzRT},\ \ \omega = \rho v,$$

$$a_i = \frac{\lambda a_{0i}}{2D}.$$

To determine the hydraulic resistance of the gas flow there is empirical formula:

$$\lambda = \alpha_1\left(\frac{\alpha_2}{\mathrm{Re}} + \frac{\alpha_3 k_{ш}}{D}\right)^{\alpha_4}, \quad (5)$$

where: $\alpha_i,\ i=\overline{1,4}$ - are some known constants, $k_{ш}$ - roughness of pipelines ($k_{ш}$ and D in mm), μ_0 - the dynamic viscosity under normal conditions, C - the Sutherland's constant. Formula (5) gives the greatest error under unsteady operating modes (laminar to turbulent flow and vice versa).

Present system (2) is a key system of equations of unsteady model of non-isothermal gas flow in the pipeline, taking into account the profile of the pipeline.

Unsteady flow model of gas transmission networks [19-21]. Mathematical model of the gas transmission system is based on its piping diagram. Structural properties of the piping diagram affect both the dimension of the system (system model) and the complexity of its solutions. Conducted numerical experiments showed that some simplification of the piping diagram provides greater stability and reduce the time for solving the corresponding systems. The basic graph operations such is the union of edges and contraction of the edges into the vertex. Important is the sequence of operations.

Building and editing piping diagrams. GTS piping diagram presented as a graph $G=\left(V,E\right)$, where V - the set of vertices (nodes), E - a set of edges. Edges represented objects that have extension in space, vertices - all other objects. In the case of mathematical modeling of processes that take place in the edges, each of which is divided into a certain amount (which depends on the length of an edge) segments. The end result is the calculation of unsteady flow, which take place in the GTS, is reduced to solving the system of equations. An important performance criterion is the choosing of the minimum number of segments of edges, to receive the smaller dimension of the system of equations, and thereafter, it will be solved. On the other hand - for higher accuracy simulation of unsteady processes need more of these segments. It should therefore be a balanced approach to reduce the dimensionality of the system of equations.

The obvious fact is that the graph must not contain zero length edges or diameters, therefore these edges are identified with one of the vertices (this includes open valves, bypass valves, and etc.). It is also appropriate to consider a sequence of edges that have the same diameter as one edge. That is, if certain adjacent edges $e_j = \left(v_{i-1}, v_i\right)$, $e_{j+1} = \left(v_i, v_{i+1}\right)$ have the same diameter $\left|D_{e_j} - D_{e_{j+1}}\right| < \varepsilon_D$, where ε_D - the tolerance value for the diameter of edges e_j and e_{j+1} and assign a value to the length of a new edge equal to the sum of the two combined $L_{e_j^*} = L_{e_j} + L_{e_{j+1}}$ and $D_{e_j^*} = D_{e_j}$. Another parameter that allows you to simplify the system of equations is to set a minimum length of edges in the graph L_{sh}. If an edge is shorter than L_{sh}, it is identified with a vertex. This reduces the number of edges, and therefore the number of equations. By choosing the value L_{sh} necessary to take care, given that the volume of the geometric edges of the modified graph was not significantly different from the original graph of the GTS, as well as the topology was not changed. Considering it is also contemplated not to conduct shrinkage of the edge, despite the fact that $L < L_{sh}$.

It should also be noted that certain parameters of the vertex v of any incident to the joint edges (pressure or inflow or outflow of gas), which is absent in the modified graph, should be considered at the vertex of the start $v_{поч}$ or end of the resulting edge e_R. The algorithm is implemented choice of the vertex with regard to the distance corresponding to the vertices, that is, if $L\left(\overrightarrow{v, v_{поч}}\right) \le L\left(\overrightarrow{v, v_{пкін}}\right)$, then the change will occur to the vertex $v_{поч}$.

Network model of unsteady flow [14-15]. Since when unsteady gas flow Kirchhoff's second law is not fulfilled, then the design of the corresponding mathematical model should be carried out on other principles - conservation equations.

For ease description, consider a system with a single vertex that contains M pipeline sections. Suppose that the system consists of the M_{in} input and M_{out} output sections that are indexed in the appropriate order. Denote x_J the point of connection. Denote the length and the diameter of the k - section through L_k and S_k respectively and ($k=\overline{1,M}$). On Each site we choose a point $\{x_{J\mp}\}_k$, which is fairly close to x_J (the "+" or "-" in the index depends on the direction of gas flow). Then for. k section system (1) takes the form:

$$\begin{cases} \left\{ \dfrac{\partial\omega(t,x)}{\partial t} + \dfrac{\partial p(t,x)}{\partial x} + C_\omega \omega(t,x) + C_P\, p(t,x) \right\}_k = 0, \\ \left\{ \dfrac{\partial p(t,x)}{\partial t} + c^2 \dfrac{\partial \omega(t,x)}{\partial x} \right\}_k = 0, \;\; k=\overline{1,M}, \end{cases} \quad (6)$$

where: c - the speed of sound in the gas, $\omega = \rho v$,

$C_\omega = \dfrac{\lambda v_c}{2S}$, $C_P = \dfrac{g}{zRT}\dfrac{dh}{dx}$,

v_c - average speed,

$x \in \left[0, \{x_{J-}\}_k\right]$, when $k \le M_{in}$ or

$x \in \left[\{x_{J+}\}_k,\ L_k\right]$, when $k > M_{in}$.

Given the equality of pressures for all sections at the point of connection and the Kirchhoff's first law we will have model of the gas flow in the vicinity of the connection vertex:

$$\begin{cases} \left\{ \dfrac{\partial\omega(t,x)}{\partial t} + \dfrac{\partial p(t,x)}{\partial x} + C_\omega \omega(t,x) + C_P p(t,x) \right\}_k = 0, \;\; k=\overline{1,M}, \\ \left\{ \dfrac{\partial p(t,x)}{\partial t} + c^2 \dfrac{\partial \omega(t,x)}{\partial x} \right\}_k = 0, \\ \{p(t,x_J)\}_i = p(t,x_J)\}_j, \qquad \forall i,j=\overline{1,M}, \\ \sum\limits_{i=1}^{M_{in}} \{S\omega(t,x_J)\}_i - \sum\limits_{j=M_{in}+1}^{M} \{S\omega(t,x_J)\}_j = 0, \end{cases} \quad (7)$$

where: $x \in \left[0, \{x_{J-}\}_k\right]$, when $k \le M_{in}$ or

$x \in \left[\{x_{J+}\}_k,\ L_k\right]$, when. $k > M_{in}$.

System (7) will describe the gas flow in the M sections which are connected at one point x_J. This approach can be easily generalized to the case of more complex network structure (with lots of vertices). To do this, we design a directed graph whose edges correspond to sections of the pipelines. Then, for every edge and vertex (vertices degree which is greater than 1) we can work out the set of equations (6) and (7) respectively.

To find a numerical approximation of the solution (6), (7) it is advisable to perform a spatial and temporal sampling of the model. On each time step we take the number of iterations to solve the linearized system of equations with sufficient accuracy, and have solutions of nonlinear equations (1).

Simulation of compressor stations [16-18]. The model of a compressor station (CS) is based on the model of the structure and the models of its facilities. The structure model is represented as a graph in which the objects that have extension represented as edges and all others as vertices. The main object is the gas compressor unit (GCU), and consist of the engine and the centrifugal compressor (CC). It is known [16] that the parameters of the gas inflow and outflow of CC are associated by a set of empirical equations:

$$\varepsilon = \varphi_1\left([q]_{пр}, \left[\frac{n}{n_H}\right]_{пр} \right),\;\; \eta_{пол} = \varphi_2\left([q]_{пр} \right),$$

$$\frac{N_i}{\gamma_n}\left(\frac{n_n}{n}\right)^3 = \varphi_3\left([q]_{пр} \right).$$

$$T_{вих} z_{вих} = T_{вх} z_{вх} \varepsilon^{\frac{k-1}{k\cdot\eta_{пол}}},$$

$$N_e^p = N_e^n K_{Ne}\left(1 - K_t \frac{t_0 - t_0^n}{t_0 + 273}\right)\frac{p_a}{0{,}1033},$$

Other operating parameters of the GCU folow the equations:

$$q_{pg} = q_{pg}^n K_t \left(0{,}75\frac{N_e}{N_e^n} + 0{,}25\sqrt{\frac{t_0+273}{t_0^n+273}\frac{p_a}{0{,}1033}}\right),$$

$$q_{pg}^n = \frac{860 N_e^n}{\eta_e^n Q_n 10^3}, \quad N_e = N_i : (\eta_m K_N).$$

where: n - speed of the CC, q - the gas flow rate through the CC, $\eta_{пол}$ - polytropic efficiency, q_{pg}^n - nominal flow rate of fuel gas, ε - pressure ration, N_e^n - rated power of the the gas turbine; K_{Ne} - coefficient of technical state of the gas turbine; K_t - coefficient, which takes into account the effect of air temperaturer; t_0 - temperature of the air at the inlet of the gas turbine; t_0^n - nominal temperature of the air at the inlet of the gas turbine; p_a - the absolute pressure of the air depending on the height above sea level H; Q_n - the nominal lower heating value; η_e^n - rated polytropic efficiency; η_m - mechanical efficiency, K_N - technical condition according to power.

The developed algorithm of CS operation for a set of input data $(\rho_c, P_1, P_2, T_1, q, \{M_i^k\})$ (the density of gas at standard conditions, the gas pressure at the inlet, outlet gas pressure, gas flow rate, count of GCU in each i workshop) calculates the operating mode of the CS $(T_2, s_{ij}^k, n_{ij}, \varepsilon_{ij}, q_{pg}^{ij}, N_{ij})$ (the outlet temperature; scheme of GCU connections; i - stage number; j - number of GCU in the stage; k - the type of GCU; CC speed; pressure ratio; the amount of fuel gas and gas turbine power). Indices $(i,j) \in \{N_i^k, N_j^k\}$ (N_i^k - set of stages of CC; N_j^k - set of CC at i - stage).

To calculate operating mode parameters at time $t_{j+1} \cdot \left(t_{j+1} = t_j + \Delta t\right)$ is necessary to solve a system of equations for the unknowns q (volume flow rate) and P (gas pressure). In this system of equations, among other conditions are met pairing. If we consider the CS as the edge of the GTS, it is necessary to set the compression ratio ε, which reached by CC, working for a given power $W = (W^1,...,W^n)$, where n - the count of workshops of the CS, and this edge will provide the fulfill of the equation $P_2 = P_1 \cdot \varepsilon$. To calculate ε we have realized function that calculates the operating mode of the CS $(T_2, s_{ij}^k, n_{ij}, \varepsilon_{ij}, q_{pg}^{ij}, N_{ij})$ using data $(\rho_c, P_1, P_2, T_1, q, \{M_i^k\})$.

Transition of the CS to the non operating mode, occurs using compression ration $\varepsilon = 1$. Turning on CS is performed within N_{On} steps of approching compression ratio ε from $\varepsilon_{\min}$ to $\varepsilon_{default}$. Then there is the operating mode of the CS in the situation that has occured and we fix the power of the CS.

Changing power of the CS (increase or decrease) is proportional to all the operating workshops by a certain percentage κ. In this case, κ defined as the percentage deviation of the monitored parameters from the optimum value

The boundary conditions. At the inputs and outputs of the network of gas pipelines are set boundary conditions on the pressure and flow rate. Some boundary conditions are calculated during the simulation of gas-dynamic processes. On calculation of the boundary conditions have a significant impact technical and technological restrictions: the work points on the characteristics of CC, surge area; CC maximum volume flow rate; CC shaft speed $n_{\min} \le n \le n_{\max}$; maximum power of the gas turbine; CC maximum initial pressure, which is determined by the strength of pipelines at the inlet of CC; the maximum temperature at the outlet of CC is defined by the insulation coating pipelines; minimum value of pressure at the outlet of each CC; conditions of the consistency of connection scheme with inlet and outlet pipelines.

The numerical experiment. The numerical experiment was conducted on a real gas transmission system, which belongs to one of the depatments of the PJSC "Ukrtransgaz" (see Fig.1). The main objective was to analyze the impact of topology changes on the dynamics of changes in the flow parameters, the distribution over time. The change of topology is the opening of three taps at a specified time. Before the simulation was carried out to identify models of gas flows in the facilities of the system. Opening taps lasted 30 minutes. Step-by-time variable was equal $\Delta t = 10 хв$.

After simulating parameters of the gas flows we got values for each facility type vertex - pressure and temperature, and type of edge – volume flow rate over a simulation time. The simulation results, as an example, are shown for one of the valves in Fig. 2.

The current system of finding of the boundary conditions and simulation of unsteady modes with variable step provides simulation and control valves - pressure reducers and valve systems for hydraulic control functions and protection. (control valves MOKVELD). The ratio of simulation time with a complex piping diagram to the real-time transmission of gas dynamic processes is in the range 1: 15 - 1: 20, which is completely acceptable for practical use. The main factor of influence on the stability of the simulation - change states of a few taps simultaneously. In this case, stability of the method is enshured by a speed of model gas dynamic processes in the vicinity of taps, as well as the reduction of the time step in the numerical analysis.

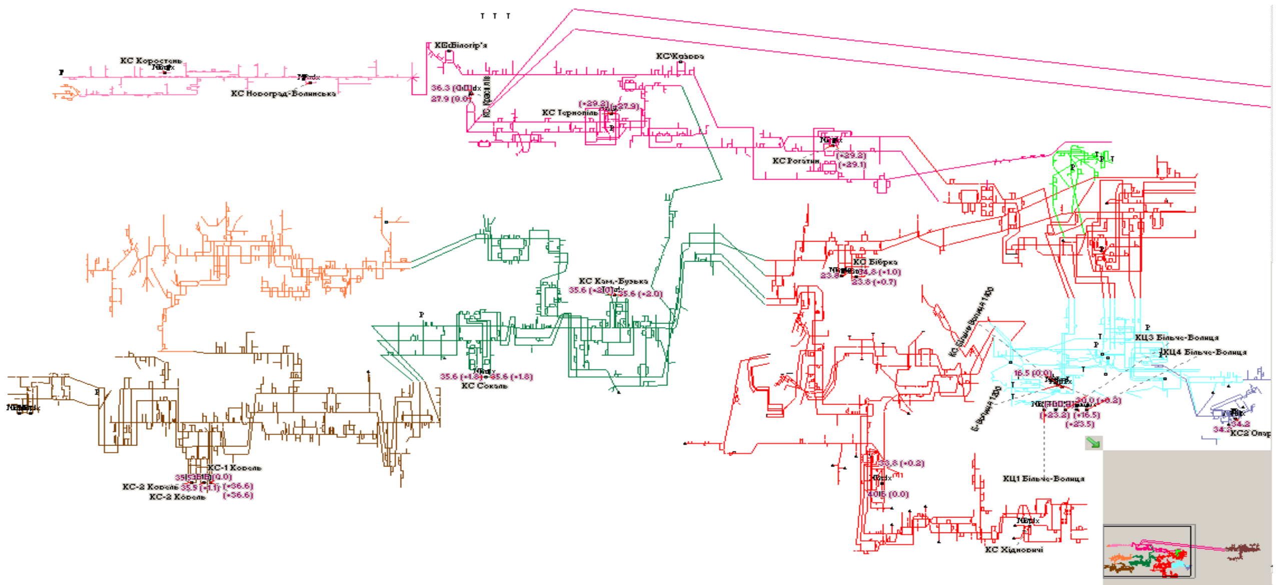

Fig.1. Piping diagram of gas transmission system of pipeline operator "Lvivtransgaz"

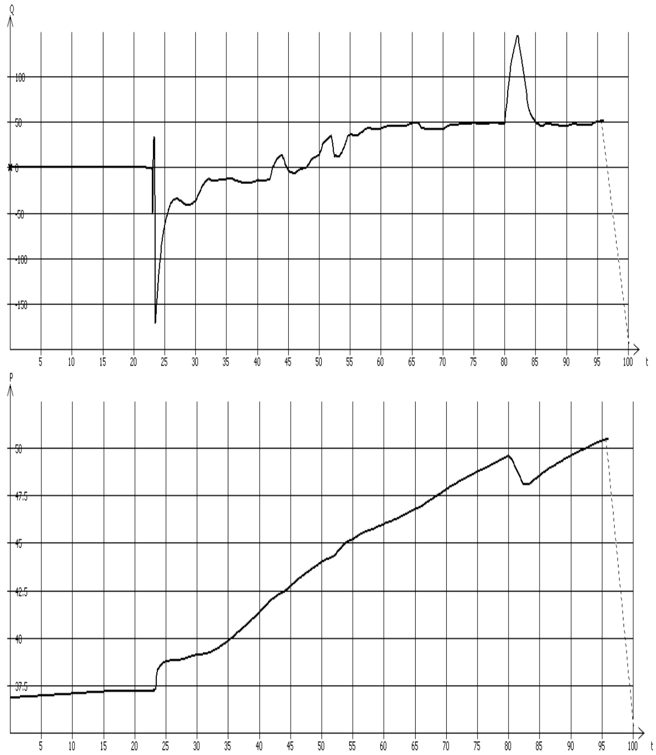

Fig. 2. The graph of the gas volume flow rate (above) and the graph of the gas inlet pressure of tap (bottom)

CONCLUSIONS

1. The proposed approach to the calculation of the parameters of gas transmission systems with complex piping diagram under the conditions of its operation in unsteady conditions has been tested on real data and demonstrated a high level of stability.
2. Stability of the method for solving systems of equations of large dimension is ensured by editing options of piping diagram and adaptive methods for passage speed of gas-dynamic processes.
3. It is remains the open problem of optimal control transition operating modes from the current to a certain optimal steady mode.

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ECONTECHMOD. AN INTERNATIONAL QUARTERLY JOURNAL – 2015, Vol.4, No.3, 65-72

MODERN TENDENTION IN THE USE OF GPS TECHNOLOGY IN TOURISM INDUSTRY

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Received July 27.2015: accepted August 20.2015

Abstract. The article is devoted to the analysis of the possibilities of GPS-technology (Global Positioning System) in the tourism industry. The study is devoted to the identification and analysis of functionality of mobile computing devices equipped with GPS receiver in tourism industry, the methods and means of their implementation, building on this basis a mobile information technology for tourist support at all stages of his journey. To achieve the goal a number of mobile information systems using data GPS, methods and means of their implementation, a comparative analysis of current cartographic services that are used in the developing of mobile information technology applications for tourist are analyzed. The study outlines the place of GPS-technology in the "Mobile tourist information assistant" system, and the role of Google Maps services for information technology support and implementation of the main tourist features in mentioned mobile information system.

Key words: GPS, global positioning system, mobile technology, tourist, tourism, location-based services, mobile application, location-based recommendations, travel guide, route planning, navigation, indoor navigation.

INTRODUCTION

The use of modern Smartphones and tablets is becoming an integral component of information support of tourist during the trip. To determine the user's location by mobile applications can use technology platform of the Internet, radio signals and GPS data (global positioning system). The most common in the sphere of tourism are mobile information systems using GPS data. The technology that is mentioned has several important advantages: free distribution, independent from the operator and the territory coverage of mobile communication technology, precision of positioning.

Location services can assist the user in obtaining travel experience while staying focused on trip’s main aim, to make the trip more comfortable, more memorable and informative [1].

In addition to new features, the emergence of mobile technologies with GPS antenna generated new needs of tourists, such as rapid and accurate determination of their location, personalized planning of tourist routes, the dynamic change of tourist route, and so on.

OBJECTIVES

The goals if this research are:

- an analysis of current tourist information systems, based on information of the user's location;
- an analysis of the structure and operation of GPS (global positioning system);
- an identification of the methods and tools for building tourist mobile information systems based on dynamic information about the current location of the user;
- detection and identification of research areas and tasks that require further scientific and technological research.

The summarizing aim of the described in the paper research is the identification and analysis of the functionality of mobile computing devices equipped with GPS receiver for tourism. The development of new methods and means of their implementation, building on their basis a mobile information technology for tourist support at all stages of the trip.

THE ANALYSIS OF RECENT RESEARCHES AND PUBLICATIONS

The analysis of up-to-date researches and profiles of the use of GPS technology in the field of tourism

The most common profiles of researches on the use of mobile computing devices equipped with GPS antennas and activity of the information services to determine the location of the user in the field of tourism are:

- information technology support during the tourist travel;
- information methods and tools for analysis of tourist behavior.

The systems of the information support of the tourists during the trip

Information systems of specified class often have functions of information processing of the current location of the user. The systems that have no such function are becoming less popular, because tourist is often unable to determine his location during the trip.

Popular mobile algorithmic applications for tourists that are based on GPS data are navigation systems, route planners, augmented reality systems and computer travel guides.

Mobile navigation systems.

The navigation task differs depending on the specifics of the environment [2].

Scientists of the International Association of Engineers (IAE) developed navigation system that provides the general information on the relevant route [3]. The approach assumes that the user creates and forms sightseeing trip plan by himself by selecting the desired tourist sites to visit from the proposed list. The optimal route is generated automatically on the mobile device but only that objects that are the part of the route are shown. During the trip, the user must rely on a digital map and GPS information. Authors of the system believe that the use of this application while traveling offers more opportunities to get richer and more positive impression from the trip to the tourists

Among the information technology developments in the field of navigation systems the navigation systems for water vehicles are becoming increasingly popular. Scientists of the University of Munich have developed an information system to support safe traveling in mined waters [4]. An essential feature of this system is particularly centimeter accuracy of the coordinate calculations and optimal route selection criteria according to the safety needs and duration of implementation of the trip

Actual profile of the research in the field of information systems that actively use GPS navigation techniques is planning indoor routes. The results of these studies are useful for the tourism industry, as numerous tourist sites have quite complex spatial structure and tourists may get lost or did not observe particularly interesting elements of objects and spaces without outside help of the professional guide [5].

Powerful navigation system GROPING (Geomagnetism and cROwdsensing Powered Indoor NaviGation) was established to support the process of movement inside buildings. The system is supported by Google Maps Indoor. The main users of the system are employees of the large corporations that are located in the complex structured buildings. The system allows managers to track the movement of their staff and new employees to find the right way in the building conveniently and quickly [6].

Route planner.

Scientists of the Masaryk University (Czech Republic) developed methods and tools for planning optimal travel routes. They took into account parameters such as comfort, value, duration and informativeness. Researchers paid particular attention to the construction and speed of the information processing of the mobile route planner. The researchers developed original mathematical methods for planning travel routes have all suggested properties [7].

Scientists from Aarhus University (Denmark) have developed a mobile software and algorithmic application for indoor route planning, based on data from the GPS receiver. The features of this system are the following [8]:

• precise definition of the location;
• good quality and fast route planning;
• Augmented reality information labels;
• audio and map indoor navigation;
• Augmented reality mode.

An original route planning information system is a mobile software and algorithmic application created by scientists Mendes and Ribeiro [9]. Its main functionality is planning "healthy routes", such that avoid areas with the highest air pollution, road congestion, and more.

Tourist computer guide.

Scientists of Cultural Heritage Management Laboratory (CHMLab) have developed a powerful mobile travel application with functionality of computer travel guide. The system uses GPS to determine user's location, and gives information according to that data. The system is under improvement and implementation now [10].

Scientists of the University of Applied Sciences Zittau / Horlitts (Germany), Ronnie Kramer, Modshinh Marco and Klaus Nahen are to developing a mobile tourist guide called DTG (Dynamic Tourist Guide, that is based on contextual information. Mentioned mobile application identifies and stores user preferences in order to provide more personalized travel information. In addition, DTG plans travel routes and uses GPS technology for navigation and information support of tourist trips [11].

Under the guidance of Bruce Thomas, scientists of the University of North Australia have developed a mobile travel guide, based on information about the current location of the user. The main functions of the system are [12]:

• providing information on tourist facilities according to the place of residence in the form of hypertext markup language;
• Displaying users position on the map;
• Good quality mapping of the information on devices with small screen size;
• planning of tourist trips;
• planned tours saving;
• spatial navigation manual of the user.

CRUMPET

In the class of information systems that actively use GPS data a powerful tourist information system CRUMPET («Creation of User-friendly Mobile Services Personalized for Tourism») developed by scientists of social organization Information Technology (IST) shows up [13]. Its feature is functionality load for quite a full range of travel needs of the user. Because of the big list of features it is difficult to attribute the mentioned system to one of the classes that were submitted previously.

The system has the following features, which are separated by type of action and specificity [13]:

- the use of personal user information involves generating of personalized recommendations, taking into account of both individual and group needs and preferences, constant dynamic studying of user preferences when using the program;
- the use of GPS data involves the use of GPS data in the selection of its services, in the formation of tourist routes, in the imaging user's location on the map and its navigation.

The operation of the system is based on a set of scenarios and multi-agent technology, that is responsible for the execution of these functions and user interface implementation [13].

Tourist behavior analysis.

With the appearance of technological innovations that are geographic information systems and GPS the behavior of tourists, their goals, desires and preferences changed significantly [14]. On this basis, new methods of analysis of human behavior while traveling were developed. The possibility of tracking the movement of tourists by using GPS signals within the city allows us to identify the most popular tourist routes and facilities, and identify those parts of the city, that tourists should avoid during his travels [15].

GPS data is usually analyzed at the macro and micro levels. The example of macroanalysis is a general study and analysis of the movement of tourists during the Biathlon World Cup [16], where GPS devices were used by every tourist, management institutions and social infrastructures that were marked on digital maps. The macroanalysis can provide general information on the movement of people and is mainly used in situations where are big groups of people such as world championships, festivals and others [17].

Microanalysis needs the information on the factors that influence the choice of the route, such as climatic and natural conditions, available activities, socio-demographic characteristics and other features of tourist destinations. [17].

During the second symposium CAUTHE (The Council for Australasian Tourism and Hospitality Education) Sven Gross and Michael Hatch introduced a mobile information system to analyze the behavior of tourists. To improve the efficiency and ensure high quality of the system they conducted [18]:

•an analysis of the trajectories of GPS system users;

•a survey of user experiences;

•an analysis of the factors of attractiveness of tourist facilities.

The system performs a navigation function and is designed for mobile devices that operate basing on operating system Android [18].

A popular class of information systems is a mobile system to analyze the movements of people in big cities. The target users of such systems is the taxi company and individual taxi drivers. The main its objective is to identify popular routes and stops to build optimal routes for public transport [19].

An innovative technology elaboration in the field of modern information technologies to analyze the behavior of tourists during the trip is GimToP Toolkit (GTK), which combines original methodological approach and processing technology trajectories obtained by using GPS navigation. The system integrates results of the analysis of users route with the survey data obtained by using special mobile applications [20].

The analysis of modern IT developments in the sphere of GPS technologies and tourism

According to the rapid growth of the developments of the tourism industry and the demand for good quality mobile travel applications leading IT companies in the world have developed a range of available tourist information of mobile technologies with GPS support. The mobile applications for route planning and navigation of the user have got the greatest popularity.

A good representative of route planners is a mobile information system Voyager: Route Planner. The goal of this application is automatized planning of optimal routes of trips. The system uses GPS technology to determine the user's location and its navigation according to a planned route. According to mobile application developers Voyager feature is the ease of interactions for the user and comfort of the interface [21].

A popular application in the field of route planning also is ViaMichelin. This software and algorithmic complex implements the following functions: determining users location by using GPS, the use of various types of maps that depends on the user desires (Michelin maps, Lite maps, satellite view maps), planning the optimal route by taking into account the mode of transport and information on the current level of traffic, the estimated cost of the route calculations by taking into account the data on toll roads, transportation fees, fuel prices, and the type of the transport, providing data on the points of interest [22].

A popular application in the sphere of route planning in general and tourism in particular is a software tool Route4Me. The main feature of this application is the existence of the possibility of forming a route between unlimited number of target points [23].

In the class of mobile navigation technologies there is a powerful software application BE-ON-ROAD. This system is a free navigation for devices based on operating system Android. BE-ON-ROAD uses cartographic database OpenStreetMaps, which are updated several times a year and can be stored in the user device and does not require a permanent connection to the Internet. Attractive features of the system are: free map update, night mode based on the local time zone, saving the route on the user device [24].

A popular offline GPS navigation application is the mobile navigator Navitel with capabilities using geo-social services and detailed maps of 62 countries [25]. The features of the system are autonomous mode, the ability to exchange information on social networks, saving the maps on the memory card in of the device, the dynamic information (the weather, traffic jams, road repairs, events, etc.), support of 3D mapping, multilingual navigation unlimited number of stop-points of the route.

In the class of mobile tourist navigation systems there should be allocated the software navigator Maps.Me. The system has all necessary features for offline GPS navigation and planning of tourist trips. The feature of the system is high detalization of maps and their dynamic update when the use connects to the Internet [26].

THE MAIN RESULTS OF THE RESEARCH

Structure and principle of the Global Positioning System (GPS)

GPS (Global Positioning System) is a set of electronic tools to determine the position and velocity of the object on the Earth's surface or the atmosphere [28]. This worldwide radio navigation system consists of 24 satellites NAVSTAR (Navigation Satellite Time and Ranging), several ground stations and nearly one million user devices. These segments of the system, namely space, surface, the user - are completely interdependent.

The space segment consists of 24 major and several additional satellites that are put on six different circular orbits located at an altitude of 20200 km above the ground and at an angle of 60 ° to each other so that from four to twelve these satellites are seen from any point of the globe (see Fig.1).

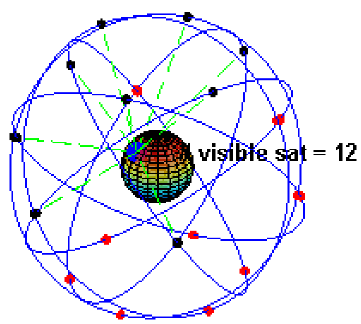

Fig. 1. The location of the satellites in space. An example of visibility from a certain point of the earth in certain time [28]

Ground segment consists of 12 stations: GPS master control station, ground antenna and monitoring stations (see Fig. 2).

Monitoring stations monitor the navigation signals of all the satellites in the continuous mode and send this data to the control station for further processing. Control station calculates the position of each satellite in the orbit and corrects data on its board time. In the future, this information is transmitted to the antenna station. In order to preserve the accuracy of calculations of the data for each satellite it is updated three times a day. Each satellite is always in sight of at least two ground stations [27].

Fig. 2. Ground Station Global Positioning System

Depending on the needs of the user the following types of GPS receivers signals can be used [27]:

• Handheld GPS receiver, that is able to determine the user's location with an error not exceeding 15m;

• Differential GPS receiver (DGPS), which is able to determine the user's location with an accuracy of 1m radius;

• Professional GPS receiver with the Real-Time Kinematic process (RTK) support, which determines the location of an object to centimeters.

When switching on the GPS receiver it is in one of three starting states [36]:

• Cold start: Receiver does not contain any saved information on the latter's location and the current time.

• Warm start: Receiver contains data about previous user's location and the current time, but the term of relevance of temporal data has expired.

• Hot start: a state when the receiver has access to all necessary data and it is valid and correct.

GPS receivers perform the following functions: accumulate the data from satellites, measure the signal parameters, calculates the position, speed and time.

To determine the exact location of the user, GPS receiver must determine the distance to each of the visible satellites and measure the duration of the movements of the signal from the satellite to the receiver, and calculate the time delay.

During the process of determining the location of the following errors may occur [27]:

• User side errors: delays caused by the ionosphere and troposphere, the satellite clock error, and so on.

• Equipment errors: interference receiver antenna direction, electromagnetic radiation, many receiving streaming data, etc.

Construction of the tourist information systems with the functions of route planning and navigation based on GPS data

Good quality location-based are available because of the GPS receivers that are embedded into custom mobile device.

Information sources of systems that are based on GPS technology

These systems in addition to data from the GPS signal receiver use information from road maps databases, data and points of interest (POI), dynamic data such as traffic and weather.

Road map databases. Databases of this kind consist of road maps converted into digital format of segments of corresponding maps. For example, the map of the United Kingdom consists of about a million individual segments of roads. Maps are stored in vector format as segments of lines (connections) that are roads and intersection points that are intersections or other road features. Each line must start and end points and data on road distortion. [29]

Among road databases and maps should be separately identified services such as Gooqle Maps, OpenStreetMap (OSM) and Yandex.

Gooqle Maps is a set of databases that are based on the free map service and technology provided by Google. Service enables the usage of cartographic data and satellite images of the earth's surface, and provides access to an integrated business listing and maps of roads, with function of routes planning [30].

OpenStreetMap is a free service of creation and use of publicly available maps of the world, founded in the UK in July 2004 by Steve Coast. OpenStreetMap, in fact, is not just a map in the conventional sense, it is most likely a base of geospatial data. It contains the geographic coordinates of individual points and information about the objects of the highest order – lines that connect points, connections, which may include points and lines, and the attributes of these objects. Therefore services that differ among themselves, by the way of mapping data or functionality, can be built basing on the same OSM data [31].

Yandex is similar to Gooqle Maps service, created by Russian developers. IT has more detailed information on cities of Russia and CIS countries [32].

Bing Maps (earlier service called Live Search Maps, Windows Live Maps, Windows Live Local, MSN Virtual Earth) is the cartographic service from Microsoft, part of the portal Bing. The feature of this service is a small need for internet traffic and high speed of drawing of the map layers. But Bing maps differ because of insufficient detalization [33].

POI databases. Mobile concierge-type services help users to identify of the location of certain institutions or attractions near a given location. To this purpose mobile travel applications use databases that include information on places that might be interesting for tourists. These databases contain detailed information on the POI, such as their location, purpose, features, photos, etc [29] These are highly structured and big databases [37].

Conventional points of interest databases are integrated with roadmaps database. For example, Google maps service has integrated POI databases. Its feature is the availability of information on the desired location that is support by the panoramas and indoor plans [30].

Yandex.Maps have a so-called cards of the facilities – tags attached to objects on the map that consist information on the location of the object, its work hours, features, review, and so on.

Dynamic data. In this representation information that is relevant for a short period of time, for example, traffic vehicles in certain segments of the route [38], information about weather, etc is given. Such information is usually useful for drivers and tourists that are limited in time, and their subsequent actions can greatly depend on its content. [29]

As a results of the analysis of available cartographic service authors formed comparative matrix functional characteristics of mentioned services (see. Table 1).

The general structure of GPS-based information systems

The basis of the location-based system, is so-called "engine" that is an essential algorithmic complex that modifies GPS data (see. Fig. 3).

The basic functions of mentioned complex are geocoding, routing and search for POI.

Table 1. Comparative matrix of functionality of cartographic services

Functional Characteristics \ Cartographic services	Google Maps	Open StreetMap	Яндекс Карти	Bing Maps
Available Road maps	+	+	+	+
Available satellite view	+	–	+	+
Available building indoor plans	+	–	–	–
Street view	+	–	+	+
Points of interests detalization (max 4 p.)	4	2	3	1
Dynamic information (traffic jams)	+	–	+	+
Dynamic information (weather conditions)	+	–	–	–
Detalization (max 4 p.)	4	3	2	1
Speed of map layers drawing (max 4 p.)	1	3	2	4

Geocoding is a transformation of the place address into earth in a pair of coordinates (longitude and latitude) to display the point on a road map. This is a basic function of geospatial application system. The precision of direct and reverse geocoding is critical when taking into consideration the results of the system as a whole [29].

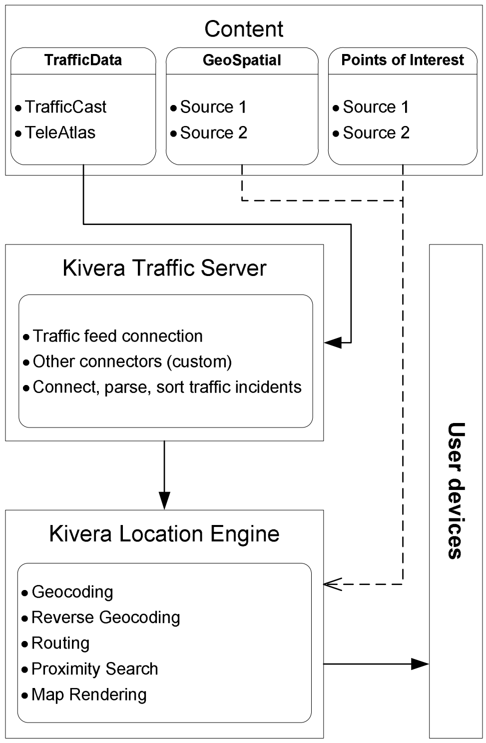

Fig. 3. Engine Architecture Systems Kivera, based on data from the GPS [29]

The implementation of routing features is about calculating optimal routes between points, taking into account a number of criterias, such as cost of the route, personal user preferences, and so on. It should be noted that the construction of a tourist route has certain peculiarities. In many cases, the system might not contain information about all the waypoints, so calculations should be based on personalized information about the user and trip duration to determine the recommended list of POI in order to create the most interesting route according to user preference.

Equally, important function of the complex is the search POI. When searching for objects the location, its preferences and schedule target objects should be taken into account.

Implementation of the navigation functions

One of the major functions of GPS-based information systems is user navigation. By performing the function of computer guides, navigation systems navigate the user to the selected object on the planned route of the trip. This function is vital for the tourist when he is in unfamiliar region during the trip.

Deploying global positioning system (GPS) radically changed the structure and quality of service navigation systems.

The example of general architecture of navigation systems is presented in Fig. 4. System components include client-side devices containing a GPS receiver (smartphone, tablet, car GPS navigator, etc.). The client device can be completely independent, in the case of the use of cloud-based technology [29].

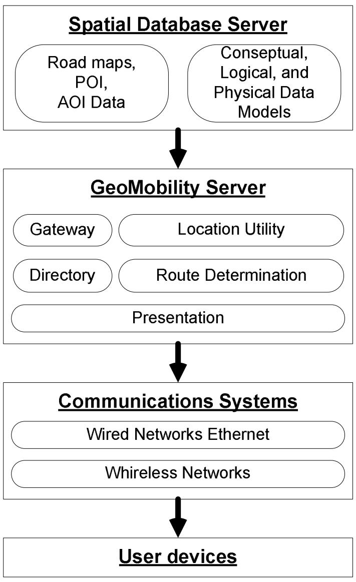

Fig. 4. General architecture of navigation systems

The server part of the system consists of spatial database server and GeoMobility server. Client devices are connected with the server side using communication components of the system [29].

Mobile tourist information assistant and GPS technology

A group of researchers from the National Lviv Polytechnic University are working on innovative technological project "Mobile tourist information assistant", within which a prototype of integrated mobile software and algorithmic complex of next generation is being developed.

As a result of preliminary analysis the authors of this article outlined of GPS technology in the "Mobile tourist information assistant ", which is a set of software and algorithmic tools to support all stages of tourist trip and the implementation of basic user information and technological motto "EVERYTHING! HERE! IMMEDIATELY!" [34]. It is proposed to implement GPS components in the system to support tourist trips to the castle "Palanok" in Mukachevo, Khust castle in Transcarpathian region, the so-called "Golden Horseshoe of Lviv" (a tourist route that includes a visit of Pidhirtsi, Olesko and Zolochiv castles) and support tourist routes in the center of the city Lviv, as historic monument, protected by UNESCO.

The need to in the use of GPS technology is embedded in the core objective of the mentioned program-algorithmic complex, that is providing tourist with full information support during the realization of the trip and after it is finished, which is impossible without tied to fast locating of the tourist on the map.

It is proposed to use GPS technology to support the following functions of the system "Mobile tourist information assistant":

- tourist route planning;
- navigation the route;
- user indoor navigation within a tourist facility;
- provisioning of tourist information in accordance with the user's location;
- generating location-based recommendations;
- analyzing the trajectories of the user to provide better quality of personalized recommendations;
- attaching the information about the location of the user to photo and video files;
- using the user trajectories when forming a trip diary.

When planning the trip route the system can use the location of the user as starting point. The system can create a route to a point on the map or offer personalized route planning according to the information on tourist attractions in the vicinity of the user and his personal preferences.

Technological realization of navigation features in travel information systems differs depending on the environment [2]. It is assumed that the system MIAT will navigation the user as in the central part of the city Lviv, as within the indoor areas of tourist sites (museums, within of historical monuments, castles). Navigation will, as in the form of traditional information support of the user movement between certain points of the route, as in the form of tourist guide that will dynamically provide the user with information about the objects that are in his sight and are parallel to trajectories of planned route.

The feature of indoor navigation in tourist facilities needs an accurately determined user's location, so there are high requirements for the development of significantly more powerful GPS data processing tools. The system should respond to small changes of user’s location. "Mobile tourist information assistant" will provide interesting tourist information about the objects that will be in close proximity to the user of the system while visiting museums of Lviv city center, which is protected by UNESCO and a number of historic castles of

Ukrainian Transcarpathia and castles of "Golden Horseshoe" tourist route.

When providing the user with the recommendations of "where to go?", "where to eat?" and so on, the system will take into account not only the preferences of the user, but also the distance between objects and the current location of the user.

GPS is a powerful source of information that can be used to support forming of the recommendations by the system and for more detailed filtering of tourist information, so to provide the user with high quality personalized support while traveling [35]. In this regard, a system MIAT is no exception. It is assumed that the system will analyze the trajectory of tourist trips, so to promote improvements of the quality of recommendations.

In addition, the system will use the data on the tourist movement for automatic generation of the diary his trip. GPS component in the system MIAT will also actively support photo and video files geo-tagging.

CONCLUSIONS

Good quality mobile travel information and technological tools of tourist support should definitely involve the use of GPS technology. They are the main base of popular mobile travel applications, as navigators, route planner, travel computer guides, augmented reality systems. A popular trend in the use of GPS technology is its use for studying user preferences and habits in order to provide good quality tourist personalized recommendations.

To build a multifunctional complex of tourist information system by using GPS technology good quality verified database of road maps and tourist sites, as well as the sources of dynamic information should be selected. The analysis of current cartographic databases suggests that the GoogleMaps service is one of the most powerful sources of map data that is available for the use in the development of mobile travel software and algorithmic applications.

Promising areas of research are:

•the development of new methods and means of indoor navigation of users;

•the development of new methods for the improving of the locating accuracy;

•the development of intelligent tourist GPS-based decision support systems.

In the "Mobile tourist information assistant" it will be provided the implementation of functions of indoor user guidance and navigation, as well as their verification on examples of the schemes of the routes in the castle "Palanok" (m. Mukachevo) Khust Castle (m. Hust), Olesko, Pidhirtsi and Zolochiv castles, of which the last three are "Golden Horseshoe of Lviv region" and within the central part of the city, which is the historical heritage of UNESCO.

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ECONTECHMOD. AN INTERNATIONAL QUARTERLY JOURNAL – 2015, Vol.4, No.3, 73-78

DECISION-MAKING RULE EFFICIENCY ESTIMATION WITH APPLYING SIMILARITY METRICS

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Received August 12.2015: accepted September 09.2015

Abstract. In article the short description of the most often used methods of classification at pattern recognition is given. The main attention is paid to the methods allowing development of a system for image recognition in a real time scale. The features formation method on the base of two-dimensional spatial spectrums of objects images is offered and application of similarity metrics in a decision-making rule for image classification is described. Experimental data of correct and erroneous recognition probabilities as well as image classification time depending on a number of features and on the identification threshold value are presented and analyzed.

Key words: image, classification, probability, recognition of images, Fourier transform, similarity criterion.

INTRODUCTION

Modern computing systems possess a sufficient performance level necessary for image recognition in real time, that allows to automate more effectively the processes preventing natural and antropogenic accidents, and hence to provide higher indicators of the population safety life and activity level. Also the mobile computing systems possessing a lower level of power consumption are under development, this allows creating compact and partially independent systems for image recognition. At present these developments are some of the most actual directions in the modern world, and new workings out of television systems for image recognition considering existing advantages and lacks of modern achievements in a science and engineering are necessary for a society. The modular structure of a system for image recognition allows to accelerate considerably the process of working out necessary modules and to simplify the process of updating components at occurrence of more productive technological decisions. The structure of a television system for objects recognition in real time assumes presence of modules realizing certain functions. Basic duties of such a system are recording and transmission of a video information stream through the data link, object detection, formation of features and classification of input images on the basis of their similarity to images of classes from a database, as well as displaying the result to inform an operator of the recognition system.

Now there are existing developed and maintained systems which are using various video analysis technologies for objects recognition. Such systems instances are VOCORD Tahion, Hawk-Eye and MOBILEYE. VOCORD Tahion carries out video surveillance outline for population vital activity provision in urban conditions. The Hawk-Eye system has been developed by the research engineers from British company Airplane-RADAR and intended for identification of landing ball location around separating lines. The advanced warning system MOBILEYE is the intellectual system for driver assistance utilized for notification about potential accident situation on a road.

THE ANALYSIS OF LAST RESEARCHES AND PUBLICATIONS

The human sight perception of surrounding space is the unique neurophysiologic process. Processing a light stream is carried out in common by an eye iris and a pupil. In the presence of bright light sources the eye iris extends, and the pupil is accordingly narrowed and on the contrary under opposite conditions. After passage of a pupil the light stream of a certain wavelength influences a retina and forms neuroimpulse influencing a specific part of a brain. The result of the given transformation is that the person is capable to see the objects which are in a surrounding space [1]. However the given process possesses some lacks. The surrounding space includes a number of radiated light streams, distinction of which is difficult to the human sight. Thus, there is a situation when the radiated light streams which have close values of a wave length are identified after transformation as the same color.

The method of objects classification used in the image recognition system is defined substantially by a source of input data. Methods of image recognition using image power indicators are based on selection of local features or on the use of a complete image description [2].

Character local image features are selected after preliminary processing of an image, that leads to reduction of the image description. Then the standard statistical approach is applied to recognition of images. For the first time the given method has been applied to extraction of sixteen face parameters of the person, and for classification the Euclid distance is used [3]. The given realization has been improved by increasing the features space up to thirty five elements that has allowed improvement of the recognition quality [2]. Also Hough transformation [4], Reisfeld operator of symmetry [5], filtering and morphological operations [6] are used for image recognition. At manual features extraction it is possible to reach more quality recognition, but at such approach system productivity worsens considerably at features formation [7]. Another widely known method of local features formation is based on the use of dynamically connected structures [8]. For each sample a graph is forming on the image according to following algorithm. On each image the set of reference points is selected, each of which is a link of a full connected graph and marked with the response of the Gabor filter applied to the area around a reference point. A set of such graphs represents the mesh structure capable to distinguish input images effectively. A serious lack of the given method is that formation of the initial set of graphs is necessary to make manually. Application of the parametrical models using deformable templates allows define automatically reference points, that decreases the lack specified above [9]. For recognition quality improvement instead of the Gabor filter, which is forming features, histograms of orientated gradients may be used [10]. An image texture allows define the qualitative parameters necessary for recognition. Object classification on the image is made by application of the structural technique. For this technique formation of the features space may be done with application of large values filters. Thus each filter is a matrix $N \times N$ containing binary values, and the set of filters defines the alphabet of features of image structure [11]. Definition of statistically dependent links allows to classify objects on the image. Holisitc classification methods are one of the most simple since they are comparing directly corresponding elements of the two-dimensional array of intensity values from input image and image from database. Though this approach has been shown as operating, but it is very sensitive to changes in image orientation or environment parameters [12]. This problem can be solved by utilizing statistical methods for extracting the most significant features thus reducing dimension of features that describe the image. For the first time such approach was implemented in the principal conponent analysis [13]. This method shows that any object image can be effectively represented in the space of its eigen images and recovered as very closed to original on using a reduced image desciription. When image eigenvectors are used for image classification, image features space can be significantly reduced thus eliminating external factors influence on recognition quality [14]. Alternative approach is to use the Fisher's linear discriminant analysis that maximises dispersion correlation between database images and hypothetically provides better image classification than the principal component analysis or method that uses difference images which are defined as difference between corresponding elements of two images [15]. Also in pattern recognition systems methods based on the usage of neural networks or machine learnings techniques has found their application. There is a method that extracts fifty basic features and then auto-associative neural network is used for transforming features into five-dimensional features space. After that standard multi-layer perceptron is used for image classification [16]. Similarly hierarchial neural networks are used which was grown automatically and not trained on gradient descent method [17]. Hybrid neural networks which are utilizing local image sampling, Karhunen-Loeve transformation and multi-layer perceptron has improved images recognition systems performance [18, 19]. Feed forward neural networks are used for classification after features space was generated using principal component analysis [20]. Other approach assumes image decomposition into three components using wavelet transform. The decision rules for every component are fused using radial basis function neural network, for the further classification of input images [21]. Similarly, an input image can be divided into defined amount of regions and for every region a module of the neural network is assigned. The output from all modules is combined using fuzzy Sugeno integral [22]. Also another method was proposed in which similarity function is trained using certain level of confidence that two images belong to the same person. Features space is formed by acquiring subregions local binary pattern histograms and Chi-square distances between corresponding histograms are used as discriminative features. AdaBoost algorithm is applied for the most efficient features extration and similarity function formation [23]. Considerable amount of classes presented in recognition system database causes some problems at classification stage. Possible decision for this problem is decomposing it into a set of binary classification problems in which every classifier is trained for corresponding pair of classes, ignoring all other classes, and then all classifiers are fused into one global classifier [24]. Also support vector machine method, in which all binary classifiers are transformed into one high-dimensional feature space, can be used for solving this problem[25]. It is also supposed that optimum hyperplane exists that can divide various classes and maximize distance between each class and hyperplane that will allow correct recognition of an input image.

THE PURPOSE

Given article is directed on studying of modern methods of image similarity determination in decision-making rules for the subsequent objective choice of a direction for engineering an image recognition system, capable to function in real time. Object achievement is carried out by fulfillment of experimental researches of the developed module for image classification and the analysis of the most important characteristics at image classification.

BASIC RESULTS OF RESEARCHES

The estimation of the developed module efficiency is made for classification of two-dimensional objects by using images from the MUCT database [26]. The module contains two components, realising the feature formation method and the decision-making algorithm.

According to conditions of image recognition system performance the images arriving to an input of the system or being in its database, preliminary pass a processing stage. The square image form is created for this purpose, and the image will be transformed to a black-and-white format as the system will work over the infra-red range.

As formation of the most informative features is the important process for maintenance of input object recognition quality, therefore the developed method makes double transformation of an image data file. Preliminary the two-dimensional discrete Fourier transform is applied for transition of an image data file into the frequency domain [27, 28].

The Fourier transform allows to form more exact image representation, as the Fourier factors are more exact approximation of an image. This results from the fact that the initial and transformed images are connected only with complex constants, describing changes in an amplitude scale and a phase shift of initial image components. Also presence of a bigger number of algorithms for fast calculation of the discrete Fourier transform allows to process images more effectively unlike other methods.

For forming more informative features, the secondary orthogonal transformation is applied, allowing to allocate eigen vectors of a transformed image data file. It will allow to limit the image feature space, that will simplify requirements to a memory configuration in the image recognition system.

The classification module component realising decision-making algorithm is constantly in a waiting mode and after reception of an input data of objects makes definition of their similarity to classes from a database. The developed algorithm of the decision-making rule for realisation of the described problem uses the metrics of similarity presented by the valid function defining similarity of two objects.

There is a theoretical assumption that a similarity value is in inverse proportion to a distance between two objects. This may be explained by the fact that each object being described with a feature set in a corresponding multidimensional space and the objects located at rather short distance, are perceived as having greater similarity, and accordingly the converse is logical [29]. Such metrics allow to calculate image similarity more effectively, as the calculation needs for insignificant computing capacities.

The decision-making rule algorithm provides initial definition of input object image similarity to all images of classes from a database. Therefore an average similarity value of the input object image to each image of a class from a database is calculated for the number of feature vectors defined by the classification module configuration under the formula:

$$S_{mean} = \frac{1}{N}\sum_{i=1}^{N} S(a_i, b_i), \quad (1)$$

where: a_i, b_i - accordingly vectors of an input object image and a class from a database, N - quantity of eigen vectors.

After forming the list of similarity the maximum similarity value is allocated. This value and a class are added in the similar classes list, provided that the similarity value exceeds an identification threshold, defined by a configuration of the classification module.

Then the maximum similarity value of the similar classes list is repeatedly defined, and the information about the corresponding class of a database is deduced on the display for the further decision-making by the operator of the computing system. In the absence of similar classes the corresponding notice is also deduced.

The similarity definition between input object image and a class from a database has been made during experimental researches with the help of similarity metrics [30]. Each object may be described with a feature set in the corresponding multidimensional space.

Hence, objects located close one to another, are perceived as having the bigger similarity, and on the contrary. Similarity between two images can be estimated on using the Dice similarity criterion:

$$D_{Dice} = \frac{2 \times \sum_{i=1}^{N} A_i B_i}{\sum_{i=1}^{N} {A_i}^2 + \sum_{i=1}^{N} {B_i}^2}, \quad (2)$$

where: A_i, B_i are data files of the input object image and image of a class from a database, and N – characterises dimension of the image.

The similarity metrics, which is close to the Dice similarity criterion, is called as the Cosine metrics and is defined by the expression:

$$D_{Cos} = \frac{\sum_{i=1}^{N} A_i B_i}{\sqrt{\sum_{i=1}^{N} {A_i}^2}\sqrt{\sum_{i=1}^{N} {B_i}^2}}. \quad (3)$$

The Tanimoto factor is also the similarity metrics:

$$D_{Tan} = \frac{\sum_{i=1}^{N} A_i B_i}{\sum_{i=1}^{N} A_i^2 + \sum_{i=1}^{N} B_i^2 - \sum_{i=1}^{N} A_i B_i}. \qquad (4)$$

Consideration of the several similarity metrics allows to define the recognition system, which performance is more rezultive and provides the best quality. During modelling it has been found out that the results received at the use of the Cosine metrics and Dice similarity criterion are identical, therefore the combined graphs will be resulted further. Preliminary experimental researches were carried out with representation of the input object image by a singl image. It has allowed to estimate the image classification module performance quality in the stably formed space.

Fig. 1 and 2 shows the correct recognition probability versus the number of eigen vectors, with different identification thresholds used in a decision-making rule.

In fig. 3 and 4 the graphs of recognition error probability are given as functions of the same parameters.

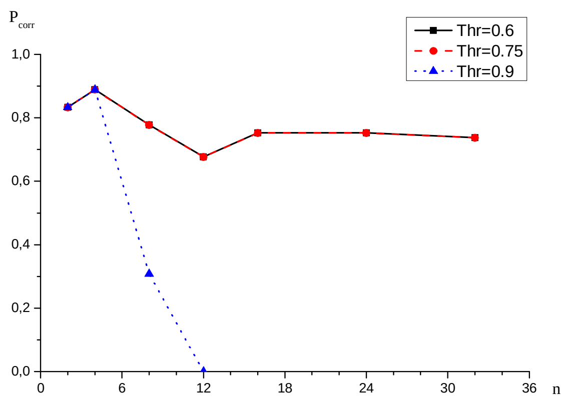

Fig. 1. Recognition correct probability for the Cosine metrics and the Dice similarity criterion

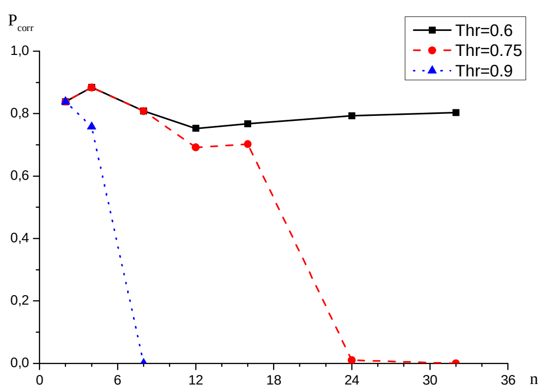

Fig. 2. Recognition correct probability for the similarity Tanimoto metrics

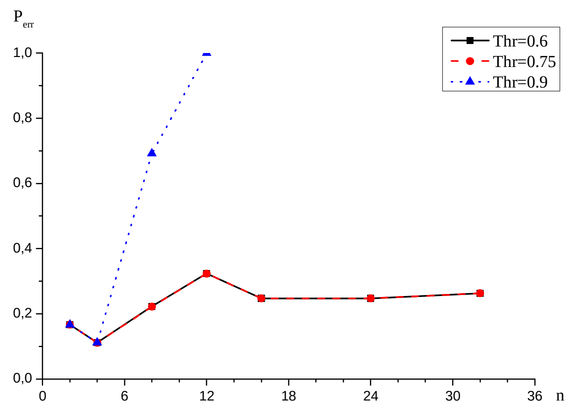

Fig. 3. Recognition error probability for the Cosine metrics and the Dice similarity criterion

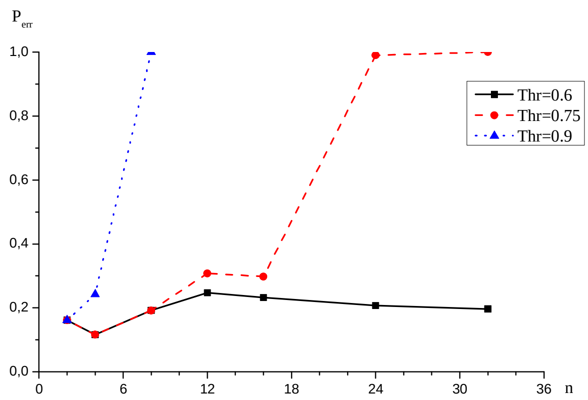

Fig. 4. Recognition error probability for the Tanimoto similarity metrics

Figures 5, 6 and 7 represent the time spent for recognition of one object with application of different similarity metrics.

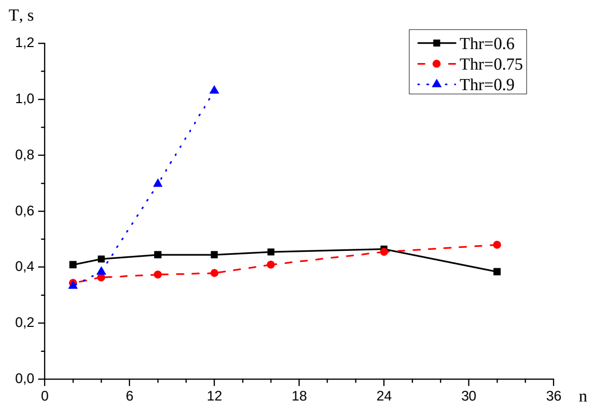

Fig. 5. Recognition time for the Cosine similarity metrics

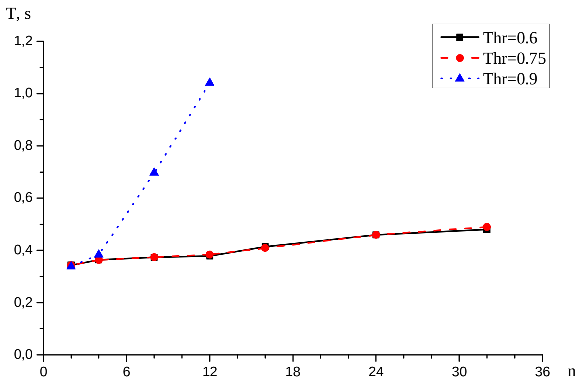

Fig. 6. Recognition time for the Dice similarity criterion

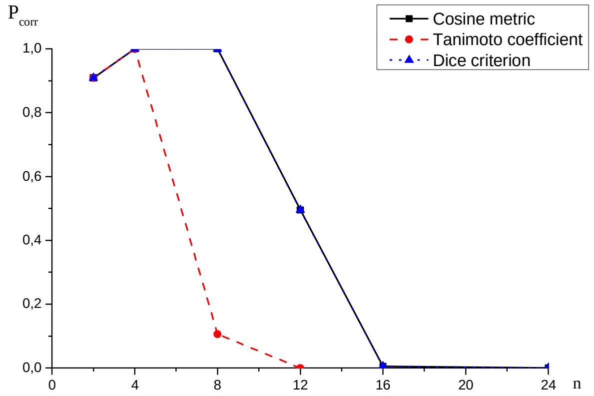

Fig. 8. Recognition correct probability for a set of video frames

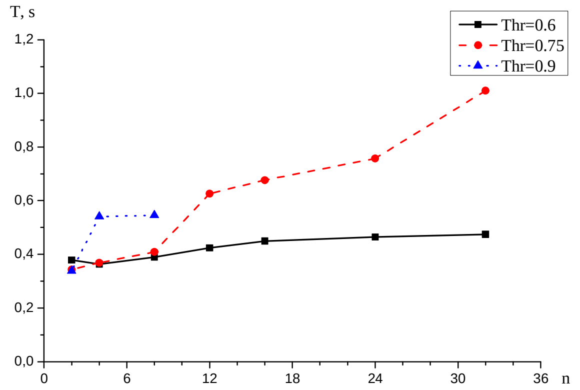

Fig. 7. Recognition time for the similarity Tanimoto metrics

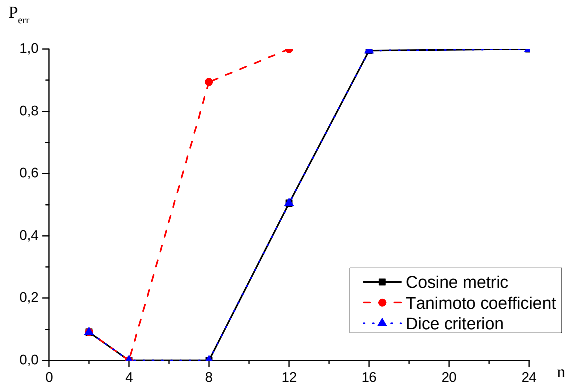

Fig. 9. Recognition error probability for a set of video frames

The analysis of the experimental graphs shows that at an increase in the identification threshold value the number of correctly distinguished objects starts to decrease. This will allow to reduce the time for recognition of input objects, as the database classes with similarity below an identification threshold will be excluded from the list of similar classes.

The minimal values of error probability coinside with a small number of feature vectors - from 2 to 8. This will allow to short the feature space and reduce the recognition time as well.

Current expermental results of the recognition system prototype efficiency allow to increase the productivity of the developed classification module considerably and start further researches.

The image classification module has been also approved at modelling the system performance in real time. For this purpose the individual image of an input object has been transformed to display its moving in a video stream.

In fig. 8 and 9 graphs of correct and error probabilities of input object recognition received for a set of video frames are shown.

Experimental researches show that the use of video frames allows to raise considerably the recognition quality.

CONCLUSIONS

1. Comparison of various similarity metrics shows that the cosine metrics and the Dice similarity criterion are less exposed to erroneous recognition. Also the cosine metrics and the Dice similarity criterion, unlike the Tanimoto similarity metrics, just slightly influence productivity of the developed method. Hence in the decision-making rule it is necessary to give preference to the cosine metrics or the Dice similarity criterion.

2. The important fact is that the correct recognition of input images is possible if the features space will be reduced to increase productivity of the image recognition system. This confirms that the most informative features are in the first eigen vectors of the image. Thus a considerable number of following nonsignificant eigen vectors is perceived by the recognition system as the raised noise level increasing a recognition error value.

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ECONTECHMOD. AN INTERNATIONAL QUARTERLY JOURNAL – 2015, Vol.4, No.3, 79-84

MODELING THE OPTIMAL STRUCTURE FOR TERRITORIAL TECHNOGENIC SAFETY SYSTEM

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Received August 20.2015: accepted September 11.2015

Abstract. Turbulence surrounding of the development programs of territory technogenic safety systems impacts the implementation of the program. Thus, it raises the need to design constructive tools of mathematical modeling configured to the phases of the development program in order to increase the efficiency of applying limited human, financial material, time and other resources being involved to solve the problem of technogenic safety systems. We consider both a static optimization model of the technological safety system structure and dynamic one taking into account the state of fixed assets of potentially dangerous industrial object, composition and quantity of hazardous substances being applied and stored at some industrial object, other factors that determine the potential possibility of technogenic incident occurrence.

As criteria of the problems one can use forms of known criteria that allow to assess the economic efficiency of different technological safety systems. The main constraints of static and dynamic optimization mathematical models have been proposed and analyzed.

In common the problems being considered are stochastic discrete (discrete-continuous) problems of multi-criteria optimization, and their decision is based on the implementation of the branch and bound approach. The approach allows organizing iterative algorithm to identify desired parameters of TTSS development program product.

Key words: technogenic safety system, turbulence surrounding, technogenic hazards, stochastic discrete programming.

INTRODUCTION

A territorial (realm) technogenic safety system (TTSS) is a complex administrative and technical system operating in a turbulent environment [1]. The turbulence of the system's environment is determined by a lot of factors and main of them are critical technical and technological state of the equipment at potentially dangerous industrial objects (PDO), uncertainty of national economy dynamics as well as violations of technological discipline and high level deterioration of TTSS fixed assets.

Moreover at present TTSS performs its functions under strong resource constraints, including permanent staff reduction and lowering everyday operation regime financing of local units of the State Emergency Service of Ukraine (SESU) along with increasing demands to territorial technogenic safety system both to its structure and management quality. To solve the problem of TTSS conformity to the today's challenges it is necessary to develop formal evaluating means of TTSS effectiveness.

Analyzing the practice of TTSS functioning one can determine state special development programs as the strategically important tool to improve TTSS structure and composition. In this connection the main stage of such a special program is generating the program mission, which is performed within the pre-investment phase of its life cycle. Namely at this stage all the parameters (quantitative characteristics of the TTSS properties) of the optimal structure TTSS would be defined on the basis of construction and implementation of appropriate predictive models.

However, taking into account long-term program performance we can face changing the program environment parameters as well as their priority for management decisions. So, there is also a need to design constructive tools of mathematical modeling in the subsequent phases of the development program in order to increase the efficiency of applying limited human, financial material, time and other resources being involved to solve the problem of TTSS development.

This makes it necessary to develop and use the program approach [1] as the framework of development and implementation of mathematical modeling apparatus intended to point out the TTSS optimal structure and parameters. This paper focuses on developing two kinds of mathematical models concerning TTSS optimal structure and parameters, specifically a static and a dynamic realizations, which are matched the stages of the state special development program.

THE ANALYSIS OF RECENT RESEARCHES AND PUBLICATIONS

Analyzing recent scientific publications on question and related matters one can stress the following points. In the paper [2] some methodological aspects of profiling the mission of the state special development programs in the field of civil defense have been discussed. The article [3] proposes an approach to find the optimal composition of complex technical system at the stage of its designing. The publication [4] deals with the design and analysis of optimization mathematical model intended to determine the structure of a complex technical system being operated under the strong impact generated by the external environment. Paper [5] proposes the quality estimation for functioning complex organizational and technical systems according to the "cost-effectiveness" criterion.

In [6] there is suggested an optimization mathematical model of the structure and parameters of the technogenic safety system on potentially dangerous industrial objects (PDIO) that is considered as a product of some development program. Under modeling the characteristics of possible hazards on the environment and people of the region arose as the result of an technogenic emergency have been taken into account. Publication [7] is concentrated on mathematical models and optimization solution methods supporting dynamic management of limited resources of the construction project as a part of program.

In [8] the whole set of activities on providing territory technogenic safety that belongs to TTSS competence has been divided into 2 types according to means of activity implementation, namely active and passive measures. As passive approach one can consider procedure of rational choice of PDIO technical and technological parameters at its design stage. In what follows we examine the set of active measures ensuring technological safety. Active measures include construction of effective technological safety systems on PDIO and modernization TTSS in general through the implementation of the TTSS optimal structure and parameters adapted to the region characteristics taking into account their dynamics of development at given planning horizon [t_0, t_0 + T], where t_0 is the beginning of the TTSS development program design and implementation.

Optimization method providing optimal allocation of financial resource along the stages of the TTSS development program has been proposed in [9]. The main feature of the method proposed consists of using the subject area specific under problem objective function and constraints definition. As a ground of computation scheme we applied the Balas additive algorithm.

Huge source of possible technogenic hazards is the engineering infrastructure of the city. Large cities in Ukraine suffer from technical and technological imperfections of engineering infrastructure, which increases the risk of technogenic incident. The article [10] discusses the ways to solve the problem of re-engineering water networks as a part of city engineering infrastructure.

Environmental aspects of air pollution by products of industry and human waists are considered in [11 - 13].

Publication [14] deals with the mathematical model and solution method for optimization problem of the allocation of limited resources of a project as a problem of the arrangement of rectangular objects, where objects being placed have variable metric characteristics that are subject to functional dependences. The partial quality criteria and the constraints of the feasible domain of the problem are formalized.

OBJECTIVES

This paper focuses on creating set of constructive tools for modeling the optimal structure and parameters of PDIO technological safety system on given territory as the product of the TTSS program development.

THE MAIN RESULTS OF THE RESEARCH

Taking into account the two-level hierarchical structure of TTSS, namely the level of PDIO and the territory level in whole, let us apply the appropriate decomposition of problem being considered. In other words the problem of modeling the PDIO optimal structure and parameters should be analyzed in accordance with the levels of the TTSS hierarchy.

Leaving aside for the moment the territorial level we concentrate now on the level of PDIO technogenic safety system.

Let $SV_{t_0}^h, h=\overline{1,H}$ be a tuple of variable characterizing current state of *h*-th element of the set PDIO on the territory being analyzed. Parameters $SV_{t_0}^h$ describe the state of fixed assets of *h*-th enterprise, composition and quantity of hazardous substances being applied and stored at *h*-th enterprise and other factors that determine the potential possibility of technogenic incident occurrence.

Besides, a tuple $SV_{t_0}^h$ defines the set U^h of dangerous impacts on the environment and population of the region that would be arise as a result of technogenic incident at *h*-th PDIO. Furthermore, we assume that the cause of the technogenic incident and, accordingly, set U^h implementation at the *h*-th PDIO are random equipment failures and systematic failures appeared due to aging of *h*-th PDIO fixed assets [10].

Suppose, the set:

$$U^h = \{u_i^h\},\ i=\overline{1,I_h}$$

has a discrete character. In general, the sets U^h form the set $U=\{u_i\},\ i=\overline{1,I}$ all the possible dangerous impacts on the environment and population:

$$U = \bigcup_{h=1}^{H} U^h .$$

Let l_i^h be a discrete random variable that quantifies (in monetary terms it will be corresponding damage) the magnitude of the impact u_i^h on the environment and population.

In general, l_i^h takes a set of values:

$$L_i^h = \{l_i^{hb_i}\},\ b_i=\overline{1,B_i},$$

with known probabilities $p_i(l_i^{hb_i})$, and the average score Λ_i^h of damage takes the form:

$$\Lambda_i^h = \sum_{b_i=1}^{B_i} l_i^{hb_i} \cdot p_i(l_i^{hb_i}) . \qquad (1)$$

If the probability distribution $p_i(l_i^{hb_i})$ is unknown, they are all considered equiprobable:

$$p_i(l_i^{h1}) = p_i(l_i^{h2}) = \ldots = p_i(l_i^{hB_i})$$

and

$$\Lambda_i^h = \frac{1}{B_i}\sum_{b_i=1}^{B_i} l_i^{hb_i}\ , \qquad (2)$$

or decision maker can formulate certain hypotheses in the form of "subjective probabilities".

The static model of the technological safety system structure

Let $Z = \{z_m\}$, $m = \overline{1,M}$ be discrete set of components possible for improving the safety system structure of some PDIO in order to counteract the set of hazards $U^h = \{u_i^h\}$, $i = \overline{1,I_h}$.

Enter into consideration the matrix $E = (E_{im})_{i=\overline{1,I};m=\overline{1,M}}$ [15] of effectiveness for a set of components *Z*. The elements E_{im} are dimensionless values that can be determined on the basis of statistical data, or expert estimates. In the case the vector $\vec{e}_m = (E_{1m}, E_{2m}, \ldots, E_{Im})$ determines the degree of effectiveness of the counteract of component z_m on a discrete set of impacts *U*. Herewith the safety system structure includes only those components that have counteract to at least one impact from *U*.

Suppose $\vec{s}_h$ be a vector defining some variant of the safety system structure at *h*-th PDIO. Moreover, $\vec{s}_h^{\,0}$ defines initial state of structure at the time moment t_0, where $\vec{s}_h^{\,0} \in SV_{t_0}^m$.

Denote as s_{hm} the element of the vector $\vec{s}_h$ responsible for the presence or absence of the *m*-th component in the safety system structure being designed. Note that the elements s_{hm} may be of two kinds. First, an item s_{hm} can take values $\{0,1\}$ indicating the presence or absence of the m-th component in the safety system structure, $m = \overline{1,Q_h}, Q_h \le M$.

For example, it would be the presence or absence of the fire automation system or others elements at *h*-th PDIO. Second, the element s_{hm} can take discrete values from a finite set of values $s_{hn} \in S_n, |S_n| = V_n$ (e.g., the quantity of fire engines), $n = \overline{1,N_h}, N_h \le M, Q + N = M$. In this case raises the question of defining the total efficiency $E_{nm}(s_{hn})$ of system components z_m.

Assuming that the total efficiency $E_{nm}(s_{hn})$ of component z_m contribution to the overall efficiency TTSS can not exceed 1, and the contribution of each subsequent unit of component z_m is less than the previous, it is possible to define the structure of function $E_{nm}(s_{hn})$ as a logistic or polynomial one.

Thus, the estimate of the number of possible variants for the modernization of PDIO technogenic safety system equals:

$$S = 2^{Q_h}\prod_{n=1}^{N_h} V_n\ .$$

Let us consider main constraints of optimization mathematical model of the technological safety system structure.

First, one should limit the total cost of the system as well as values of specific resources.

The amount $C_j(\vec{s}_h)$ of *j*-th resource to develop technogenic safety system of *h*-th PDIO is equal to:

$$C_j(\vec{s}_h) = \sum_{m=1}^{M} s_{hm}\cdot c_{jm}^{\Delta}\ , \qquad (3)$$

where: c_{jm}^{Δ} is the assessment of the *j*-th resource value to supply the modernization of the TTSS, including the dismantling obsolete equipment and entering element z_m to the safety system of *h*-th PDIO. Then the cost of the safety system of *h*-th PDIO is generally defined as:

$$C(\vec{s}_h) = \sum_{j=1}^{J} C_j(\vec{s}_h)\cdot r_j = \sum_{j=1}^{J} r_j \sum_{m=1}^{M} s_{hm}\cdot c_{jm}^{\Delta}\ , \qquad (4)$$

where: r_j is the cost of *j*-th resource unit.

Thus restriction of the overall cost of the safety system has a kind:

$$\sum_{j=1}^{J} r_j \sum_{m=1}^{M} s_{hm}\cdot c_{jm}^{\Delta} \le C_{max}^{h} \qquad (5)$$

where: C^{max} is the maximum amount of financial resources.

Similarly one can define constraints on the value or cost of certain types of resources.

Another important limitation is the possible incompatibility of the components $\{m_i, m_j\}$ of safety system. To generate the appropriate restriction one should form the conformity matrix $W=(w_{ij})_{M\times M}$, where $w_{ij} = 1$ if the components $\{m_i, m_j\}$ are compatible, and $w_{ij} = 0$ otherwise.

Then constraint on simultaneous presence in the *h*-th safety system incompatible combination of components is determined as follows:

$$s_{hi}\cdot s_{hj}\cdot w_{ij} = 1, i, j = \overline{1,M}, i \ne j\ . \qquad (6)$$

Each variant $\vec{s}_h$ of the system structure is estimated by the vector quality criterion:

$$F(E,C,\vec{s}) \to \underset{\vec{s}\in G\subset R^M}{extr}\ , \qquad (7)$$

where: *G* is the set of feasible solutions that is defined by a system of financial, technological, technical, time constraints taking into account the type of functions (3-6).

Criterion (7) makes it possible to evaluate the properties of the solution $\vec{s}_h$ being selected.

The dynamic model of the technological safety system structure

Consider now the main features of the dynamic optimization model of the technological safety system structure.

As before, structure S of h-th PDIO safety system is defined by a set of components:

$$Z(U) = \{z_m\},\ m = \overline{1,M}\ ,$$

which counteract hazard impacts on the environment and population of the territory from possible technogenic incident: $\mathfrak{R} = \mathfrak{R}(Z)$. Under modeling we will assume that time period [0, T] (T – given planning horizon) is divided into intervals [t, t + 1], $t = \overline{0,T-1}$ 0n which impacts of the environment U are constant, i.e. the time will be considered as discrete variable.

On the borders of time intervals it is possible to change the nature of environmental effects. In what follows it causes changes in the safety system structure. Consequently it need to include to the system new components Z^{t_in}, and to eliminate components Z^{t_out} ineffective for the next stage, $Z^{t\_in} \subset Z$.

Let E^n_{tm} denote the effectiveness of system component z_m to counteract to possible hazardous impact u_n in the time period [t, t + 1]. In general, each element z_m of the set $Z(U)$ can be characterized by a efficiency matrix:

$$E_m = (E^n_{tm})_{t=\overline{1,T},n=\overline{1,N}}\ .$$

As TSTB should include only those components that resist at least one destabilizing effect within a specified time interval [0, T], then the matrix E is to be imposed the following condition:

$$\sum_{t=1}^{T}\sum_{i=1}^{I} E_{tim} > 0\ . \qquad (8)$$

Values E_{tim} are dimensionless quantities and can be determined on the basis of statistical data or using peer reviews [4, 5]. Note under certain stages of implementation of safety system development programs TTSS and as a result of changing conditions of performing TTSS values E_{tim} may also change along with the number M, i.e. $M = M(t)$ in accordance with the condition (8).

Assumption 1. Let condition:

$$\exists t \in [0,T]: s^{t-1}_{mh} \neq s^{t}_{mh} \ \Rightarrow \ \forall\tau \in [t+1,T]: s^{\tau}_{mh} \geq s^{t}_{mh}\ . \qquad (9)$$

takes place.

The genesis of the system structure development is represented by matrix

$$\Sigma = (s_{tm})_{t=\overline{1,T},m=\overline{1,M}}\ ,$$

that determines the composition of safety system during the time interval [0, T]. Vectors $\vec{s}_t$ are rows of matrix Σ.

The exogenous parameters of the model. The construction of TTSS needs to spend a lot of resources, $\mathfrak{R} = \{r_j\},\ j = \overline{1,J}$, including material, financial ones, time and others. The resources $\mathfrak{R}$ are spent both on the inclusion new components Z^{t_in} to the system structure and the elimination of inefficient Z^{t_out} components from the system structure.

Suppose that to include the new component to safety system needs c_{jm} units of resource r_j and to withdraw component $z_m \in Z^{t\_out}$ from the system takes b_{jm} units of this resource. Cost ρ_{jt} of unit resource r_j is a function of time and it is equal to:

$$\rho_{jt} = \rho_{j0}(1+\xi)^t\ ,$$

where ξ is the interest rate. Then the values:

$$c_{mt} = \sum_{j=1}^{J} c_{jm}\cdot\rho_{jt} \quad \text{and} \quad b_{mt} = \sum_{j=1}^{J} b_{jm}\cdot\rho_{jt}$$

determine the cost of inclusion (exclusion) component z_m respectively.

Remark 1. When designing the optimal TTSS variant it is advisable to take into account the operating costs of system components during the period of its depreciation.

In summary, we state the problem of defining the optimal system structure for a given quality criterion $F(E,b,c,\Sigma,v)$ as follows:

$$F(E,b,c,\Sigma,s,t) \rightarrow \underset{G\in R^M}{extr}\ . \qquad (10)$$

Analysis of problem constraints. The set G of feasible solutions of the optimization problem (10) is formed by a system of constraints that along with inequalities (8,9) contains the following restrictions:

- on the resources that are used to construct some variant of safety system:

$$C_{jt}(\Sigma) \leq C_{jt}^{max},\ j = \overline{1,J}\ , \qquad (11)$$

where: C_{jt}^{max} is the available value of j-th resource at time t taking into account the discount of a kind:

$$C_{jt}(\Sigma)=\sum_{m=1}^{M}(s_{(t-1)m}-s_{tm})b_{jtm}+c_{jm}(s_{tm}-s_{(t-1)m}),$$
$$t=\overline{1,T}.$$

- on the total cost of safety system variant:

$$C(\Sigma)\le C^{max}, \qquad (12)$$

where: the total amount of resources available to build version of the system:

$$C(\Sigma)=\sum_{j=1}^{J}\sum_{t=1}^{T}C_{jt}(\Sigma)p_{jt}.$$

- on the minimal acceptable level of system components efficiency to counter the destabilizing impacts of possible technogenic incident:

$$\exists i\mid E_{tim}>E_{tig}\ \text{for}$$
$$\forall m,g\mid m\ne g, s_{tm}^{k}=1,\ s_{tg}^{k}=1, \qquad (13)$$

- on minimal acceptable level of system efficiency to counter the destabilizing effects of the environment:

$$E_{ti}^{k}\ge E_{ti}^{min}, \qquad (14)$$

where: E_{ti}^{min} is the minimum allowable efficiency to counteract embodiment of the *i*-th hazardous impact in the time period *t*.

- on possible combinations of system components

$$\forall t\ \ o_{km}(s_{tk}+s_{tm})\le s_{tk}s_{tm}, \qquad (15)$$

where: $o_{km}\in\{0,1\}$ – the element of the matrix O designating the compatibility of system components z_k and z_m.

To determine the structure of criteria $F(E,C,\vec{s})$ (7) and $F(E,b,c,\Sigma,v)$ (10) one can use forms of known criteria that allow in some way to assess the economic efficiency of different technological safety systems, for example, the criterion of a maximum average loss prevention [16]; economy criterion of damage [17]; the criterion of minimizing the total cost of safety systems' equipment and industrial exploitation [18], etc.

The exact solution method for the dynamic problem of construction the technogenic safety system

Since the set Z of feasible components is of discrete kind and time t is the discrete variable then all the possible realizations of the technological safety system structure within $t=\overline{1,T}$ can be represented as decision tree vertices. A decision tree is a convenient way to order the set of feasible solutions for discrete optimization problem according to the ideology of the branch and bound [19] method.

Each node of the decision tree determines some variant $\vec{s}_h$ of the TTSS structure during the interval [t, t + 1]. The arcs of the decision tree are designated as $z_m t_\tau$ and determine the presence of appropriate component z_m for time period $\tau\in[t,t+1]$ as a part of the technological safety system being constructed.

Each node except the root one has an input arc and

$$(T+1-\tau)\cdot M-m$$

output arcs, which are indexed as $z_{m'}t_{\tau'}$ and satisfy the condition:

$$\left[\begin{array}{l}\tau'=\tau, m'>m,\\ \tau'>\tau.\end{array}\right.$$

As a result of constructing the decision tree is the ordered set S containing all manner of variants $\vec{s}_h$. However, some variants $\vec{s}_h$ from S would not satisfy certain constraints of kind (3-6) or (8-9), (11-15). So, appropriate set of cutting rules based on constraints () is to be introduced into consideration.

These cutting rules allow discarding elements of the set S, which are not belong to the set of feasible solutions. Moreover, cutting rules being considered also reject part of the solutions, which are not Pareto-optimal ones [20]. As the result one can obtain an reduced set H of structure variants of kind:

$$\mathrm{H}\mid P\subseteq H\subseteq G\subseteq S,$$

where P is the set of Pareto-optimal solutions.

CONCLUSIONS

1. The modeling environment to generate optimal structure of the territorial technogenic safety system has been proposed. In general, the problems (7), (10) being considered are stochastic discrete (discrete-continuous) problems of multi-criteria optimization, and their decision is based on the implementation of the branch and bound approach. Taking into account the hierarchical essence of TTSS construction one can define parameters $\vec{\mathrm{s}}_{\mathrm{h}}^{*}$ assigning optimal structure of h-th industrial object that is potentially dangerous, $\mathrm{h}=\overline{1,\mathrm{H}}$ as exogenous ones for the optimization problem of higher hierarchy level, namely for determining the optimal characteristics of territorial technogenic safety system. This approach allows organizing iterative algorithm to identify desired parameters of TTSS development program product.

2. The dynamic optimization problem (10) as well as its static analog (7) refer to the class of NP-hard [21] problems. Thus, the direct application of the branch and bound method to solve the problems of the practical dimension definition does not always point out optimal result in a reasonable time. Therefore, it seems appropriate to use locally-optimal or heuristic approaches to find quasi-optimal solutions.

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ECONTECHMOD. AN INTERNATIONAL QUARTERLY JOURNAL – 2015, Vol.4, No.3, 85-90

DYNAMIC BALANCE RESEARCH OF PROTECTED SYSTEMS

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Received August 21.2015: accepted September 15.2015

Abstract. The dynamic models of the complex ergatic objects' behavior, presented in the form of differential equations and their systems were studied. The stability and other properties are researched. The methods of analysis and reduce of harmful factors and their impact on people were theoretically proved. The methods of analysis and critical points removal in dynamic models of hazards distribution are offered.

The object of study is the system of the harmful external factors protection. Subject of research is the system of two nonlinear differential equations as a model of technical systems with protection. The object of protection is described by logistic equation. and defense system - by non-linear differential equation with a security functions of rather general form. This paper describes critical modes analysis and stationary states' stability of protected systems with harmful influences. Numerical solution of general problem and also the analytical solution for the case of fixed expected harmful effects have been obtained. Various types of general models for "Man-machine-environment" systems were studied. Each of describes some kind of the practically important quality of object in an appropriate way. And all together they describe the object in terms of it's safe operation. Their further detailing process results to either well-known, or some new subsystems' models. Systems with "fast" protection at a relatively slow dynamics of the object were studied. This leads to the models with small parameter and asymptotic solutions of differential equations. Some estimates for protection cost in different price-functional and for different functions in the right part of equation, which describes the dynamics of defense were obtained. For calculations, analysis and graphical representations some of mathematical packages was applied.

Key words: Non-linear system, singular points, eigenvalues, asymptotic behavior, first approximation, linearization.

INTRODUCTION

One of the most important elements of Ukrainian economy has always been and remains to be industrial production, which is not safe at all. And it is pretty out of date both morally and physically. In this regard, the devices and their integrated systems of protection the staff and surrounding population are particularly important today [1, 2]. It is known that safety and efficiency are conflicting criteria. Their junction is possible only in a complex supersystem [3]. This approach allowed to consider a model of "Human-Machine-protected Environment" as a known model of competition of two factors – safety and efficiency [4, 5].

In this context, let us first examine the general "Man-Machine-Environment" system. Input information for this system is the information from the higher-level system (targets, instructions, etc.); output of this system is the labor result.

When the system operates, it's internal state changes. The element "Human" has three functional parts: control the "Machine", object of influence by the environment and the "Machine" either.

The element "Machine" fulfills a major technological function – impact on the subject of labor and a side function – to change parameters of environment.

Different types of common models of "Human-Machine Environment" were studied in this paper, each of which describes in a proper way some of practically important object's quality. And all together describe an object in terms of its safe functioning [6]. Their further detailing leads to well-known and as well as to some new models of subsystems [7]. This work is on quantitative analysis of an important model - protection of person from harmful effects from external environment and from impact of the "Machine "subsystem.

THE ANALYSIS OF RECENT RESEARCH AND PUBLICATIONS

In works [8, 9] a model of dynamic system that describing a situation where primary subsystem "produces" a harmful factor, and second sub-system - protection - is trying to reduce it completely, or at a reasonable price. As the base model – the basis for modification – a system of ordinary differential equations was taken. It describes fundamental laws of competition [10], and also known in ecology as a model of coexistence of species [11 – 14].

We need to check that despite the model has been simplified [15], basic characteristics and dependents on the system should be available. Based on the results obtained in the course of work the bifurcation of protection system must be analyzed, i.e. we should figure out a scenario of stability's loss [16] and protective effectiveness.

We follow [4] to introduce the basic assumptions directly following from everyday experience. They are evident, i.e. they do not require additional justification and only need to be formalized. Below they are called the Axioms [4].

Consider the Bio Impact U:

$$U = \int_0^T u(t)dt \qquad (1)$$

where: the intensity of harmful factor u is an alternating function of time t; T is total exposition time.

The total Bio Impact may also depend on the intensity of the other harmful factor *v*. Similarly, *V*(*t*,*v*,*u*).

In the first approximation the additive property is provided [6]:

$$\text{«overall harmfulness»} = k_1U + k_2V,$$

where k_i are the weights.

Axioms (natural positions):

1. Auto cumulativeness.

The harmful effects is growing faster than its value *u*.

2. Mutual cumulativeness.

The harmful effects grow as other factors together with *u* are growing.

3. In regular situation $\frac{\partial}{\partial t}u \le 0$. In critical situation (positive feedback) $\frac{\partial}{\partial t}u > 0$.

4. Protection *z*(t) can be controlled programmatically or adaptively, depending on the value *u*(*t*).

5. The cost of protection *C*=*C*(*z*) it is natural to consider as a steady increasing function of its intensity.

Let *f* and *g* be smooth functions, steadily increasing in both arguments,

$$f(0,V) = g(V,0) = 0, \forall U,V .$$

Then it is natural to suppose

$$U' = f(U,V);\ V' = g(U,V).$$

It is rather general case for a system of differential equations describing behavior of the object to have under conditions $u \ge 0,\ z \ge z_0$ the form of:

$$\begin{cases} u'(t) = \alpha u(t) - \beta z u(t) \\ z'(t) = F(u(t), z(t)) \end{cases}, \qquad (2)$$

where: z_o is stationary protection; *F*(*u*, *z*) is protection ability function.

OBJECTIVES

First, we conduct a formal description of the model researched in this work. Harmful effects can be written in the first approximation, as the integral (1).

Protection ability function *F*(*u*, *z*) from (2) in this work is considered in either of the following general enough forms:

1) $F(u(t), z(t)) = \gamma u(t)$;

2) $F(u,z) = \gamma u - \delta z$;

3) $F(u,z) = \gamma_1 u + \gamma_2 u^2 - \delta_1 z - \delta_2 z^2$.

Solution of the differential equations system (2) is not always possible to be found analytically. That is why for finding protection functions and harmful impact effects some numerical methods are used to solve this system of differential equations. So, the objective is to study for stability the system (2) under different forms of protection ability function and values of the subsystem protection parameters (α, β, γ). It is also necessary to evaluate the cost of protectionability for different functions *F*(*u*,*z*).

THE MAIN RESULTS OF THE RESEARCH

1. Methods for studying stability.

The theorem of linearization establishes a relation of phase portrait of a nonlinear system in the neighborhood of the stability point with phase portrait of its linearization [16, 17].

The origin of coordinates is a simple fixed system's point for

$$\dot{y} = X(y), y \in S \subseteq R^2 ,$$

if its corresponding linearized system is simple.
This definition extends the meaning of simplicity on fixed points of nonlinear systems. It can be used also in the case when singular point, which interests us is not at origin of coordinates; then we have to enter local coordinates.

Let nonlinear a system $\dot{y} = Y(y)$ have a simple fixed point *y*=0. Then in a neighborhood of the origin phase portraits of this system and its linearization are qualitatively equivalent, unless a fixed point of linearized system is not a center [17].

The theorem on linearization forms the basis of one of the main methods of investigation the non-linear systems – the method of investigating stability in linear approximation.

By applying in practice the linearization theorem the significant simplification in calculations are achieved since with linear terms of new system it is more convenient to carry out a qualitative analysis than with nonlinear.

Application of theorems on linearization are similarly considered in analysis of environmental models and competition in economic systems [18 – 20].

2. The problem of fast and slow variables.

Dynamical systems include a large number of processes with different time scales meanwhile the hierarchy of these times is such that they differ greatly [20, 21].

The level of detailing in modeling of studied phenomena depends on purpose of modeling. However in any case the problem of modeling is to build a model of phenomenon having as smaller number of variables and arbitrary parameters as possible and at the same time to correctly reflect properties of phenomena.

Accounting for time hierarchy process lets the reducing of the number of differential equations. "Very slow" variables do not change on time scales of these processes and can be regarded as constant parameters. For "fast" variables instead of differential equations the algebraic equations for their steady-state values can be written. As "fast" variables reach their steady-state values almost instantly compared with "slow" ones [8].

3. Research algorithm.

1. We find, if possible, an analytical solution of the system (1) using the functions in the standard mathematical set [22]. If a solution cannot be found in a general way, then let us solve it by numerical methods (in default package is proposed to use a fairly universal method by Adams [19]), by using inner functions, suppose *NDSolve*.

2. Once the solution of (1) is found, let us analyze function of hazard: at what times its value exceeds the value of stationary protection, i.e. protection system activates. By finding these time intervals, we make a decision – to increase the impact on the harmful factor (so, the cost of protection system increases), to leave system unchanged, or there is an opportunity to reduce the cost of protection system, suppose by reducing stationary protection.

3. By choosing a solution we repeat steps 1-2 until we go beyond restrictions (time of system's work or its cost).

4. Analytical model's study.

Let us study a system of differential equations (1) with a small parameter ε:

$$\begin{cases} u'(t) = \varepsilon \alpha u(t) - \beta z(t) u(t) \\ \varepsilon z'(t) = \gamma u(t) - \delta z(t) \end{cases}. \quad (3)$$

The difference of this system from the previously considered is the quasi-stationary harm. Let us solve the system (3) using asymptotic method for $\varepsilon^0, \varepsilon^1, \varepsilon^2$.

To start with, we write out the system (3), taking into account the dependence of functions $u(t,\varepsilon)$ and $z(t,\varepsilon)$ on time and small parameter.

Let us solve system (3) for the case ε^0 (zero approximation).

Let us write functions' asymptotic of $u(t,\varepsilon)$ and $z(t,\varepsilon)$.

$$u(t,\varepsilon) = u_0(t) + \overset{=}{o}(\varepsilon), \quad z(t,\varepsilon) = z_0(t) + \overset{=}{o}(\varepsilon).$$

System (3) for zero approximation becomes as follows:

$$\begin{cases} u_0'(t) = -\beta u_0(t) z_0(t) + \overset{=}{o}(\varepsilon) \\ 0 = \gamma u_0(t) - \delta z_0(t) + \overset{=}{o}(\varepsilon) \end{cases}. \quad (4)$$

When doing substitutions $u_0(t) = \frac{\delta}{\gamma} z_0(t)$, we get:

$$\frac{\delta}{\gamma} z_0'(t) = -\beta z_0^2(t). \quad z_0(t) = \frac{1}{\beta t}, \quad u_0(t) = \frac{\delta}{\beta \gamma t}.$$

Protection and harm functions obtained for zero approximation have the form of:

$$z(t) = \frac{1}{\beta t}, \quad u(t) = \frac{\delta}{\beta \gamma t}.$$

Now let us solve system (3) including member with ε^1.

Similarly, we write functions' asymptotic of $u(t,\varepsilon)$ and $z(t,\varepsilon)$.

$$u(t,\varepsilon) = u_0(t) + \varepsilon u_1(t) + \overset{=}{o}(\varepsilon^2),$$
$$z(t,\varepsilon) = z_0(t) + \varepsilon z_1(t) + \overset{=}{o}(\varepsilon).$$

System (3) for the first approximation has the form of:

$$\begin{cases} u_0'(t) + \varepsilon u_1'(t) = \varepsilon \alpha u_0(t) - \beta u_0(t) z_0(t) - \\ - \varepsilon \beta (u_1(t) z_0(t) + u_0(t) z_1(t)) + \overset{=}{o}(\varepsilon^2) \\ \varepsilon z_0'(t) = \gamma u_0(t) + \varepsilon \gamma u_1(t) - \delta z_0(t) - \varepsilon \delta z_1(t) + \overset{=}{o}(\varepsilon^2) \end{cases}. \quad (5)$$

Members of sum with multiple factors ε with level 2 and higher are converted to a remainder term $\overset{=}{o}(\varepsilon^2)$.

Let us write system (5) in details by grouping terms standing by ε^0 and by ε^1.

$$\begin{cases} u_0'(t) = -\beta u_0(t) z_0(t) \\ 0 = \gamma u_0(t) - \delta z_0(t) \\ u_1'(t) = \alpha u_0(t) - \beta (u_1(t) z_0(t) + u_0(t) z_1(t)) \\ z_0'(t) = \gamma u_1(t) - \delta z_1(t) \end{cases} \left| \begin{matrix} \varepsilon^0 \\ \varepsilon^0 \\ \varepsilon^1 \\ \varepsilon^1 \end{matrix} \right. \quad (6)$$

We provide the replacement

$$u_0(t) = \frac{\delta}{\gamma} z_0(t).$$

Substitute into the first equation of system (6) and solve differential equation:

$$\frac{\delta}{\gamma} z'_0(t) = -\beta z_0^2(t).$$

In result of differential equation solution it was found the function $z_0(t)$. And then, with its help the function $u_0(t)$ was also found:

$$z_0(t) = \frac{1}{\beta t}, \quad u_0(t) = \frac{\delta}{\beta \gamma t}. \quad (7)$$

To find functions $z_1(t)$ and $u_1(t)$ let us make a substitution in the third and fourth equation of system (6) functions $z_0(t)$ and $u_0(t)$ from (7). The obtained system has a form of:

$$\begin{cases} u_1'(t) = \alpha \frac{\delta}{\beta \gamma t} - \beta (u_1(t) \frac{1}{\beta t} + \frac{\delta}{\beta \gamma t} z_1(t)) \\ -\frac{1}{\beta t^2} = \gamma u_1(t) - \delta z_1(t) \end{cases} \quad (8)$$

We provide replacement

$$u_1(t)=\frac{1}{\gamma}(\delta z_1(t)-\frac{1}{\beta t^2}).$$

Let us substitute it into the first equation of system (8) and solve differential equation:

$$\frac{1}{\gamma}(\delta z_1'(t)+\frac{2}{\beta t^3})=\alpha\frac{\delta}{\beta\gamma t}-\beta(\frac{1}{\gamma}(\delta z_1(t)-\frac{1}{\beta t^2})\frac{1}{\beta t}+\frac{\delta}{\beta\gamma t}z_1(t)).$$

In result of solution of this differential equation function $z_1(t)$ was found and with its help, the function $u_1(t)$ too:

$$z_1(t)=\frac{1}{2\beta}(\alpha-\frac{2\ln t}{t^2\delta}),$$

$$u_1(t)=\frac{1}{2\beta\gamma t^2}(t^2\alpha\delta-2\ln t-2).$$

These obtained protection functions and functions of harm for the first approximation have the form of:

$$z(t)=\frac{1}{\beta t}+\varepsilon\frac{1}{2\beta}(\alpha-\frac{2\ln t}{t^2\delta}),$$

$$u(t)=\frac{\delta}{\beta\gamma t}+\varepsilon\frac{1}{2\beta\gamma t^2}(t^2\alpha\delta-2\ln t-2).$$

Now we solve the system (3) including members with ε^2.

We write in details asymptotic behavior of function $u(t,\varepsilon)$ and $z(t,\varepsilon)$.

$$u(t,\varepsilon)=u_0(t)+\varepsilon u_1(t)+\varepsilon^2u_2(t)+\overset{=}{o}(\varepsilon^3),$$

$$z(t,\varepsilon)=z_0(t)+\varepsilon z_1(t)+\varepsilon^2z_2(t)+\overset{=}{o}(\varepsilon).$$

System (3) for the second approximation has the form of:

$$\begin{cases} u_0'(t)+\varepsilon u_1'(t)+\varepsilon u_2'(t)=\varepsilon\alpha u_0(t)+\varepsilon^2\alpha u_1(t)- \\ -\beta u_0(t)z_0(t)-\varepsilon\beta(u_1(t)z_0(t)+u_0(t)z_1(t))- \\ -\beta(u_2(t)z_0(t)+u_1(t)z_1(t)+u_0(t)z_2(t))+\overset{=}{o}(\varepsilon^3). \\ \varepsilon z_0'(t)+\varepsilon^2z_1'(t)=\gamma u_0(t)+\varepsilon\gamma u_1(t)+\varepsilon^2\gamma u_2(t)- \\ -\delta z_0(t)-\varepsilon\delta z_1(t)-\varepsilon^2\delta z_2(t)+\overset{=}{o}(\varepsilon^3) \end{cases} \quad (9)$$

Members in the sum with multiple factors ε with level 3 and higher transfer to remainder term $\overset{=}{o}(\varepsilon^3)$ as before.

We write system (9), grouping the terms with ε^0, ε^1 and ε^2.

$$\begin{cases} u_0'(t)=-\beta u_0(t)z_0(t) & \varepsilon^0 \\ 0=\gamma u_0(t)-\delta z_0(t) & \varepsilon^0 \\ u_1'(t)=\alpha u_0(t)-\beta(u_1(t)z_0(t)+u_0(t)z_1(t)) & \varepsilon^1 \\ z_0'(t)=\gamma u_1(t)-\delta z_1(t) & \varepsilon^1 \\ u_2'(t)=\alpha u_1(t)-\beta(u_2(t)z_0(t)+u_1(t)z_1(t)+u_0(t)z_2(t)) & \varepsilon^2 \\ z_1'(t)=\gamma u_2(t)-\delta z_2(t) & \varepsilon^2 \end{cases} \quad (10)$$

Let us provide the replacement

$$u_0(t)=\frac{\delta}{\gamma}z_0(t).$$

Substitute into the first equation of system (10) and solve differential equation:

$$\frac{\delta}{\gamma}z'_0(t)=-\beta z_0^2(t).$$

In result of solving the differential equation it was found the function $z_0(t)$ and with its help, it was found the function $u_0(t)$.

$$z_0(t)=\frac{1}{\beta t},\qquad u_0(t)=\frac{\delta}{\beta\gamma t}. \quad (11)$$

In order to find functions $z_1(t)$ and $u_1(t)$ we are doing replacement in the third and the fourth equation of system (10) for the functions $z_0(t)$ and $u_0(t)$ from (11). Newly obtained system has the form of:

$$\begin{cases} u_1'(t)=\alpha\frac{\delta}{\beta\gamma t}-\beta(u_1(t)\frac{1}{\beta t}+\frac{\delta}{\beta\gamma t}z_1(t)), \\ -\frac{1}{\beta t^2}=\gamma u_1(t)-\delta z_1(t). \end{cases} \quad (12)$$

Now, we make the replacement

$$u_1(t)=\frac{1}{\gamma}(\delta z_1(t)-\frac{1}{\beta t^2}).$$

Let us substitute it into the first equation of system (12) and solve the differential equation:

$$\frac{1}{\gamma}(\delta z_1'(t)+\frac{2}{\beta t^3})=\alpha\frac{\delta}{\beta\gamma t}-\beta(\frac{1}{\gamma}(\delta z_1(t)-\frac{1}{\beta t^2})\frac{1}{\beta t}+\frac{\delta}{\beta\gamma t}z_1(t)).$$

In the result of differential equation’s solution the functions $z_1(t)$ and $u_1(t)$ were found.

$$z_1(t)=\frac{1}{2\beta}(\alpha-\frac{2\ln t}{t^2\delta}),$$

$$u_1(t)=\frac{1}{2\beta\gamma t^2}(t^2\alpha\delta-2\ln t-2). \quad (13)$$

In order to find functions $z_2(t)$ and $u_2(t)$ let us make a replacement into the fifth and sixth equation of system (10) for functions $z_0(t)$, $u_0(t)$, $z_1(t)$, $u_1(t)$ from (11)–(13). The obtained system has a form of:

$$\begin{cases} u_2'(t) = \frac{1}{4t^2\beta\gamma\delta}(t^2\delta(t^2\alpha^2\delta - 2\alpha - 4t\beta(\gamma u_2(t) + \\ \delta z_2(t))) - 4\ln t - 4\ln^2 t)\times \\ \frac{1}{2\beta}(\alpha - \frac{2\ln t}{\beta t^2}) = \gamma u_2(t) - \delta z_2(t). \end{cases} \quad (14)$$

Making the replacement

$$u_2(t) = \frac{1}{\gamma}(\delta z_2(t) + \frac{1}{2\beta}(\alpha - \frac{2\ln t}{\beta t^2})),$$

by substitution into the first equation of system (14) we solve the differential equation:

$$\frac{1}{\beta\delta\gamma t^4}(5 - 6\ln t + \beta\delta^2 t^4 z_2'(t)) =$$
$$= \frac{1}{4\beta\delta\gamma t^4}(4 - 2\alpha\delta t^2 + \alpha^2\delta^2 t^4 - 12\ln t - \quad (15)$$
$$-4\ln^2 t - 8\beta\delta^2 t^3 z_2(t)).$$

As a result of differential equation solving (15) function $z_2(t)$ was found and with its help the function $u_2(t)$ was also determined:

$$z_2(t) = \frac{1}{12\beta\delta^2 t^3}(36 - 6\alpha\delta t^2 + \alpha^2\delta^2 t^4 - 12\ln t +$$
$$+12\ln^2 t),$$
$$u_2(t) = \frac{1}{12\beta\delta\gamma t^3}(24 - 6\alpha\delta t^2 + \alpha^2\delta^2 t^4 +$$
$$+12\ln t + 12\ln^2 t).$$

The obtained protection functions and the functions of harm for the second approximation have a form of:

$$z(t) = \frac{1}{\beta t} + \varepsilon\frac{1}{2\beta}(\alpha - \frac{2\ln t}{t^2\delta}) + \varepsilon^2\frac{1}{12\beta\delta^2 t^3}(36 - 6\alpha\delta t^2 +$$
$$+\alpha^2\delta^2 t^4 - 12\ln t + 12\ln^2 t),$$
$$u(t) = \frac{\delta}{\beta\gamma t} + \varepsilon\frac{1}{2\beta\gamma t^2}(t^2\alpha\delta - 2\ln t - 2) +$$
$$+\varepsilon^2\frac{1}{12\beta\delta\gamma t^3}(24 - 6\alpha\delta t^2 + \alpha^2\delta^2 t^4 + 12\ln t + 12\ln^2 t).$$

Next we minimize the function $u(t)$ in parameters β and ε for zero, first and second approximation in order to calculate the price of protection system. And also to see, how adequately is to regard ε to be small.

To do this, we first have to define for which time interval the hazard function reaches an acceptable result (for us it is not critical the stabilization time for normal, non-critical, system's indicators). In the case when running time of protection system is a critical parameter it is obligatory to define, under which values of β parameter, the harm function takes acceptable values. At the same time we are limited by the time response of protection system.

Let us take for specification of system parameters in (3) so close to the real values:

$$\alpha = 0.2,\ \gamma = 0.5,\ \delta = 2,\ z_0 = 12.$$

Let the cost of stationary protection be $c_0 = 1200$.

As the value of stationary protection is $z_0 = 12$, then we have to find time t, after which protection function will take the value less than $z_0 = 12$ and relatively, the appropriate parameters' values β and ε.

For $z(t) = \frac{1}{\beta t}$ the parameters equal:

t=2.01701, β = 0.0413154.

For $z(t) = \frac{1}{\beta t} + \varepsilon\frac{1}{2\beta}(\alpha - \frac{2\ln t}{t^2\delta})$:

we have t=4.55546, β =0.0182969, ε =0.000734976.

For

$$z(t) = \frac{1}{\beta t} + \varepsilon\frac{1}{2\beta}(\alpha - \frac{2\ln t}{t^2\delta}) + \varepsilon^2\frac{1}{12\beta\delta^2 t^3}(36 - 6\alpha\delta t^2 +$$
$$+\alpha^2\delta^2 t^4 - 12\ln t + 12\ln^2 t),$$

we have t=1.18948, β =0.0700591, ε =0.000101185.

To evaluate the protection cost we use the function:

$$\tilde{C}(T) = \int_0^T c(z - z_0)dt + C_0,$$

where: C_0 – cost of stationary protection; z_0 – value of stationary protection; $c(z)$ – costs function, which can take forms of a), b) and c) given below.

Let us integrate by taking T=6.5 (time during which protection system will take the value less than z_0) and record the obtained results:

a) $c(z) = z$; $\tilde{c} = \int_0^T c(z(t) - z_0)dt + C_0$ = 73+1200 =1273;

b) $c(z) = z^2$; $\tilde{c} = \int_0^T c(z(t) - z_0)dt + C_0$ =544+1200=1744;

c) $c(z) = z\ln z;\ \tilde{c} = \int_0^T c(z(t) - z_0)dt + C_0$ = 221.33+1200 = 1421.33.

CONCLUSIONS

1. So, the main results of the work are:

– for the system (3) the asymptotic method was first used and the direct formulas for solution were obtained;

– the value of parameter ε was obtained by numerical solution of original system and this means legitimacy of asymptotic approach: smallness of parameter ε is confirmed;

– the found expressions and values for intensity of protection allow us to determine its optimal value.

2. In addition to receiving the solutions in closed analytic form and their research, this approach allows to obtain real estimates for the cost of protection and even to reduce this cost in time when the intensity of harmful factor u does not exceed the threshold of dynamic protection $c(z(t)\text{-}z_0)$=0.

3. The asymptotic approach appears to be very useful. So, it will be next applied to the models protection systems that are more complicated than (2).

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ECONTECHMOD. AN INTERNATIONAL QUARTERLY JOURNAL – 2015, Vol.4, No.3, 91-97

BASIC LAWS OF AIRCRAFT DESIGN

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Received August 27.2015: accepted September 17.2015

Abstract: Questions of attraction to tasks of aviation technical designing of the regularities of general nature which are earlier not used in this field which are on a joint of basic problems of modern natural sciences, technology, philosophy and the new directions of science which treat, for example, synergy, and others are considered. A conceptual design of civil and transport airplanes with representations of the seven basic laws of the design is offered: 1. Thought or mental associated with the formation of the idea, as well as the visualization of forms and structures designed object. 2. The law of analogies. 3. The Law of Vibration. 4. The law of opposites. 5. The law of cycles and rhythms. 6. The Law of Cause and Effect. 7. Law of design and creativity. The approach to formation of new hierarchy of the criteria of design based on the analysis and synthesis of these laws is also offered. The task of the structural formation and composition of the energy space design, allowing determining the grid of power lines and types of elementary energy and the crystal structures of the elements is considered. Seven basic laws of design are presented and described on a number of examples. The space of design is described with use of the scheme of the Tree of Life divided into ten Spheres of the Worlds which are forming four levels of manifestation: the Design ideas; Realization of Ideas (thinking process); Radiation (including emotions and feelings); Action (implementation), and also division of each of these spheres into sublevels. Possibility of calculation and use of discrete power levels to the description and characteristics of the projected products, and tendencies to replacement of usual options on integrated, hybrid and morphing are shown.

Key words**:** law; design; analogy, the golden section, magneto-hydrodynamic analogy, electro-hydrodynamic analogy.

INTRODUCTION

By the basic laws of engineering aeronautical engineering constructor is not usually drawn, trying to solve a lot of problems with a variety of conflicting requirements and rules established on the basis of statistics, as well as the rich experience of the previous design, manufacture and operation of aviasrtucture. In aviation, these requirements are: aerodynamic, technology, durability, reliability and service life, operation, optimization, environment and others. Despite the sufficient reliability and testing of the current approach, which is based on theoretical and experimental, as well as the purely empirical regularities, it is not possible to understand the truths of the deeping the nature of the laws, and apply new approaches and solutions in the design process.

THE ANALYSIS OF RECENT RESEARCH AND PUBLICATIONS

In the design of modern aircraft structures developer seeks to fulfill the bearing surface maximum aerodynamic efficiency, having a minimum mass, which can accommodate large amounts of fuel, having a predetermined resource was simple, i.e. technologically to manufacture, etc. Project objectives usually multicriteria, but virtually all of the criteria are contradictory, because the art of Designers is the ability to find compromise solutions, which complicates the implementation of the project objectives. Practice establish certain design problems technology that uses a hierarchy of optimality criteria and a number of other methods, in particular, the use of prior experience in the form of statistical data on the prototype [1, 2]. We study the prospects of development and projected changes in the basic flight performance and relative parameters of this type of aircraft in the coming years. To this end, according to the statistical tables built dynamic and static graphics retro series of important parameters of prototypes, Are sought for their function trends to estimate the error of approximation and are pro-its forecasted values [2]. The practice of designing complex technical systems shows that crucial in the effectiveness of the system and its future viability of a design phase and in particular the initial stage - the choice of concept, selection of basic parameters, and that this step can take up to 50-70% of the project's success. Simulate this stage, in view of the inevitable changes in market conditions [3], including the emergence of new systems, change in priorities and logistics, new technologies, materials, equipment, systems, and many others [4] with sufficient reliability is almost impossible.

Therefore, there was the so-called conceptual design [2]. The level of conceptual design of civil and transport aircraft most commonly assessed by weight and aerodynamic perfection, including economic indicators, such as the cost of transportation and the cost of flight personnel hours, environmental requirements for noise and emissions

In the process of building scientific and technical progress, there is a search for new technical solutions, mainly due to the widespread use of methods and means of CAD systems with the use of 3D volumetric and mass layout of the aircraft in accordance with the principles of CALS-technologies [1]. The core of CALS-technologies is a common information space (SIS). The SIS information is created, transformed, stored and transferred from one party to another by means of software. Such tools include automated design and process engineering (CAD / CAM / CAE). Interact with each other in a single information space is the basis of modern CALS-techniques. But this raises the problem of the structural form and design of the space and energy.

OBJECTIVES

The aim of the article is article is to prove the possibility of applying the basic laws of design already in the preliminary design stage, and to develop strategies to use these basic laws of a new type, based on a non-traditional approach to the basic concepts that have emerged at the crossroads of new scientific fields of science (synergy), art and philosophy, the design of aircraft as well as models of space allocation for the designing aircraft.

1. BASIC LAWS OF AIRCRAFT DESIGN

Designing any complex natural and technical systems, such as aircraft and other technical facilities: cars, ships, but also technical and society communications - due to the application of certain universal laws that exist in the various branches of science, philosophy and art that reflect basic laws of nature, physical and mathematical aspects of the creation of the aircraft, as well as the creative process of the human mind. The author of the article developed a number of physical and mathematical methods for solving problems of continuum mechanics, allowing to prove some common fields of interaction and communication with the unified field [5-9], but also show the possibility of quantization Macromedia, saying the presence of discrete layers and around the macroscopic [10 - 12], which is confirmed by several other studies [13, 14].

An important novelty of this article is the concept of the use of not only some generalized criteria, but of the world's laws, of which the criteria are derived and explained them. There are seven basic laws of design, according to the number of basic natural laws applied in these areas.

These are the laws: 1. Thought or mental, associated with the formation of the idea, as well as visualization of forms and structures of the proposed facility. 2. The law of analogies. 3. The Law of Vibration. 4. The law of opposites. 5. The law of cycles and rhythms. 6. The Law of Cause and Effect. 7. Law of design and creativity.

1.1 First law - thinking or mentalism, as well as visualization of the designed object

The main content of the law is that, before anything design and build, you need to present in the consciousness itself created object as a complete, reflecting the work in the coordinates of the "here-now" and a vision of how this object It performs the task.

This is the law of priority thinking or creative consciousness, the creation of any new facility. The law allows the designer-thinking designer to concentrate on getting exactly what is the content of the job's technical, and will consist only of those energies and imagery that draws its creator thought. In this law of thought there are two main embodiments. First - this is when the idea of the scheme is the energy, without the inclusion of the senses. The second option - when connected to the realization of the true feelings and emotions associated with them. Despite its apparent simplicity, is the basic design of the basic law, but it is not taught in our contemporary higher technical institutions and universities.

1.2 Second Law - analogies

The content of the second law states: "What is below is like that which is above; device like the forehead-century structure of the Universe" [1], so the essence of it is in the likeness of the hierarchical structures of matter in form and content.

For example, there is a similarity in structure between the cell, atom and the solar system (Figure 1).

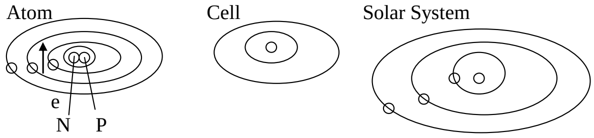

Fig. 1. The similarity between the atom, cell and the solar system

Also, every manifestation of the cell, a piece of manifestation of matter, an element of creative structures has structural parts, repeating through the levels as shown in Fig. 2.

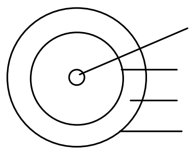

Fig. 2. Typical diagram of the manifestation matter cell structure

In accordance with the law of analogies every object in our world is structurally built on a similar basis. Each object has three structural components (Fig. 2) - this is the core of consciousness, sensation, or simply the core, intermediate medium and the shell adapted to the existence of consciousness in the particular circumstances. By analogy with the structure of the cell, the person also consists of:

- 0 - the highest spark;
- 1 - the spirit (the nucleus);
- 2 - soul (intermediated substance);
- 3 - flesh (shell).

Flesh (shell), in turn, consists of three components:

1. the mind, the intellect (nucleus);
2. staging environment, having three co-constitute:
   - mental,
   - emotional and sensual,
   - energy;
3. the physical body (the shell).

It is obvious that in addition to the separation of man into three components we can talk about the dividing of his own for seven structural component or states: the spiritual; soul; mental; intelligent; psyche; conscious; emotional and feelings (sensual) (category of feelings, emotions and desires); Energy, which includes the state of the field known as well as unknown nature science field;

natural, study, for example, modern medicine, biology, which went over to the medical term "anatomy".

In addition, each object has a higher state, referring to the category "higher consciousness", which is of a different nature to the human and natural objects: animals, plants, minerals. Higher consciousness is connected with the object of special energy fields which we can identify the information-energy channels of communication. Similar channels associated with the human subconscious. They have three structural components: the superconsciousness, a common consciousness and subconsciousness. Separation of the field of consciousness to these three sectors is widely used in modern science (medicine, psychology, philosophy), but in contrast to the traditional, we slightly expanded the concept of ordinary consciousness, adding energy-components.

The reason is the presence of law analogies in the nature of the Unified Field of interaction from which all the rest of the field. Consider some types of analogies that may clarify the structure of the universe and give some idea of the nature of the unified field of interactions existing in nature [2, 5 - 8].

The analogy between the electromagnetic and gravitational phenomena, it may be noted, comparing the record of the laws of Newton and Coulomb (1) for cooperation between the two bodies or charges:

$$Fgr. = Gx(M_1 x M_2)/r^2 ;$$
$$Fe = \frac{1}{4\pi\varepsilon\varepsilon_0} x \frac{q_1 q_2}{r^2}. \quad (1)$$

This analogy allows to compare time-personal processes Continuum Mechanics: stretching the orifice plate (Fig. 3a) with the passage of electrical current through the conductive plate (paper), in which the analogous opening (Fig. 3b), as well as flow around the cylindrical body fluid flow (Fig. 3c).

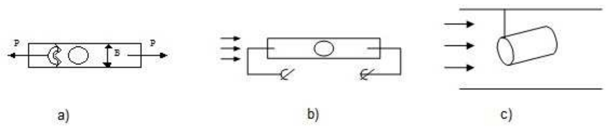

Fig. 3. The analogy between the aeroelastic and electrical phenomena: a) stretching the plate with a hole; b) a conductive plate with a hole; c) the cylinder, blown air flow

By comparing the elastic and aerodynamic variables and processes, we see the analogy between stress (σ) $\sigma \sim \nabla\nabla\Phi$ in the theory of elasticity and speed (v) $V \sim \nabla\varphi$ in aerodynamics (Fig. 4, Fig. 5), which is based on the similarity of the mathematical description of processes with potential functions: biharmonic for voltage and speed, where the - ∇ operator (gradient), and φ and F - potential function speeds and voltages, respectively, satisfying the Laplace equation for the harmonic function φ and the biharmonic equation for the function F.

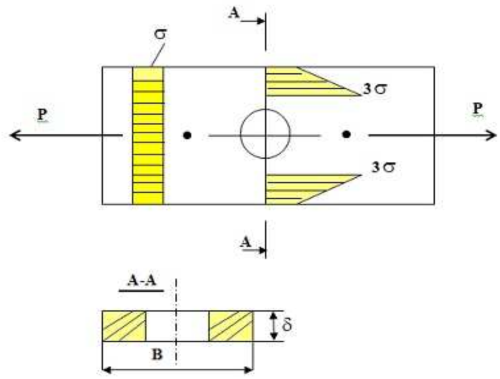

Fig. 4. Stretching the orifice plate

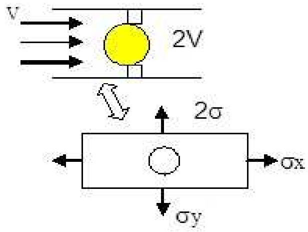

Fig. 5. The analogy between the flow around the cylinder and bilateral tension plate

Electro-hydrodynamic analogy (EHDA) - makes it possible to find a correspondence between the aeroelastic, hydrodynamic and electromagnetic phenomena, and Magda allows to take into account the volume factor and compare the results of studies with an aerodynamic experiment in pipes and dynamically similar models. Magda is performed on the models of aircraft covered by a layer of electrically conductive and placed in an electromagnetic cell (Fig. 6).

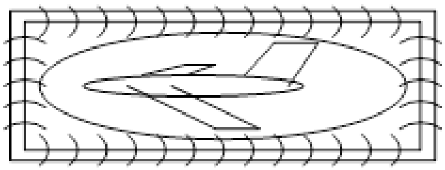

Fig. 6. Scheme of modeling the flow using the method of Magda

In a model of electrical conduction layer is deposited, which allows to measure the strength and potential electromagnetic field.

In the design process of the objects represented by the law of analogy, for example, in the form of analysis of statistical data on the aircraft defined performance characteristics.

1.3 Third Law of Vibration

These law states that every phenomenon has a certain range of vibrations and reflection-pressed in mathematical and physical laws that describe the state and dynamics of the object. In particular, this applies to space flight and exploration. If we want to get to the other space-time field, we need to learn how to change the vibration of the vehicles and sustainably support the new state.

The law of vibration recorded mathematical equations used to describe this picture of the World (PW). In particular, one of the world's species are tensor equations of Einstein's law [15]:

$$T_{ik} = -\aleph \times G_{ik}, \quad (2)$$

where: T_{ik} - energy-momentum tensor of matter;

G_{ik} - the Einstein tensor, which reflects the metric and the curvature of space.

From this law we can obtain equations of continuum mechanics, are widely used in the calculation of aircraft.

1.4 Fourth Law of dialectic and oppositions

The law of unity and struggle of opposites, on the basis of dialectical, allows us to understand how to achieve harmony by overcoming the conflict demands. At the level of the law introduced the concept of three major bond or forces of the world: the power of activity (rajas), the power of passive (Tamas), as well as the power of harmonization (sattva), which for some reason is not present in our Este-governmental science, and in most Western philosophies. In natural sciences, the law known as Newton's third law: action equals reaction. Taking into account our amendments, action equals reaction only when sufficient neutralizing, harmonizing force (sattva). As for the philosophical laws: unity and struggle of opposites, the transition from quantitative to qualitative changes, the law of the negation, then they also need a new understanding, a new perception that takes into account all the same harmonizing effect on the nature and effect of which is necessary to think seriously, at least in terms of testing and staging of the plan.

The principle of opposites in aviation is related to optimization problems, such as the definition of functional minimum takeoff weight of the aircraft, depending on the geometric parameters of the glider, as well as optimization of finding a minimum weight of structural elements, depending on the geometric parameters of the airframe, the external load, and fatigue life.

1.5 Fifth Law - the cycles and rhythms

This law determines the nature of cyclical patterns in nature, subject to periodic changes that have small periods of change (rate) within large (cycles). Thus, the specified lifetime of the aircraft is usually associated with a resource, which is about 20 ... 30 years for a passenger or transport aircraft. This cycle will be the smallest military aircraft, such as fighters, as well as an easy technique: the life of two - four years.

Rhythm of using aircraft, in particular, it is possible to determine the annual bloom. Each aircraft has its own border, use their rhythm, but if the plaque is more than 4000 hours per year, it will mean the continued use of the aircraft for more than 10 hours each day. In order to properly dispose of the objects of aviation equipment, you need not only the knowledge of the service life of materials, components and assemblies, and the aircraft itself, but also the correlation of external natural cycles with the cycles of operation. Otherwise, it may lead to unnecessary accidents and disasters that could have been avoided if we start to consider the impact of natural systems and their cycles.

1.6 Sixth Law- causes and consequences

Everything in the world is the law of cause and effect, i.e., everything happens for a reason. For example, 85% of aircraft accidents occur from the destruction of compounds in the area. In this case, the reason NE-one to poor performance of the compounds in the assembly, as a consequence - early failure during operation, the inability to sustain service life. One consequence of this law is the need to act on a reason to avoid the investigation, rather than parrying permanent adverse effects. This requires a system synthesizing synergy approach.

1.7 Seventh law - design and creativity

Act of design and creativity associated with the "golden section" and Fibonacci numbers, which are manifested-in a variety of tasks and related to the partition of the interval into unequal parts - $\frac{B}{a} = \frac{a}{A}$ in the following proportion (Fig. 7).

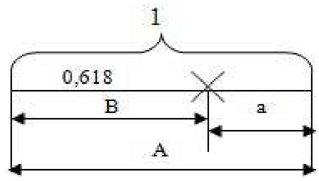

Fig. 7. Splitting lengths in the ratio of the golden section

As shown by research, the structures of living systems are best described pentagonal symmetry, which entered the golden section and the specified number.

Act of design and creativity aimed at balancing and harmonizing inert (Yin) and active (yang) energies of the male and female implementations. From a scientific point of view, we are talking about right-handed and left-handed symmetry vortex tubes and processes in these fields of force. Mathematically this law is supported by a group of equations such as the equation of Schrödinger type. As shown in works [9 - 11] of the author Schrödinger equation type are derived from the joint examination of the dynamics equations of a continuous medium (e.g., the Euler equations) and the continuity equation for the density of the medium. Given that this satisfies the entropy of laws affecting information processes, we can note that in the seventh law provides the possibility of mathematization process of design and creativity, resulting from the analysis of the solutions of these equations, used in quantum mechanics and nuclear physics

2. THE SPACE OF DESIGN

The space design - it is a physical volume within which the process of creativity and design. The idea of considering the design space is not new, but in some cases is more related to matters of purely computer-aided design. For example, a conceptual diagram of the methodology of top-down design provides for multi-tier management structure comprising a tree structure of individual blocks, the model space allocation, model master geometry of the assembly, interface, interfaces, the kinematics of the various elements of the product, as well as the creation of a virtual layout of the designed products, allowing to formulate the conceptual framework designed product. The space design in this case belongs to the category of virtual and exists in the information field of the computer system.

The question is how to build a true real space and to realize, to besiege the idea of designing an object, not only from a purely technical point - this is an issue that we are presenting to the study. This is important not only for the aircraft designer, but also for the designer cottage, gardens, designer recreation and creativity, as well as in shaping the comfort of their own apartment.

The place that you choose a designer-designer for his work, in this case, must meet certain requirements and have a special structure Fig. 8; Fig. 9. It is known from the popular modern methods of distribution of energy metering parameters of distribution space in the process of design and construction of buildings, structures must be, first of all, take into account the direction of light. Most of Earth's sacred buildings constructed with the account of this principle. At the same time, awareness of the principles of creation, design and construction of new facilities, largely lost, and mostly draws attention to the external criteria for the implementation and use, indoor comfort of the consumer, as well as an acceptable appearance of the design object

Without deep study design factors that must also be taken into account. The author spent a quite long and painstaking research to offer a special division of space design in the form of the Tree of Life scheme. If we are talking about a system that is arranged on the surface of the Earth, every space was originally to be oriented along the axis of the magnetic compass on "North - South" and even then divided into two parts through the "East-West".

This separation may take place, such as maps of the city, settlements. If the dis-regarded three-dimensional picture, then the direction of the north will be directed upwards.

Fig. 8 shows a diagram of the main part of the Tree of Life and the ten spheres of the world, forming the four levels of existence: 1) the idea of the design; 2) realization of ideas (thinking process); 3) radiation (including emotions and feelings); 4) action (implementation). Fig. 9 shows the division of the data fields in the sub-levels.

Fig. 8. Scheme of ten spheres of the world of design space

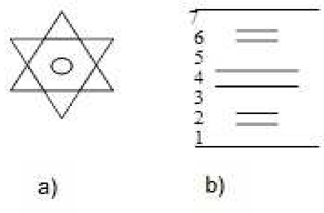

Fig. 9. Scheme of division of space design:
a) top view, spatial volume as merkaba;
b) the division of one of the seven-layer model levels

The three higher realms (1, 2 and 3) - make up the upper level, the world of ideas, Plan Design: Crown (1); Wisdom (2) and understanding (3). Further there are three areas of the world thinking process: Scope of Mercy (4) Scope of Severity (5) The scope of Radiance (6), and then - three areas of the World Radiation: Industry senses (7) Scope of Logic, Reason (8) and the world of Inspiration, Ground (9). Last - is the world of action, security sphere (10) (Figure 8).

Center for the construction of a sphere 6 Shine, Splendour - is the main place where the designer has to stay permanently or long enough to be in the process of creativity. The whole space of the Earth is divided into enormous power cubes that make up the cells of the power of space and forming the so-called geopathic zones on the Earth's surface and it is adjacent to the surface of the volume.

Each of these zones has its own characteristics. In particular, the spiritual - it is the first area, the Crown (1), and the most mundane - the physical world, our natural kingdom (10). Applying the fourth basic law of design, in particular the principle of the dialectic of unity and struggle of opposites, we share the design space of each sphere on the top (B), and a lower (H) of the separated wall, diaphragm, and which are further divided each into three and the sum - into seven pieces that fill the energy fields (and the elements of the design). The principle of the triad, which introduces an element of harmonization (through the principle of sattva) is said membrane, average boundary of the zone. Thus, in addition to the vertical division of the Tree of Life in the four areas (Fig. 8), we divided each of the 10 zones of the space design on the top, bottom, and 7 sub-levels (Fig. 9b).

In turn, each of these sublevels concentrates crystalline energy of five types of natural energies, called elements (Fig. 10): Land (2 first-crystal cube), water (4 first-crystal icosahedron), fire (1 first-crystal tetrahedron), the air (3 first-crystal octahedron), ether (5 first-crystal dodecahedron), because in the space design in the process of design may appear resonators and amplifiers special properties of these five elements.

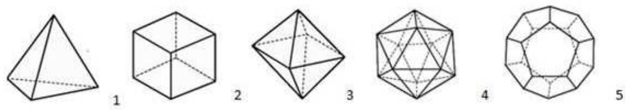

Fig. 10. Main crystal basic elements

Any object contains elements of the crystal structure, even such as the giant planet (Fig. 11).

Fig. 11. Earth as a giant icosahedron-dodecahedron crystal [16]

In particular, the planet Earth itself is an icosahedron, dodecahedron crystal, held a more than two-billionth evolutionary growth of the fire tetrahedron to icosahedron and dodecahedron is now passing to the structure. But technical and complex objects, such as modern aircraft integrated circuit (Fig. 12), which also contain a certain power grid, that can be calculated using the patterns shown here.

In particular, the tests of the model "EC-1" in the wind tunnel TsAGI WT-106 showed a high aerodynamic efficiency of the model and the prospect of continuing work on the development of technical proposals aircraft integrated circuit [17].

Fig. 12. The first prototype of the integrated circuit "IC-1" [17]

Fig.13. Morphing wings-13 [18]

This will not only operate and maintain these aircraft at a new level, but also to begin the actual design of integrated structures, seamlessly flat rectangular and cylindrical bodies into each other, as well as using composite materials to stack design with linking power line elements consistent by the power lines energy fields.

Another idea of integrated structures, using the law of analogies living natural systems, this design morph - the transformation of the airplane wings, like living systems: birds, fish (Fig. 13). [18] University of Pennsylvania showed the first results of their research, in which the wings of the aircraft change shape as the wings of a bird, and shut scales like a fish. Wings that can smoothly change its shape in a wide range of interest for commercial aircraft, fighter aircraft and unmanned reconnaissance vehicles (UAVs). Morphing wings, developed at the University of Pennsylvania, and can change their area, and the cross-sectional shape. The basis of these wings - changeable cell or cell power structure, serving as "bones and ligaments" and segmented scaly "skin". Polygonal cell frame disposed along the upper and lower surfaces of the wing can be folded differently by bending, thus the wings up and down. If they transform the concert, the changing span.

CONCLUSION

As a result of the study, consider the use of new concepts in the process of designing a pro-aviation technology is to use earlier in this area is not applied the seven laws of the new type. These laws are universal in nature and may also be useful in other areas of creation and creativity, from the creation of technical devices to design the family and society. In addition, the scheme has been proposed for the structuring of the Tree of Life arrangement implementing the idea and concept design phases from idea before its physical implementation. Also available as space allocation planning, taking into account the factor of the energy distribution. Explore the possibility of the application of the laws of the world of data for the design of specific aeronautical products will significantly improve the physical side of understanding not only the design, but also the manufacture and operation of aeronautical products.

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