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SOLUTION OF THE COMPROMISE OPTIMIZATION PROBLEM OF NETWORK GRAPHICS ON THE CRITERIA OF UNIFORM PERSONNEL LOADING AND DISTRIBUTION OF FUNDS

The object of research is a model network schedule for performing a complex of operations. One of the most problematic areas is the lack of a unified procedure that allows finding a solution to the problem of compromise optimization, for which the optimization criteria can have a different nature of the influence of input variables on them. In this study, such criteria are the criteria for the uniformity of the workload of personnel and the distribution of funds. Two alternative cases are considered: with monthly planning and with quarterly planning of allocation of funds and staff load.

The methods of mathematical planning of the experiment and the ridge analysis of the response surface are used.

The peculiarities of the proposed procedure for solving the problem of compromise optimization are its versatility and the possibility of visualization in one-dimensional form – the dependence of each of the alternative criteria on one parameter describing the constraints. The solution itself is found as the point of intersection of equally labeled ridge lines, which are curves that describe the locally optimal values of the output variables.

The proposed procedure, despite the fact that it is performed only on a model network diagram, can be used to solve the trade-off optimization problem on arbitrary network graphs. This is due to the fact that the combination of locally optimal solutions in a parametric form on one graph allows visualizing all solutions to the problem. The results obtained at the same time make it possible to select early dates for the start of operations in such a way that, as much as possible, take into account possible difficulties due to the formation of bottlenecks at certain stages of the project. The latter may be due to the fact that for the timely execution of some operation, it may be necessary to combine two criteria, despite the fact that the possible costs may turn out to be more calculated and estimated as optimal.

Keywords: *compromise optimization, model network schedule, network schedule optimization, uniformity of funds distribution, uneven workload of personnel, ridge line.*

1. Introduction

Systemic approaches to solving problems of optimization of network diagrams, if the optimization criteria are different, would be a necessary solution to the problem noted in [1]. It is associated with insufficient validity of formalization methods and problem solving. In such cases, one has to choose one, the most important, criterion, sacrificing the rest. This approach is justified if the selected criterion is a priority in the planned project. However, if there are several such criteria, it is necessary to choose some kind of compromise solutions. This situation is more real if, within the framework of planning, it is necessary to take into account the need for prompt and best in the chosen sense of the exchange of information and time synchronization of production processes [2]. Relevant criteria should be taken into account if the use of alternative business models is expected and it is necessary to opti-

mally allocate enterprise resources [3, 4] or to solve the problems of integrating workspace management [5, 6]. It is obvious that the optimization of the network schedules of the project when choosing only one of the criteria in such cases is not a very good solution. Therefore, it is possible to consider as relevant those studies that are aimed at finding compromise solutions in the problems of optimal planning and organization of project implementation processes.

2. The object of research and its technological audit

The object of research is a model network schedule for performing a complex of operations [1].

The subject of research is the optimization procedure according to different criteria. The uniformity of the workload of personnel was chosen as such criteria, as the ratio of the maximum and minimum intensities $y_1 = q_{max}/q_{min}$, and the

uniformity of distribution of funds over the stages of performing operations $y_2 = S_{max}/S_{min}$. This choice is justified by the fact that it can be used for any network schedule, for the construction of which it is sufficient to conduct a technological audit and expert assessments of the parameters of network schedules. Table 1 shows the initial data [7], adopted in the study.

<div align="right">**Table 1**</div>

Initial data for optimization of the network schedule by criterion $y_2 = S_{max}/S_{min} \to 1$

No.	Opera-tion ID	Duration, unit of time	Immediately pre-ceding operations	Intensity, per-son/unit time	Funds, c. u.
1	A	1	–	8	2000
2	B	4	A, C, D	13	13000
3	C	1	–	20	5000
4	D	1	–	20	5000
5	E	2	–	4	2000
6	F	3	D, E	16	12000
7	G	4	F	5	5000
8	H	1	C	4	1000
9	I	5	B, G, N	3	4000
10	K	2	C	2	1000
11	L	2	H	6	3000
12	M	2	H	2	1000
13	N	4	A, D	1	500
14	P	2	F	10	5000
15	Q	6	–	10	15000
16	R	3	Q	7	5000

The choice of specific numerical data is not fundamental and, in the general case, can be carried out from considerations of the practical problem being solved.

3. The aim and objectives of research

The aim of research is to develop a procedure for solving the problem of compromise optimization of the network schedule according to the criteria of uniformity of staff load and distribution of funds.

To achieve the aim, the following objectives are set:

1. Build mathematical models describing the impact of early start dates of priority operations on the uniformity of funds distribution in cases of monthly and quarterly planning options.

2. Find optimal solutions for the selection of an early start date for priority operations according to the criterion of uniformity of funds distribution.

3. Compare the optimization results for the selected criteria.

4. Research of existing solutions of the problem

A variant of solving the problem of optimizing network models in terms of time and resources is described in [8], but the criteria are considered as independent and the proposed solutions are considered as alternative.

The concept of integral risk analysis, implying the optimization of the project schedule according to several criteria, is used in [9]. The authors of this work proposed several scenarios for graph optimization, based on risk management processes [10], taking into account that the risk management process should be continuous [11]. However, the formalization of the problem at the level of mathematical models is not presented.

A variant of simplifying the structure of complex network diagrams, based on the use of the set-theoretic approach and the theory of directed graphs, was proposed in [12]. The solution to the problem is considered for two stages – design and optimization. In [13], a technique of analytical and simulation modeling for a generalized stochastic network graph is proposed, which allows obtaining the probabilistic parameters of a generalized stochastic network graph of interest to the user. However, the work does not highlight aspects related to the choice of parameters related to optimization.

In [14], the objective function is the sum of the durations of all critical jobs, which should tend to a minimum. A feature of the obtained results of this work is the revealed regularity, which makes it possible to reach a compromise in which the initial critical path is preserved, and further redistribution of resources is impossible. However, the presented results contain only a general formulation of the optimization problem, without offering specific practical examples of implementation.

The presentation of the solution to the optimization problem when choosing several criteria is presented in [15]. Criteria such as «time», «time – labor resources», «time – costs» are considered. However, the results of the work are mostly conceptual.

Optimal solutions for choosing the parameters of network diagrams can be obtained using the tools of the response surface methodology (RSM). In this case, it is necessary to obtain a mathematical description of the influence of the considered input variables on different output variables. The latter form the optimization criterion [1, 16]. The procedure for finding optimal solutions in this case for two alternatives includes studying the behavior of the response surface at three points of the D-optimal design. However, how to use the obtained solutions in the case of a different nature of the influence of the input variables on the output is not specified.

The presented results of the analysis of existing solutions to the problem indicate that a unified procedure has not been found that allows one to find a solution to the problem of compromise optimization, for which the optimization criteria can have a different nature of the influence of the input variables on them.

5. Methods of research

The following research methods are used in the work:
– network planning – to adjust the network schedules of operations within the overall project;
– methods of mathematical planning of the experiment [17, 18] – to build a mathematical model of the influence of priority input variables on the uniformity of distribution of funds at the stage of operations;
– ridge analysis [19] – to find the optimal timing of the start of operations in the presence of restrictions;
– method for constructing nomograms in terms of parametric description of the optimal values of input variables [20].

The validity of the choice of the methods used is based on their successful application to solve a number of problems in different applied areas:
– control of technological processes [21];
– optimization of organizational and technical systems [22];
– strategic planning [23].
All calculation formulas and principles for adjusting network diagrams, performed in this work, correspond to those set forth in [1, 17].

6. Research results

6.1. Mathematical models of the uniformity of distribution of funds.
Table 2 shows the results of calculating the output variable $y_2 = S_{max}/S_{min}$, obtained by adjusting the network diagrams according to the normalized values of the input variables, in the case of choosing a monthly period of funds allocation.

Table 2 the following designations are adopted:
– y_2 – uniformity of funds distribution by stages of operations;
– S_{max} – the maximum amount of allocated funds for the i-th period;
– S_{min} – the minimum amount of funds allocated for the i-th period;
– x_1 – early start date of operation Q (priority operation of alternative No. 2), varying in the range [0; 4];
– x_2 – early start date of operation P (priority operation of alternative No. 2), varying in the range [5; 11];
– x_3 – early start date of operation C (operation of alternative 1), varying in the range [0; 4].

Normalization, which transform the values of the input variables into the dimensionless range [–1; +1], was carried out according to the formula:

$$x_{inorm} = \frac{2x_i - (x_{imax} + x_{imin})}{x_{imax} - x_{imin}}, \quad i = 1,2,...,N, \quad j = 1,2,...,n, \quad (1)$$

where x_{imax} – the maximum value of the i-th input variable in the selected area of variation in natural form; x_{imin} – the minimum value of the i-th input variable in the selected range of variation in natural form; x_{inorm} – the value of the i-th input variable in normalized form; x_i – the value of the i-th input variable in natural form ($i=1, 2$ for alternative No. 2, $i=3$ for alternative No. 1).

Table 2

The results of calculating the output variable $y_2 = S_{max}/S_{min}$, obtained in the case of choosing the monthly period of funds allocation

No. of experiment	x_0	x_1	x_2	$x_1 x_2$	y_2		
					$x_3 = -1$	$x_3 = 0$	$x_3 = +1$
1	+1	+1	+1	+1	10.125	16.6	15.2
2	+1	–1	+1	–1	11.375	11.75	8.75
3	+1	+1	–1	–1	10.125	18.2	17.2
4	+1	–1	–1	+1	11.375	5.056	10
5	+1	+1	0	0	10.125	18.8	15.2
6	+1	–1	0	0	11.375	11.75	8.75
7	+1	0	+1	0	11.25	18.8	15.2
8	+1	0	–1	0	11.375	18.2	17.2
9	+1	0	0	0	11.25	18.8	15.2

Table 3 shows the results of calculating the output variable $y_2 = S_{max}/S_{min}$ in the case of choosing a quarterly period of funds allocation.

Table 3

The results of calculating the output variable $y_2 = S_{max}/S_{min}$, obtained in the case of choosing a quarterly period of funds allocation

No. of experiment	x_0	x_1	x_2	$x_1 x_2$	y_2		
					$x_3 = -1$	$x_3 = 0$	$x_3 = +1$
1	+1	+1	+1	+1	3.314815	3.778	4.5
2	+1	–1	+1	–1	6.294118	7.941	5.588
3	+1	+1	–1	–1	4.871795	5.897	5.795
4	+1	–1	–1	+1	9.166667	5.056	8.333
5	+1	+1	0	0	4.589744	6.154	5.795
6	+1	–1	0	0	8.916667	11.25	7.917
7	+1	0	+1	0	5.358974	6.923	5.026
8	+1	0	–1	0	9.166667	10.833	8.583
9	+1	0	0	0	8.708333	11.25	8.583

The mathematical model built on the basis of the data in Tables 2, 3 has the form:
– in case of choosing a monthly allocation period:

$$y_2 = \begin{cases} 11.49642 - 0.62513x_1 - 0.02084x_2 - \\ -0.70563x_1^2 - 0.14313x_2^2, & \text{if } x_3 = -1, \\ 20.02836 + 4.17484x_1 + 0.94919x_2 - \\ -5.13726x_1^2 - 1.91226x_2^2 - 2.0735x_1x_2, & \text{if } x_3 = 0, \\ 15.55610 + 3.35067x_1 - 0.87518x_2 - \\ -3.55450x_1^2 + 0.67050x_2^2 - 0.1875x_1x_2, & \text{if } x_3 = +1; \end{cases} \quad (2)$$

– in case of choosing a quarterly period for allocating funds:

$$y_2 = \begin{cases} 8.57411 - 1.93390x_1 - 1.37314x_2 - \\ -1.653x_1^2 - 1.14339x_2^2 + 0.32889x_1x_2, & \text{if } x_3 = -1, \\ 11.69794 - 1.40328x_1 - 0.5241x_2 - \\ -3.10447x_1^2 - 2.92847x_2^2 - 1.251x_1x_2, & \text{if } x_3 = 0, \\ 8.28268 - 0.95819x_1 - 1.26642x_2 - \\ -1.1762x_1^2 - 1.2277x_2^2 + 0.3625x_1x_2, & \text{if } x_3 = +1. \end{cases} \quad (3)$$

6.2. Optimal solutions for choosing an early start date for priority operations.
The search for optimal solutions was carried out in a parametric form, where the value of the parameter λ was found from the results of calculations in the domain of definition:
1) in case of choosing a monthly period for the allocation of funds:
– at $x_3 = -1$:

Ridge line I: $\lambda =]-\infty; -0.70563[$;
Ridge lines II–III: $]-0.70563; -0.14313[$;
Ridge line IV: $]-0.14313; +\infty[$;

– at $x_3 = 0$:

Ridge line I: $\lambda =]-\infty; -5.44182[$;
Ridge lines II–III: $]-5.44182; -1.6077[$;
Ridge line IV: $]-1.6077; +\infty[$;

– at $x_3 = +1$:

Ridge line I: $\lambda =]-\infty; -3.55658[$;
Ridge lines II–III: $]-3.55658; 0.672581[$;
Ridge line IV: $] 0.672581; +\infty[$;

2) in case of choosing a quarterly allocation period:
– at $x_3 = -1$:

Ridge line I: $\lambda =]-\infty; -1.70144[$;
Ridge lines II–III: $]-1.70144; -1.09496[$;
Ridge lines IV: $] -1.09496; +\infty[$;

– at $x_3 = 0$:

Ridge line I: $\lambda =]-\infty; -3.64813[$;
Ridge lines II–III: $]-3.64813; -2.38481[$;
Ridge line IV: $] -2.38481; +\infty[$;

– at $x_3 = +1$:

Ridge line I: $\lambda =]-\infty; -1.38507[$;
Ridge lines II–III: $]-1.38507; -1.01883[$;
Ridge line IV: $] -1.01883; +\infty[$.

The calculation results for the case of choosing a monthly period for the allocation of funds are shown in Fig. 1–9.

Comparing Fig. 3, 6, 9, it can be seen that the best result is for $x_3 = +1$, since it ensures the fulfillment of the condition $y_2 = S_{max}/S_{min} = \min = 11.4$. This condition is achieved on the ridge line I at $r \approx 0.7$.
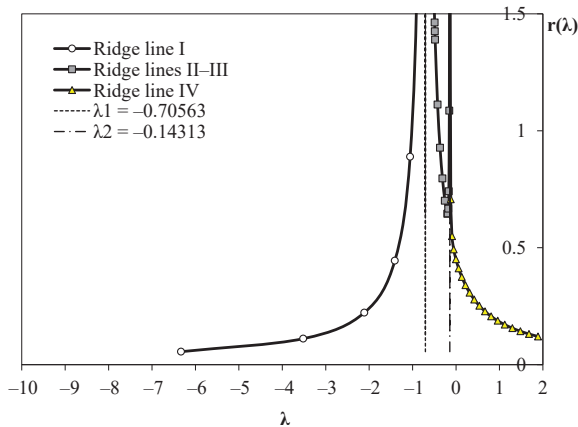

Fig. 3. Function $y = y(r)$ in case of choosing a monthly period of funds allocation $x_3 = -1$

Fig. 4. Function $r = r(\lambda)$ in the case of choosing a monthly period of funds allocation for $x_3 = 0$

Fig. 5. Function $y = y(\lambda)$ in case of choosing the monthly period of funds allocation $x_3 = 0$

Fig. 1. Function $r = r(\lambda)$ in case of choosing a monthly period of funds allocation for $x_3 = -1$
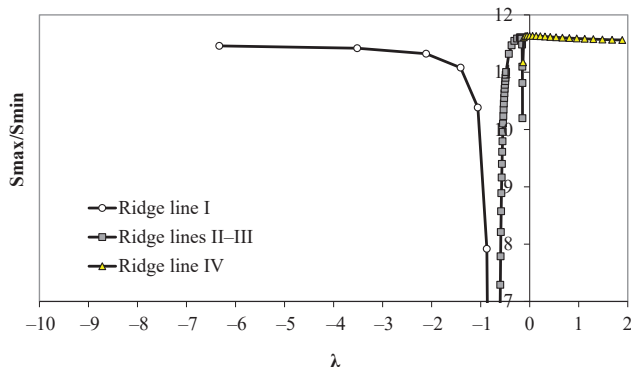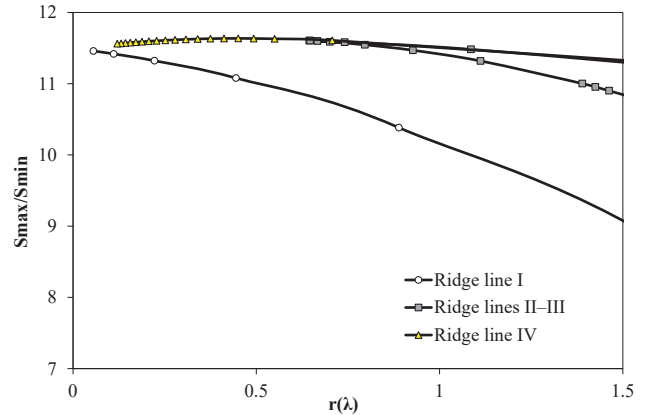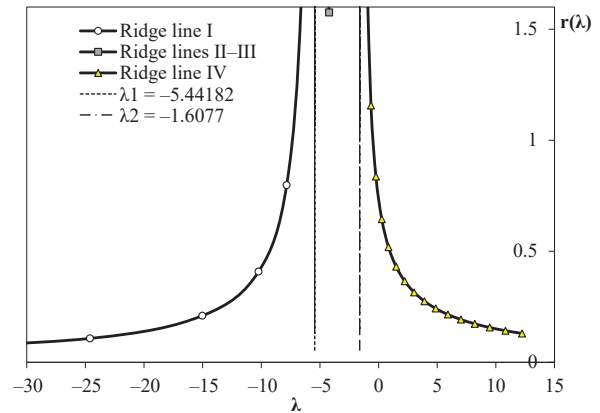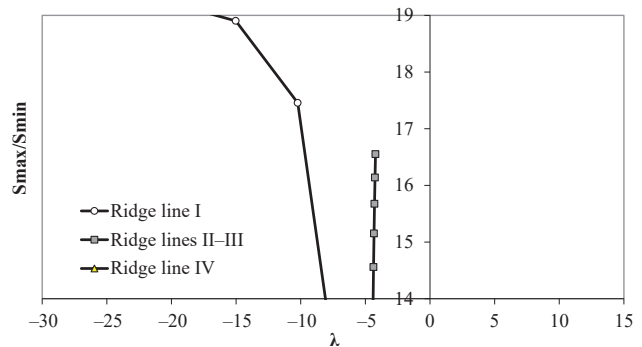

Fig. 2. Function $y = y(\lambda)$ in case of choosing a monthly period of funds allocation $x_3 = -1$
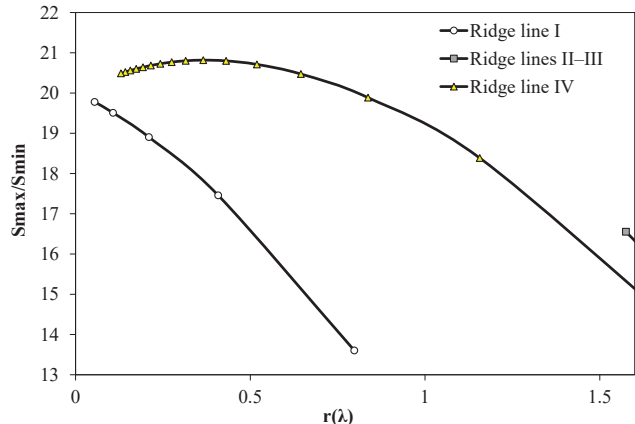

Fig. 6. Function $y = y(r)$ in case of choosing the monthly period of funds allocation $x_3 = 0$
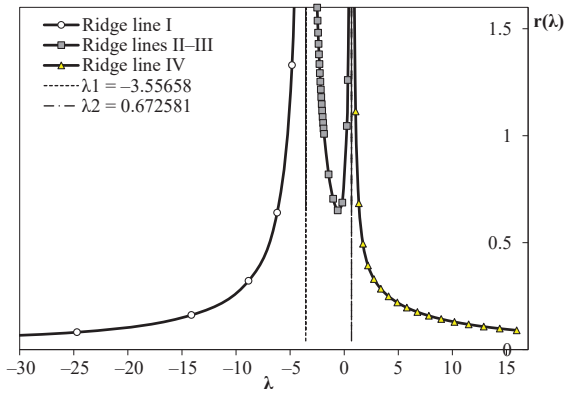
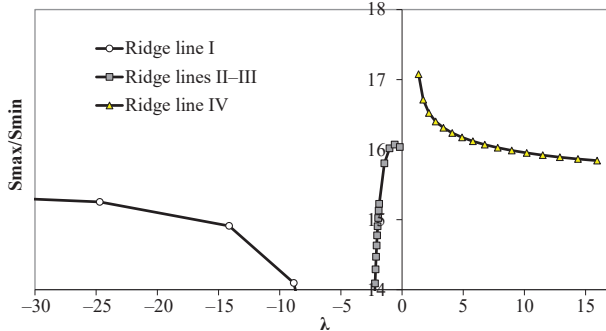**Fig. 7.** Function $r = r(\lambda)$ in the case of choosing a monthly period of funds allocation for $x_3 = +1$

Fig. 8. Function $y = y(\lambda)$ in case of choosing a monthly period of funds allocation $x_3 = +1$

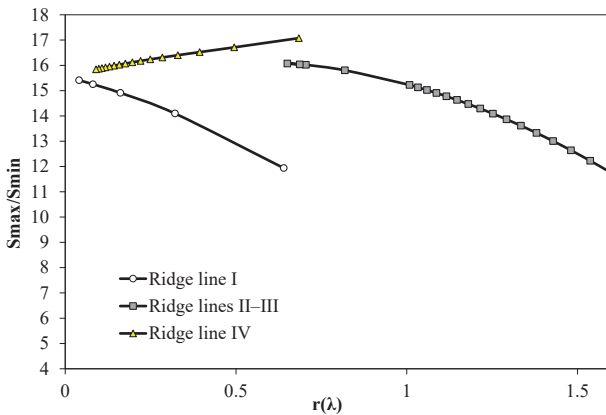**Fig. 9.** Function $y = y(r)$ in case of choosing a monthly period of funds allocation $x_3 = +1$

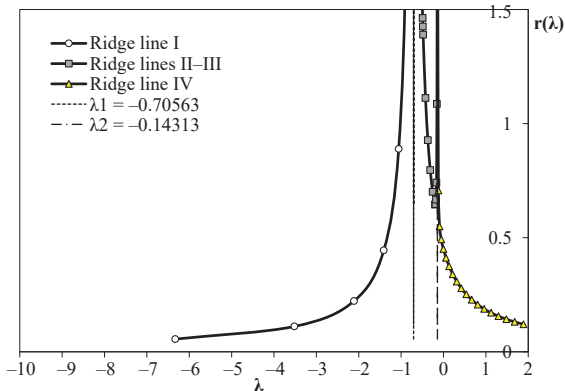The calculation results for the case of choosing a quarterly period for allocating funds are shown in Fig. 10–18.

Fig. 10. Function $r = r(\lambda)$ in the case of choosing a quarterly period of funds allocation for $x_3 = -1$

Fig. 11. Function $y = y(\lambda)$ in case of choosing a quarterly period of funds allocation for $x_3 = -1$

Fig. 12. Function $y = y(r)$ in case of choosing a quarterly period of funds allocation for $x_3 = -1$

Fig. 13. Function $r = r(\lambda)$ in the case of choosing a quarterly period of funds allocation for $x_3 = 0$

Fig. 14. Function $y = y(\lambda)$ in case of choosing a quarterly period of funds allocation for $x_3 = 0$

Fig. 15. Function $y = y(r)$ in the case of choosing a quarterly period of funds allocation for $x_3 = 0$
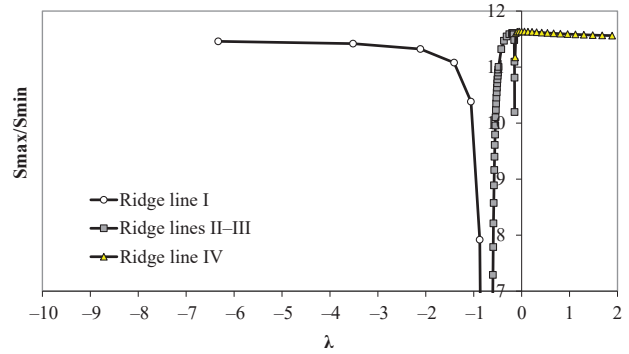

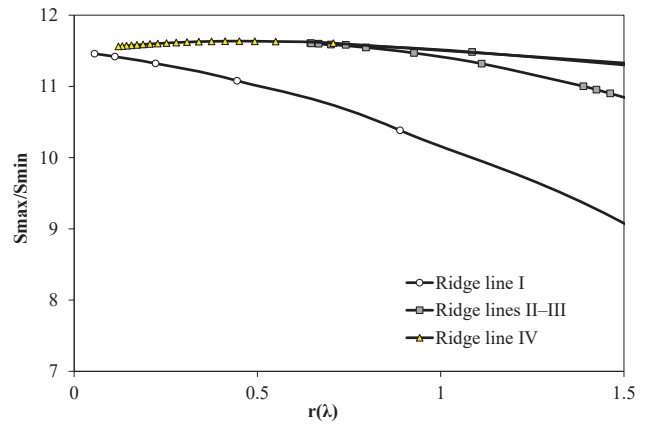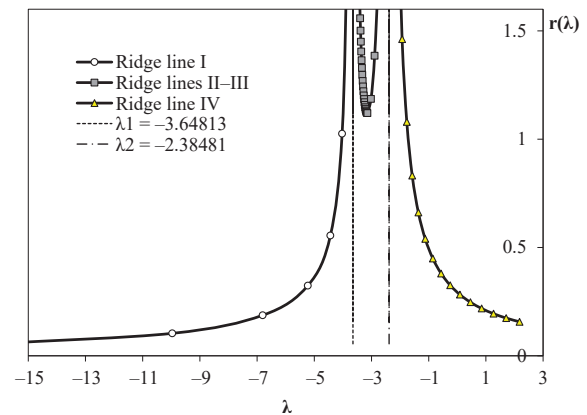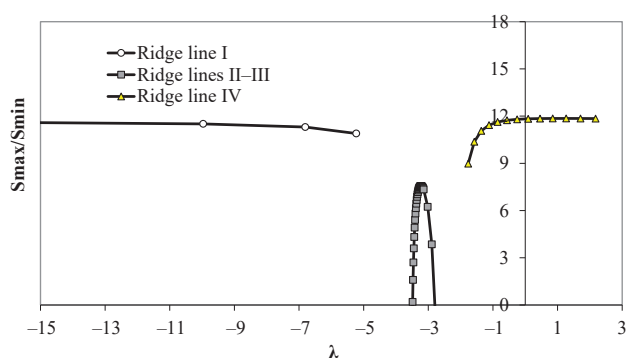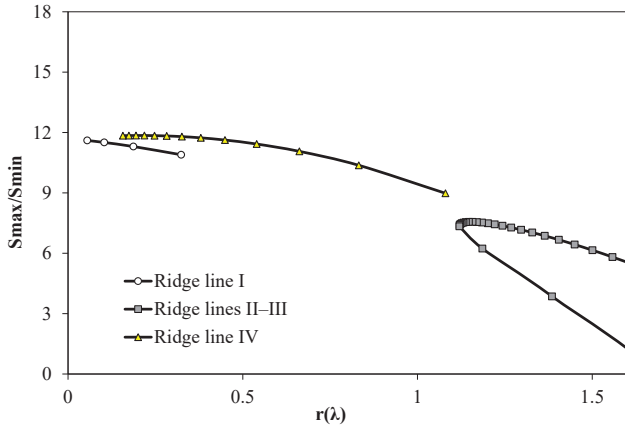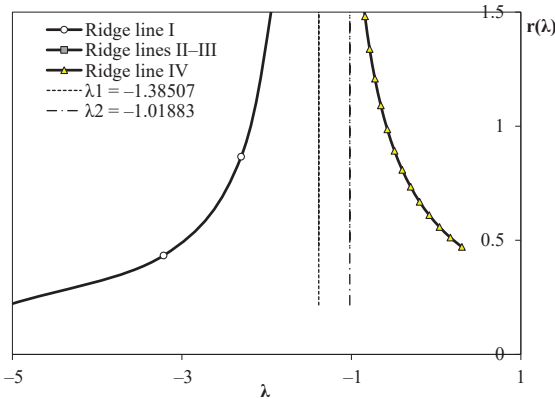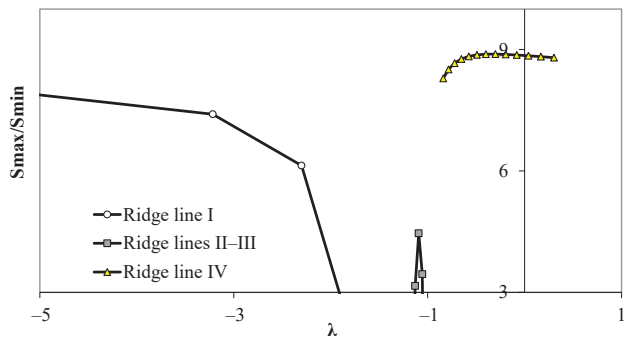**Fig. 16.** Function $r = r(\lambda)$ in the case of choosing a quarterly period of funds allocation for $x_3 = +1$

Fig. 17. Function $y = y(\lambda)$ in the case of choosing a quarterly period for allocating funds for $x_3 = +1$

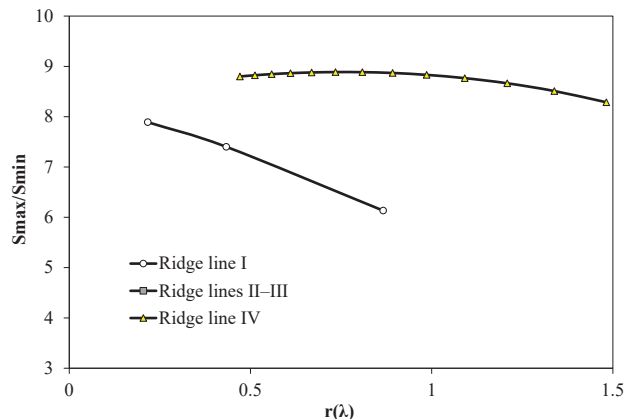**Fig. 18.** Function $y = y(r)$ in case of choosing a quarterly period of funds allocation for $x_3 = +1$

Comparing Fig. 12, 15, 18, it can be seen that the best result is for $x_3 = +1$, since it ensures the fulfillment of the condition $y_2 = S_{max}/S_{min} = \min = 6$. This condition is achieved on the ridge line I at $r \approx 0.85$.

Based on the conclusions regarding the analysis of Fig. 3, 6, 9, 12, 15, 18, it is necessary to search for a compromise optimal solution for $x_3 = +1$.

6.3. Comparison of optimization results for criteria of uniformity of workload and distribution of funds. Tables 4, 5 show the results of calculating the output variables $y_1 = q_{max}/q_{min}$, obtained by adjusting the network diagrams according to the normalized values of the input variables, according to [17], in the case of choosing a monthly and quarterly period for assessing the workload of personnel, respectively.

Table 4, 5, the following designations are adopted:
- y_1 – uniformity of staff loading;
- q_{max} – the maximum staff load for the i-th period;
- q_{min} – the minimum workload for the i-th period.

Table 4

The results of calculating the output variable $y_1 = q_{max}/q_{min}$, obtained in the case of choosing the monthly period for assessing the staff load

No. of experiment	x_0	x_1	x_2	$x_1 x_2$	$y_1 = q_{max}/q_{min}$		
					$x_3 = -1$	$x_3 = 0$	$x_3 = +1$
1	+1	+1	+1	+1	17.333	14	15.667
2	+1	−1	+1	−1	20.667	16.333	15.667
3	+1	+1	−1	−1	17.333	16.667	16
4	+1	−1	−1	+1	20.667	17.333	17.333
5	+1	+1	0	0	17.333	16.667	15.667
6	+1	−1	0	0	20.667	17.333	17.333
7	+1	0	+1	0	17.333	16.667	15.667
8	+1	0	−1	0	17.333	18	16
9	+1	0	0	0	17.333	16.667	15.667

Table 5

The results of calculating the output variable $y_1 = q_{max}/q_{min}$, obtained in the case of choosing a quarterly period for assessing the workload of personnel

No. of experiment	x_0	x_1	x_2	$x_1 x_2$	$y_1 = q_{max}/q_{min}$		
					$x_3 = -1$	$x_3 = 0$	$x_3 = +1$
1	+1	+1	+1	+1	3.362	3.304	2.957
2	+1	−1	+1	−1	7.684	6.842	5.684
3	+1	+1	−1	−1	5.949	6.718	5.744
4	+1	−1	−1	+1	16.222	16.333	11.444
5	+1	+1	0	0	5.949	6.256	5.744
6	+1	−1	0	0	16.222	14.667	12
7	+1	0	+1	0	5.25	5.5	4.5
8	+1	0	−1	0	14	16.667	13.111
9	+1	0	0	0	14	14.667	12.111

Fig. 19, 20 show the solution to the problem of compromise optimization in the case of monthly and quarterly estimates of the optimization criteria, respectively.
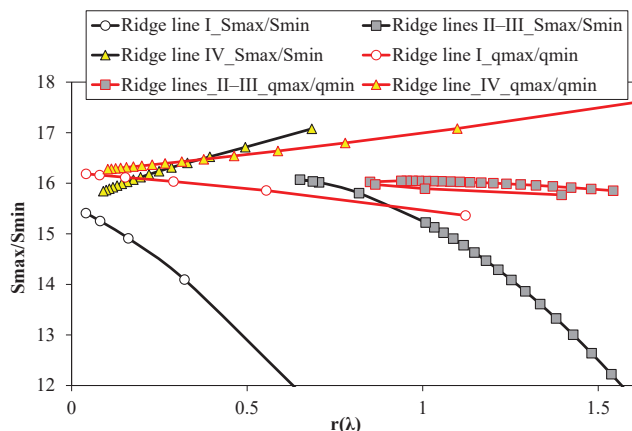
Fig. 19. Solution of the problem of compromise optimization in the case of monthly evaluation of optimization criteria
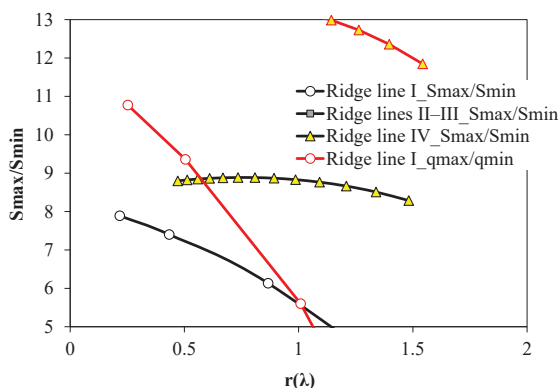

Fig. 20. Solution of the problem of compromise optimization in the case of quarterly evaluation of optimization criteria

The solution to the problem of compromise optimization is found as the point of intersection of equally marked ridge lines.

From the results of the analysis it can be seen (Fig. 19) that in the case of a monthly assessment of the optimization criteria, a compromise is possible only for ridge line IV. It allows to obtain a conditionally minimum value at the level $y_1 = y_2 \approx 16.3$ at $r \approx 0.4$. In other cases, a compromise is impossible and one has to choose which of the optimization criteria is more preferable for the given conditions.

From the results of the analysis for the case of a quarterly assessment of the optimization criteria, it can be seen (Fig. 20) that a compromise is possible only for the ridge line I. It allows obtaining a conditionally minimum value at the level $y_1 = y_2 \approx 5.5$ at $r \approx 1$. In other cases, a compromise is impossible and one has to choose which of the optimization criteria is more preferable for the given conditions.

7. SWOT analysis of research results

Strengths. Among the strengths of this research, it should be noted that the proposed procedure for finding a solution to the trade-off optimization problem gives a certain freedom of choice when planning. This allows to choose early dates for the start of operations in such a way as to take into account possible difficulties as much as possible. They may be related to the fact that for the timely execution of an operation, it may be necessary to combine two criteria, despite the fact that the pos-

sible costs may be more than the optimal possible. Such a situation can arise, for example, when there is a risk that a certain number of personnel may leave the project at this stage of its implementation. In addition, it should be noted that the proposed procedure is universal and its application is possible for any variant of the network schedule for performing operations within the framework of a single project.

Weaknesses. The weaknesses of this research are related to the fact that the solutions obtained can be applied only for the considered schedule. Since this graph is a model, the solutions obtained are mainly theoretical.

Opportunities. Additional opportunities when using the above results in real projects are associated with the fact that, using the proposed procedure, it is possible to find optimal compromise solutions, anticipating possible problems. Predicting the participation of staff at different stages of the project and varying the distribution of funds can eliminate potential bottlenecks that arise due to the fact that at some stage of the project there may be a shortage of staff.

Threats. Risks when using the proposed procedure are associated with the fact that it does not consider the factors of personnel competence. This can lead to completely different results than those obtained using the proposed procedure. In particular, bottlenecks may arise where, according to the calculation, they should not be. This will cause the need for additional recruitment of personnel with additional costs that even exceed those that are not optimal, but are compromises.

8. Conclusions

1. The constructed mathematical models describing the influence of the early start of priority operations on the uniformity of the distribution of funds, in cases of monthly and quarterly planning options, are polynomials of the second degree. The proposed system of such polynomials is a regression equation for three levels of values of the early start date of the operation of alternative No. 1 [17].

2. It is shown that the best solution for the considered model network schedule in the case of a monthly planning option is the solution $y_2 = S_{max}/S_{min} = \min = 11.4$, achieved at $r \approx 0.7$. The best solution for the considered model network graph in the case of a quarterly planning option is the solution $y_2 = S_{max}/S_{min} = \min = 6$, achieved at $r \approx 0.85$. Proceeding from the fact that the named best solutions are obtained for the level $x_3 = +1$, the solution to the problem of compromise optimization of the considered model graph should be sought for precisely this value of the early start of the operation of alternative No. 1 [17].

3. The solution to the problem of compromise optimization is found as the intersection point of equally marked ridge lines. In the case of monthly evaluation of optimization criteria, a compromise is only possible for ridge line IV. Conventionally, the minimum value is at the level $y_1 = y_2 \approx 16.3$ and is reached at $r \approx 0.4$. In other cases, a compromise is impossible and one has to choose which of the optimization criteria is more preferable for the given conditions. For the case of a quarterly assessment of the optimization criteria, a compromise is possible only for the ridge line I. Conventionally, the minimum value is at the level $y_1 = y_2 \approx 5.5$ and is achieved at $r \approx 1$. In other cases, a compromise is impossible and one has to choose

which of the optimization criteria is more preferable for the given conditions.

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