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Повышение эффективности деятельности промышленного предприятия

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Аннотация. *Активное развитие технологий требует новых подходов в планировании деятельности предприятий. Для выявления «слабых мест» в компании рекомендуется применять методы системного анализа. Они позволяют оценить нынешнее состояние предприятия, спрогнозировать будущее, а также выявить ошибки в прошлом. В представленной статье разработаны рекомендации по повышению эффективности деятельности промышленного предприятия по производству бетона. Выводы были сделаны с помощью имитационной модели системы массового обслуживания и проведения вычислительного эксперимента. Сформированные советы помогут предприятию избежать рисков переработок сотрудников, а также распределить нагрузку на оборудование.*

Ключевые слова: производство бетона, имитационное моделирование, системный анализ, эффективность деятельности, факторный план, вычислительный эксперимент

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Research article

Increasing the efficiency of an industrial enterprise

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Abstract. *The active development of technologies requires new approaches in planning the activities of enterprises. To identify "weak points" in the company, it is recommended to use methods of* *system analysis. They allow you to assess the current state of the enterprise, predict the future, and identify mistakes in the past. In the presented article, recommendations have been developed to improve the efficiency of an industrial enterprise for the production of concrete. The conclusions were drawn using a simulation model of a queuing system and a computational experiment. The formed tips will help the company avoid the risks of overworking employees, as well as distribute the load on the equipment.*

Keywords: concrete production, simulation modeling, system analysis, efficiency of the worker-news, factor plan, computational experiment

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Introduction. All organizations strive to increase profits and efficiency in their activities. For a qualitative assessment of the enterprise, methods of system analysis are used, which allow to conduct a study of the company's activities, as well as develop recommendations for improvement [1, 2]. These methods help to assess the influence of factors on a particular indicator of the efficiency of the enterprise, predict the values of indicators for the future billing period, etc. V.V. Mikhelev in the article "System-object approach to system analysis: features and advantages" notes that methods of system analysis imply a logical and consistent approach [3]. There is also confirmation of this - each method has the same structure: identifying the problem, setting a goal, building a model, developing a solution algorithm. The author of the article "System analysis solves problems" - T.V. Galagan - describes that any object can be considered as a set of subsystems interacting with other systems [4]. Indeed, one or another object is always affected by disturbing forces. Due to this impact, uncertainty arises, in which it is quite difficult to make a decision or predict the value for the future.

Methods of system analysis are applicable in various fields of activity. With their help, it is possible to identify the indicator that most influences the productivity of the RBU [5], or to develop a conceptual model of an oil field capable of reflecting and predicting changes in the reservoir under conditions of changing parameters of the field operation mode [6].

Limited Liability Company (hereinafter referred to as LLC) "StarorusStroyBeton" was selected as the object of the study.

A.O. Khubaev, R.A. Baichorov, A.A. Urusov in the publication “System Analysis of Winter Concreting Methods in the Construction of Monolithic Residential Buildings and Structures” conducted an analysis and selected a profitable solution for concreting in extreme winter conditions and proved that low temperatures are not a reason to stop construction and erection of buildings [7]. This article is an example of the application of system analysis methods in construction.

In the article "Innovative technologies in concrete production: problems and prospects" M.M. Ergashev claims that concrete is currently a fairly popular and widespread building material [8]. One cannot but agree with the author, since in the modern world it is impossible to imagine the construction of buildings without concrete. It is even used in decorating buildings, for example, lions that decorate this or that building - a small-sized reinforced concrete product.

O.E. Astafyev examines new technologies for the production of building materials, including concrete, in his article “The Use of Ash and Slag Waste in the Building Materials Industry” [9]. This publication proves that concrete production is indeed a relevant and necessary topic.

Since 1994, the company has specialized in various construction works. This enterprise has specialized equipment, a mortar concrete plant (RCP). In order to fulfill larger orders, a MEKAMIX 20 concrete plant was purchased in 2011 instead of the outdated RCP. The enterprise is engaged in the production and delivery of concrete, mortar, cement-sand mortar, foundation blocks, paving slabs, but the work deals exclusively with the process of concrete production.

Planning an experiment to build factor models and test the working model for measurement reproducibility, factor significance and adequacy plays an important role in analyzing the system. In the article by N.D. Sizov and I.A. Mikheev "Algorithm for solving the problem of designing concrete composition by the method of mathematical planning of an experiment" to determine the optimal composition of concrete, a complete factorial plan of the experiment is built and the result of the work is the regression equations [10]. The resulting expressions help to determine the significance of factors on the target function and calculate the value depending on the selected factors.

In order to check the functioning of a particular business process or technological process, you can build its simulation model, which will be close to reality. This will help analyze the efficiency of the system, as well as formulate recommendations for improvement. In the article "Simulation Modeling of a Business Process" D.O. Simakhin and M.V. Savkov note that the construction of simulation models plays an important role in production for solving problems or for determining parameters that will help meet high market requirements [11].

This article will present an analysis of the work of the delivery department of the enterprise using simulation modeling and a computational experiment.

Statement of the problem. Since there are not many publications in the field of construction concrete production related to the analysis of the efficiency of enterprises, this article presents one of the research methods - simulation modeling with a computational experiment. This method will help to assess the current equipment and employee load, obtain a mathematical model describing the average waiting time for applications in the system and the average queue length, and develop recommendations for improving efficiency.

Materials and research methods. Let's consider three models: linear, logarithmic and exponential. Let's determine the determination coefficient for each of them.

Linear model

$$\hat{y}_i = a + bt_i, \#(1)$$

where $\hat{y}_i$are theoretical levels; a is the average number of Internet users; b is the average annual absolute growth; $t_i$is the time designation.

To determine the parameters a and b using the least squares method, the following formulas were used:

$$\frac{\sum t \qquad \bar{t}\bar{y}}{\sum t \qquad \bar{t}} \#(2)$$

$$\bar{y} - b\bar{t}. \#(3)$$

To determine the accuracy of the model, the determination coefficient is calculated as follows:

$$\frac{\sum(\hat{y} \qquad \bar{y})}{\sum(y \qquad \bar{y})} \#(4)$$

$$\#(5)$$

$$\#(6)$$

The trend equation is : $\hat{y}$.

Table 1 – **Calculation table of the linear model**

Year	at	t	t^2	t*y	at_{progn}	$(y_i - y_{prog})^2$	$(y_i - y_{cp})^2$
2012	9567	1	1	9567	9356	12003293	10587431
2013	10156	2	4	20312	9986	80352624	71013367
2014	10235	3	9	30705	10616	48608378	66865340
2015	11435	4	16	45740	11246	24800193	19205340
2016	11583	5	25	57915	11876	89280694	15322314
2017	12856	6	36	77136	12506	99200771	12366944
2018	13245	7	49	92715	13136	99200771	17991736
2019	13427	8	64	107416	13766	89280694	36743803

2020	13674	9	81	123066	14396	24800193	72789336
2021	15427	10	100	154270	15026	48608378	67921047
2022	15678	11	121	172458	15656	80352624	81634014
2023	16567	12	144	198804	16285	12003293	14033765
Sum	153850	78	650	1090104		5674284	58093823

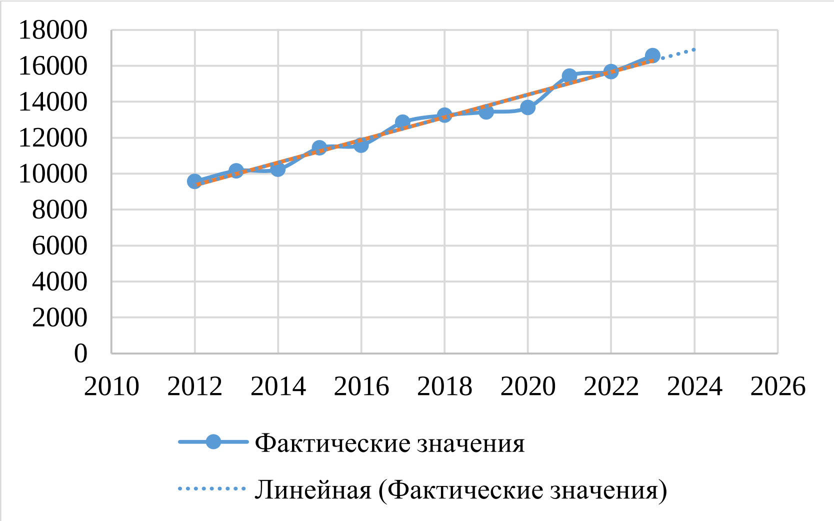

Figure 1 – Linear trend chart

Exponential model

$$\hat{y}_i = ae^{bt_i}. \#(7)$$

$$\frac{\sum \qquad \bar{t}\bar{y}}{\sum \qquad \bar{t}} \qquad \#(8)$$

$$\bar{y} - \bar{t} \qquad \#(9)$$

Table *Ошибка! Текст указанного стиля в документе отсутствует.*– **Exponential Model Calculation Table**

Year	at	t	ln(y)	ln(y)t	t^2	at_{progn}	$(y_i - y_{prog})^2$	$(y_i - y_{cp})^2$
2012	9567	1	9,16607	9,166075	1	9615,4693	10274358,5	10587431
2013	10156	2	9,22582	18,45164	4	10104,471	7378620,92	7101336,6
2014	10235	3	9,23356	27,70070	9	10618,342	4850965,65	6686534
2015	11435	4	9,34443	37,37773	16	11158,346	2763861,52	1920534
2016	11583	5	9,35729	46,78646	25	11725,813	1199068,73	1532231,3
2017	12856	6	9,46156	56,76939	36	12322,138	248696,129	1236,6944
2018	13245	7	9,49137	66,43962	49	12948,791	16373,1798	179917,36
2019	13427	8	9,50502	76,04018	64	13607,312	618548,857	367438,02
2020	13674	9	9,52325	85,70926	81	14299,322	2185930,98	727893,36
2021	15427	10	9,64387	96,43874	100	15026,526	4865080,86	6792104,6
2022	15678	11	9,66001	106,2601	121	15790,712	8820179,75	8163401,3
2023	16567	12	9,71516	116,5820	144	16593,761	14234985,2	14033764
Sum	153850	78	113,327	743,7220	650		57456670,3	58093823

$$\#(10)$$

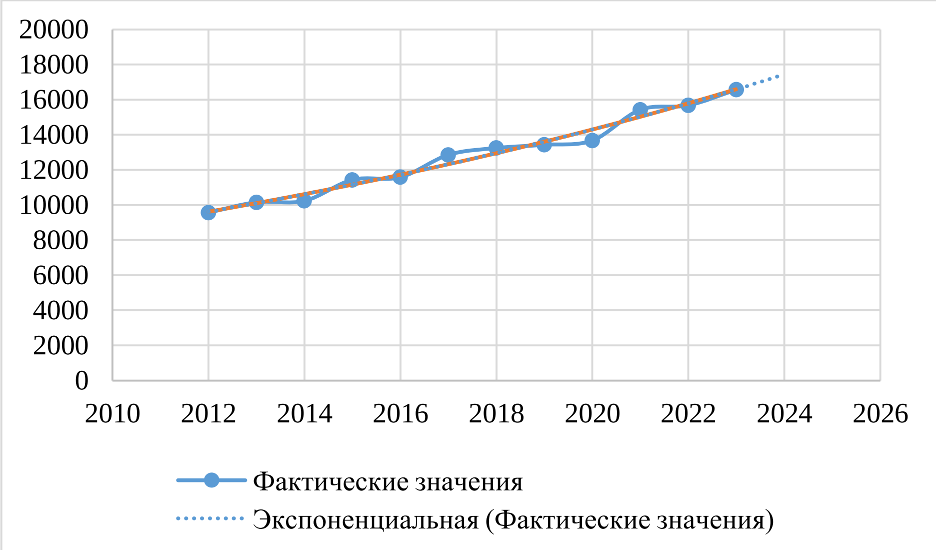

Figure Ошибка! Текст указанного стиля в документе отсутствует.**Exponential trend chart**

Logarithmic model

$$\hat{y} \qquad \ln(t_i)\,.\#(11)$$

$$\frac{\sum \qquad \bar{t}\bar{y}}{\sum \qquad \bar{t}} \qquad \#(12)$$

$$\bar{y} \qquad ln(\bar{t}) \qquad \#(13)$$

Table 3 – Calculation table of the logarithmic model

Year	at	t	ln(t)	ln(t)y	$ln(t)^2$	at_{progn}	$(y_i - y_{prog})^2$	$(y_i - y_{cp})^2$
2012	9567	1	0	0	0	8160,481	21718882	10587431
2013	10156	2	0.693	7039,602	0.480453	10099,907	7403440,2	7101336,6
2014	10235	3	1,099	11244.29	1,206948	11234,398	2516775,9	6686534
2015	11435	4	1,386	15852,27	1,921812	12039,333	610743,11	1920534
2016	11583	5	1,609	18642,11	2,590290	12663,688	24694,519	1532231,3
2017	12856	6	1,792	23034,86	3,210401	13173,824	124602,51	1236,6944
2018	13245	7	1,946	25773,58	3,786566	13605,138	615133,41	179917,36
2019	13427	8	2,079	27920,66	4,324077	13978,759	1340790,8	367438,02
2020	13674	9	2,197	30044,84	4,827795	14308,316	2212603,2	727893,36
2021	15427	10	2,303	35521,98	5,301898	14603,114	3176525,2	6792104,6
2022	15678	11	2,398	37594,20	5,749901	14869,792	4198232	8163401,3
2023	16567	12	2,485	41167,44	6,174761	15113,249	5255173,9	14033764,
Sum	153850	78	19,987	273835,8	39,57490		49197597	58093823

$$\frac{\qquad}{\qquad} \qquad \#(14)$$

Plot comparing actual data and logarithmic trend

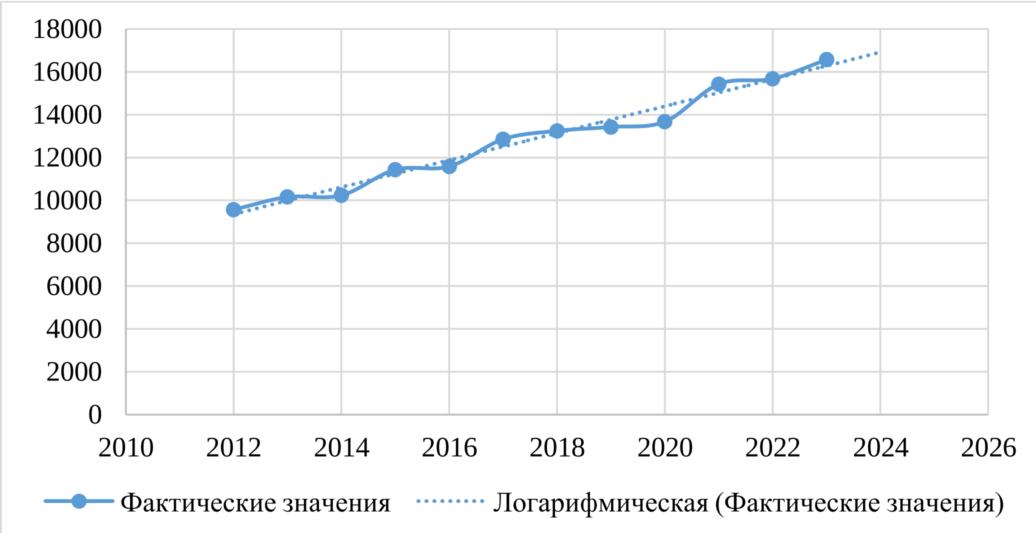

Figure 3 – Logarithmic trend graph

Received data reduced V table:

Table 4 – Summary comparison of models

Trend line type	Trend equation	Coefficient of determination
Linear	$\hat{y}_i = 8726{,}333 + 629{,}333 * t_i.$	0.9 8
Exponential	$\hat{y}_i = 9150{,}132e^{0{,}049t_i}$	0, 99
Logarithmic	$\hat{y}_i = 1{,}666 + 2798 * \ln(t_i)$	0, 85

Based on the data presented in Table 2.5, it can be concluded that it is more efficient to calculate the forecast value using the exponential model trend equation. The correctness of the forecast can only be verified in the future by comparing the calculated value with the actual one. However, it should be expected that a model that describes the existing data well will also forecast well.

The delivery department was chosen for building the simulation model, since it can be considered as a mass service system.

The enterprise has three service channels - three concrete mixers that directly mix all the ingredients needed to produce concrete, bring this mass to the required consistency and load concrete trucks. The maximum queue length is five, since the enterprise owns five concrete trucks (volumes: 6; 6; 7; 7; 10 m ^{3}).

The working hours of the QMS were chosen to be 8 hours, i.e., a full working day (excluding possible overtime).

The intensity of the incoming requests is λ = 4, i.e., the enterprise receives 4 requests per hour. The simulated system uses an exponential distribution of the incoming requests, because they enter the system randomly.

The average service time can be calculated since we know the volumes of concrete trucks, the production and loading time of 1 cubic meter of concrete, as well as the average distance over which the company delivers the product and the average speed of the concrete truck.

The average error was also calculated, which is equal to 0.01 hours.

Thus,

T_{work} = 8 hours, λ = 4 units/hour, n = 3 units, m = 5 units, $\bar{t}_{об}$= 1.074 hours, ε = 0.15.

The constructed simulation model is presented in Fig. 4.

```
Smes STORAGE 3
GENERATE (Exponential(1,0,1/4))
TEST L Q$Ocher,5,out
QUEUE Ocher
ENTER Smes
DEPART Ocher
ADVANCE 1.074,0.01
LEAVE Smes
out TERMINATE 0

GENERATE 8
TERMINATE 1
START 1
```

Figure 4. Simulation model in GPSS World

In Fig. 4 it is evident that a simulation model of a multi-channel QS with a limited queue (5 applications) has been constructed.

Calculation of performance indicators

To calculate the performance indicators, we will use the data from the report after simulating the working day of the delivery department (Appendix 2).

- Absolute throughput: 3.028;
- Relative bandwidth: 0.757;
- Average number of occupied channels: 2,926 units;
- Employment rate: 0.975;
- Denial of Service Probability: 0.243;
- Average queue length: 3,214 units;
- Average waiting time: 0.918 h.

Modes of operation of the queuing system

With a given value of λ = 4 units/hour (intensity of the request flow), it was found that the system operates in an overloaded mode, since the channel occupancy rate is 0.975, and the probability of failures = 0.243 (24% failures).

In order to determine the nominal operating mode, it is necessary to reduce the parameter λ. By varying it was found that the system operates in the nominal mode at λ = 3 (channel occupancy factor is 0.947, failure probability is 0.040).

The system becomes underloaded when λ = 2 or less.

The number of model runs that do not exceed the specified error ($\varepsilon = 0{,}15$) was determined. For this, the program was launched 7 times in the nominal operating mode. The channel occupancy rate was taken as the analyzed efficiency indicator. The results of the runs are presented in Table 1.

Table 5 – Channel occupancy factor values for different generators

Generator number	Channel occupancy rate
1	0.947
2	0.955
3	0.902
4	0,860
5	0.753
6	0.894
7	0.934

To determine the number of runs, the standard deviation of the channel occupancy factor was found.

$$\sigma = \sqrt{\frac{\sum_1^7 \left(k_з - \bar{k}_з\right)^2}{7}} = 0{,}065 \#(15)$$

The number of runs is calculated using the formula:

$$N = \frac{t^2 \sigma^2}{\varepsilon^2} \#(16)$$

where t is the Student's criterion for 7 measurements and P = 0.95 is equal to 2.365.

———————— #(17)

The sufficient number of runs is 2. The report of the program operation with the found value is presented in Fig. 5.

```
GPSS World Simulation Report - Имитационная модель работы отдела доставки.678.1

                Tuesday, March 19, 2024 20:23:31

          START TIME          END TIME  BLOCKS  FACILITIES  STORAGES
               0.000            16.000    10        0          1

              NAME                        VALUE
          OCHER                        10001.000
          OUT                              8.000
          SMES                         10000.000

 LABEL              LOC  BLOCK TYPE     ENTRY COUNT CURRENT COUNT RETRY
                    1    GENERATE            47             0       0
                    2    TEST                47             0       0
                    3    QUEUE               44             1       0
                    4    ENTER               43             0       0
                    5    DEPART              43             0       0
                    6    ADVANCE             43             3       0
                    7    LEAVE               40             0       0
OUT                 8    TERMINATE           43             0       0
                    9    GENERATE             2             0       0
                   10    TERMINATE            2             0       0

QUEUE              MAX CONT. ENTRY ENTRY(0) AVE.CONT. AVE.TIME   AVE.(-0) RETRY
 OCHER               5    1     44     10     1.837      0.668      0.864   0

STORAGE            CAP. REM. MIN. MAX.  ENTRIES AVL.  AVE.C. UTIL. RETRY DELAY
 SMES                3    0    0    3       43    1   2.790  0.930    0    1

FEC XN   PRI          BDT       ASSEM  CURRENT  NEXT  PARAMETER    VALUE
    44    0          16.069      44      6       7
    50    0          16.323      50      0       1
    45    0          16.543      45      6       7
    46    0          16.929      46      6       7
    51    0          24.000      51      0       9
```

Figure 5. QMO simulation report with the found number of runs

Performance indicators

- Absolute throughput: 2.796;
- Relative bandwidth: 0.932;
- Average number of occupied channels: 2,790 units;
- Employment rate: 0.930;
- Denial of Service Probability: 0.068;
- Average queue length: 1,837 units;
- Average waiting time: 0.668 h.

Full factorial design

Let us present the object of study in the form of a structural diagram, shown in Fig. 6.

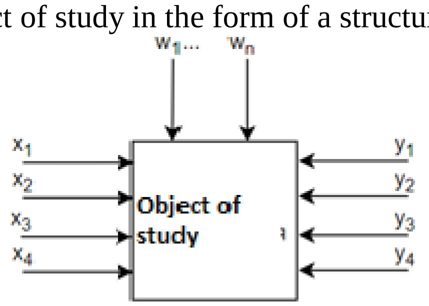

Figure 6 – **Structural diagram of the research object**

The representation of the research object in the form of a diagram, shown in Fig. 6, is based on the “black box” principle.

Parameters indicated in the diagram:

- x_i – input parameters (factors);
- y_i – output parameters (states);

- w_i – disturbing influence.

For x_1, the parameter λ was taken – the intensity of the flow of requests, x_2 – n (the number of service channels, in this case – concrete mixers), x_3 – m (the maximum queue length), x_4 – $\bar{t}_{об}$(average service time). The output parameter y denotes the number of requests serviced.

Response function:

$$\hat{y}_i = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4 \#(18)$$

Let us consider a full factorial experiment using a linear model as an example. To conduct a full factorial experiment, 2^k experiments are needed, where 2 is the number of levels, which is sufficient to construct a linear model, and k is the number of factors.

To obtain y_i, work was carried out with a simulation model, namely, the factors x_1 and x_4 ± 25% of the original value, x_2 and x_3 ± 1 were varied.

Below are presented all possible options for conducting the experiment (Table 6).

Table 6 – Experimental Design Matrix

No.	x_0	x_1	x_2	x_3	x_4
1	+	-	-	-	-
2	+	-	-	-	+
3	+	-	-	+	-
4	+	-	-	+	+
5	+	-	+	-	-
6	+	-	+	-	+
7	+	-	+	+	-
8	+	-	+	+	+
9	+	+	-	-	-
10	+	+	-	-	+
11	+	+	-	+	-
12	+	+	-	+	+
13	+	+	+	-	-
14	+	+	+	-	+
15	+	+	+	+	-
16	+	+	+	+	+

A computational experiment for average queue length

The tests were carried out 5 times in one mode. The results are presented in Table 7.

Table 7 – Planning matrix taking into account the interaction effect

No.	x_0	x_1	x_2	x_3	x_4	y_1	y_2	y_3	y_4	y_5	$\bar{y}$
1	+	-	-	-	-	2,453	1,888	2,141	1,767	1,436	1,937
2	+	-	-	-	+	2,716	2.67	2,765	2,402	2,076	2,526
3	+	-	-	+	-	3,753	2,939	3.26	1,855	2,262	2,814
4	+	-	-	+	+	4,131	4,033	4,046	3,722	2,955	3,777
5	+	-	+	-	-	0.166	0.323	0.261	0.119	0.363	0.246
6	+	-	+	-	+	0.621	1,404	1,649	0.689	1,267	1,126
7	+	-	+	+	-	0.166	0.323	0.385	0.119	0.363	0.271
8	+	-	+	+	+	2,217	2,349	2,708	0.689	1,959	1,984
9	+	+	-	-	-	2,688	2,736	3,046	2,824	2,668	2,792
10	+	+	-	-	+	3,016	3,366	3,378	3,256	2,975	3,198
11	+	+	-	+	-	4,149	4,354	4,615	4,416	3,995	4,306
12	+	+	-	+	+	4,527	4,998	4,948	4,894	4,339	4,741
13	+	+	+	-	-	0.482	0.913	1,465	0.72	1.85	1,086
14	+	+	+	-	+	2.85	1,933	2,653	2.34	2,503	2,456
15	+	+	+	+	-	2,901	1,496	2,734	0.72	3,065	2,183
16	+	+	+	+	+	4,549	3,452	4,172	3,771	3,804	3,950

M = 5 – number of tests

$N = 2^4 = 16$

It is necessary to find the coefficients of the regression model b_j.

$$b_j = \frac{1}{N}\sum_{i=1}^{N} x_{ij}\bar{y}_j \ \#(19)$$

For example,

$$b_0 = \frac{1}{16} * \begin{pmatrix} 1{,}937 + 2{,}526 + 2{,}814 + 3{,}777 + \\ +0{,}246 + 1{,}126 + 0{,}271 + 1{,}984 + \\ +2{,}792 + 3{,}198 + 4{,}306 + 4{,}741 + \\ +1{,}086 + 2{,}456 + 2{,}183 + 3{,}950 \end{pmatrix} = 2{,}462 \ \#(20)$$

$$b_1 = 0{,}623;\ b_2 = -0{,}799;\ b_3 = 0{,}541;\ b_4 = 0{,}508$$

Then

$$\hat{y}_i = 2{,}462 + 0{,}623x_1 - 0{,}799x_2 + 0{,}541x_3 + 0{,}508x_4 \ \#(21)$$

It was found that x_2 is the most significant factor, and x_4 is an insignificant factor. This conclusion was made based on the coefficients found b_j. The most significant factor is the factor whose coefficient is smaller in modulus than the others, and the insignificant factor is the coefficient whose coefficient is smaller in modulus than the others.

Next, the error-free execution time values were calculated. An example of the calculation $\hat{y}_1$ is presented below.

$$\hat{y}_1 = 2{,}462 - 0{,}623 + 0{,}799 - 0{,}541 - 0{,}508 = 1{,}586\#(22)$$

S_i^2 is also calculated using the formula.

$$S_i^2 = \frac{\sum_{m=1}^{M}(y_{im} - \hat{y}_i)^2}{M-1} \ \#(23)$$

For example,

$$S_1^2 = \frac{\begin{matrix}(2{,}453 - 1{,}586)^2 + (1{,}888 - 1{,}586)^2 + (2{,}141 - 1{,}586)^2 + \\ +(1{,}767 - 1{,}586)^2 + (1{,}436 - 1{,}586)^2\end{matrix}}{5-1} = 0{,}302 \ \#(24)$$

Calculated values $\hat{y}_i$ and S_i^2 are presented in Table 8.

Table 8 – Intermediate calculations

No.	$\hat{y}_i$	S_i^2
1	1,586	0.302
2	2,601	0,090
3	2,668	0.607
4	3,683	0.247
5	-0.013	0.095
6	1,002	0.223
7	1,069	0.811
8	2,085	0,610
9	2,839	0.026
10	3,855	0.576
11	3,922	0.242
12	4,937	0.133
13	1,241	0.344
14	2,256	0.171
15	2,323	1,077
16	3,339	0.644

To check the reproducibility (stability of tests), the Cochran criterion was calculated [12].

$$G_p = \frac{S_{imax}^2}{\sum_{i=1}^{N} S_i^2} = \frac{1{,}077}{6{,}197} = 0{,}174 \ \#(25)$$

Since 0.174 < 0.276 ($G_{кр} = 0{,}276$), therefore the measurements in the experiment are considered reproducible.

Then the significance of the factors was checked [13]. For this purpose, the value of S_y^2 was calculated.

$$\Sigma \quad \#(26)$$

Next, the calculation of S_{bj} is performed.

$$\sqrt{} \quad \sqrt{} \quad \#(27)$$

To calculate t_{pj} was used.

$$\frac{|b_j|}{} \#(28)$$

For example,

$$\#(29)$$

p4

Since all calculated values are greater than the Student's t-test, all factors are significant.

To test the adequacy of the model, the value of S_{ad}^2 was calculated.

$$\frac{\sum_{i=1}^{N}(\hat{y}_i - \bar{y}_i)}{(k \quad 1)} \#(30)$$

where k is the number of factors for which the Student's criterion is greater than the critical one, that is, k = 2.

$$\frac{}{(4 \quad 1)} \quad \#(31)$$

$$\#(32)$$

To determine F_{cr} calculated $\vartheta_1 = N - (k + 1) = 16 - (4 + 1) = 11$and $(M \quad 1) = 16 * (5 - 1) = 64$, therefore $F_{cr} = 1.92$.

Since $F_p < F_{cr}$, then it can be stated that the model is adequate [14].

A computational experiment for average waiting time

The tests were conducted 5 times in one mode. The results are presented in Table 9.

Table 9 – Planning matrix taking into account the interaction effect

No.	x_0	x_1	x_2	x_3	x_4	y_1	y_2	y_3	y_4	y_5	$\bar{y}$
1	+	-	-	-	-	0.892	0.795	0.745	0.643	0.604	0.736
2	+	-	-	-	+	1,448	1,526	1,383	1,281	1,186	1,365
3	+	-	-	+	-	1,251	1,12	1,043	0.645	0.862	0.984
4	+	-	-	+	+	1,944	2,017	1,798	1,751	1,477	1,797
5	+	-	+	-	-	0.055	0.108	0.08	0,041	0.126	0.082
6	+	-	+	-	+	0.226	0.511	0.528	0.24	0.483	0.398
7	+	-	+	+	-	0.055	0.108	0.114	0,041	0.126	0.089
8	+	-	+	+	+	0.657	0.783	0.802	0.24	0.681	0.633
9	+	+	-	-	-	0.896	0.912	1.06	0.982	0.97	0.964
10	+	+	-	-	+	1,508	1,683	1,689	1,628	1,487	1,599
11	+	+	-	+	-	1,276	1.34	1,477	1,413	1,332	1,368
12	+	+	-	+	+	2,012	2,221	2,199	2,175	1,929	2,107
13	+	+	+	-	-	0.107	0.215	0.326	0.156	0.411	0.243
14	+	+	+	-	+	0.814	0.552	0.786	0.668	0.801	0.724
15	+	+	+	+	-	0.516	0.332	0.575	0.156	0.645	0.445
16	+	+	+	+	+	1,213	0.921	1,151	1,006	1,127	1,084

M = 5 – number of tests

$N = 2^4 = 16$

It is necessary to find the coefficients of the regression model b_j.

For example,

$$b_0 = \frac{1}{16} * \begin{pmatrix} 0{,}736 + 1{,}365 + 0{,}984 + 1{,}797 + \\ +0{,}082 + 0{,}398 + 0{,}089 + 0{,}633 + \\ +0{,}964 + 1{,}599 + 1{,}368 + 2{,}107 + \\ +0{,}243 + 0{,}724 + 0{,}445 + 1{,}084 \end{pmatrix} = 0{,}914\#(33)$$

$$b_1 = 0{,}153;\ b_2 = -0{,}452;\ b_3 = 0{,}150;\ b_4 = 0{,}300$$

Then

$$\hat{y}_i = 0{,}914 + 0{,}153x_1 - 0{,}452x_2 + 0{,}150x_3 + 0{,}300x_4\ \#(34)$$

It turns out that x_2 is the most significant factor, and x_3 is an insignificant factor. This conclusion was made based on the coefficients found b_j. The most significant factor is the factor whose coefficient is smaller in modulus than the others, and the insignificant factor is the coefficient whose coefficient is smaller in modulus than the others.

Next, the error-free execution time values were calculated. An example of the calculation $\hat{y}_1$ is presented below.

$$\hat{y}_1 = 0{,}914 - 0{,}153 + 0{,}452 - 0{,}150 - 0{,}300 = 0{,}762\ \#(35)$$

S_i^2 is also calculated.

For example,

$$S_1^2 = \frac{\begin{matrix}(0{,}892 - 0{,}762)^2 + (0{,}795 - 0{,}762)^2 + (0{,}745 - 0{,}762)^2 + \\ +(0{,}643 - 0{,}762)^2 + (0{,}604 - 0{,}762)^2\end{matrix}}{5 - 1} = 0{,}014\ \#(36)$$

Calculated values $\hat{y}_i$ and S_i^2 are presented in Table 10.

Table 10 – Intermediate calculations

No.	$\hat{y}_i$	S_i^2
1	0.762	0,014
2	1,362	0,018
3	1,062	0.063
4	1,661	0.067
5	-0.141	0.063
6	0.459	0.028
7	0.159	0,008
8	0.758	0.072
9	1,069	0,018
10	1,668	0,015
11	1,368	0.006
12	1,968	0,041
13	0.166	0.023
14	0.765	0,015
15	0.465	0,040
16	1,065	0,014

To check the reproducibility (stability of tests), the Cochran criterion was calculated [12].

$$G_p = \frac{0{,}072}{0{,}505} = 0{,}142\#(37)$$

Since 0.142 < 0.276 ($G_{кр} = 0{,}276$), therefore the measurements in the experiment are considered reproducible.

Then the significance of the factors was checked [13]. For this purpose, the value of S_y^2 was calculated.

$$S_y^2 = \frac{0{,}505}{16} = 0{,}032\ \#(38)$$

Next, the calculation of S_{bj} is performed.

$$S_{bj} = \sqrt{\frac{0{,}032}{16 * 5}} = 0{,}020\ \#(39)$$

To calculate t_{pj} was used.

For example,

$$t_{p1} = \frac{0{,}153}{0{,}020} = 7{,}709\#(40)$$

$$t_{p2} = 22{,}726;\ t_{p3} = 7{,}538; t_{p4} = 15{,}090;\ t_{\text{кр}} = 2{,}12$$

Since all calculated values are greater than the Student's t-test, all factors are significant.

To test the adequacy of the model, the value of S_{ad}^{2} was calculated.

$$S_{\text{ад}}^2 = \frac{5 * 0{,}143}{16 - (4 + 1)} = 0{,}052\ \#(41)$$

$$F_p = \frac{0{,}052}{0{,}032} = 1{,}646\ \#(42)$$

To determine F_{cr} calculated $\vartheta_1 = N - (k + 1) = 16 - (3 + 1) = 12$and $\vartheta_2 = N * (M - 1) = 16 * (5 - 1) = 64$, therefore, $F_{cr} = 1.92$.

Since $F_p > F_{cr}$, then it can be stated that the model is adequate [14].

After statistical analysis, factor models were constructed for average queue length, occupancy rate and average waiting time (51, 52 and 53 respectively).

$$\hat{y}_{\text{icдо}} = 2{,}462 + 0{,}623x_1 - 0{,}799x_2 + 0{,}541x_3 + 0{,}508x_4\ \ \#(43)$$

$$\hat{y}_{\text{icво}} = 0{,}914 + 0{,}153x_1 - 0{,}452x_2 + 0{,}150x_3 + 0{,}300x_4\ \ \#(44)$$

All models were also tested for test stability, factor significance, and model adequacy.

All models are stable.

In both models, all criteria are significant.

All models are adequate.

To test the construction of the simulation model, it was built in Matlab Simulink.

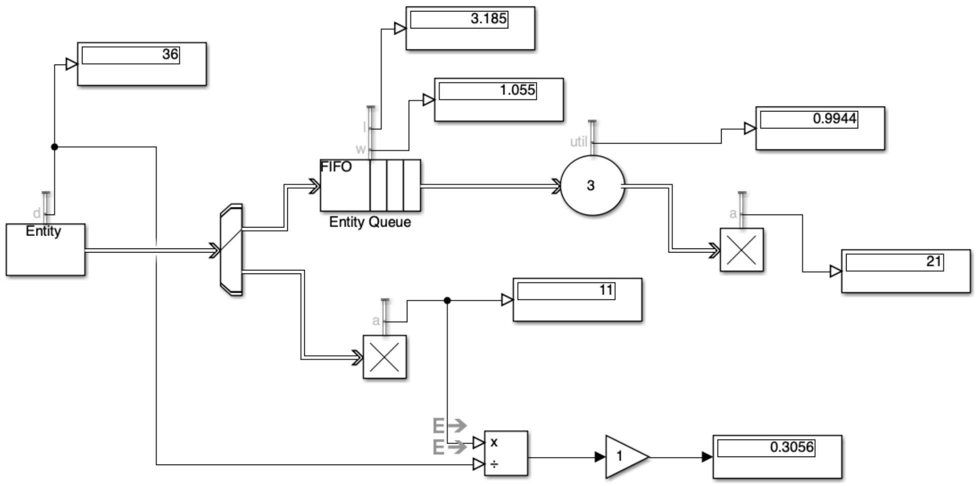

Figure 7 – **Simulation diagram**

For convenience, the data obtained from the two software products are presented in Table 11, and the deviation calculated in %.

Table 11 – Comparison of the obtained data

	Data from GPSS	Data from Simulink	Deviation
Number of applications received	**37**	**36**	**3%**
Average queue length	**3,214**	**3,185**	**1%**
Average waiting time	**0.918**	**1,055**	**15%**
Channel occupancy rate	**0.975**	**0.994**	**2%**
Number of failures	**9**	**11**	**22%**
Probability of failure	**0.243**	**0.306**	**26%**
Number of requests processed	**21**	**21**	**0%**

Table 11 shows that the maximum deviation of values from each other is 26%, which is within the acceptable limits.

Research results and their discussion. The conducted research allows us to draw the following conclusions: at the moment, the enterprise has quite a lot of orders, this can be judged by the channel occupancy rate of 0.975 and the probability of failure of 0.243. There are several options for changes to ensure the efficient operation of the enterprise.

The first option is to increase the number of service channels, i.e., install another concrete mixer. This change will not speed up concrete production, but 4 orders will be serviced at a time instead of 3. With n = 4, the probability of failure is 0.003, and the average queue length and average waiting time are 2.860 and 0.673, respectively.

The second option is to increase the number of concrete mixers (purchase a concrete mixer with a capacity of 6 cubic meters). Due to this, it is possible to reduce the service time of one order and increase the number of requests in the queue. Then the service time will be equal to 1.064 hours, the maximum number of requests in the queue will be 6. The probability of refusal will be 0.125, which is less than in the original system, the average queue length and average waiting time are 3.640 and 1.040.

Conclusion. By constructing forecast models, a point value of the volume of concrete produced for 2024 was obtained. The calculated value shows that the volume of concrete production will increase by 5%, and, consequently, the workload on departments will also increase.

Using the simulation modeling method, an analysis of the delivery department's operation as a mass service system was conducted. It was found that the system is currently operating in an overloaded mode, so recommendations were developed to improve efficiency.

In order to rationally distribute human resources, using simulation modeling of the delivery department as a mass service system, recommendations were developed: purchase of new equipment - a new concrete mixer or a new concrete truck.

The presented methods can be used to analyze any system represented as a QMS. For example, they can be adapted for a system for monitoring the concentration of toxic and flammable gases for coal mines [15].

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