Research and Development of an Algorithm for Solving the Problem of Control over the Input–Output Material Flows of an Industrial Company

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Abstract. A discussion is given of a universal mathematical economic model designed to find optimal strategies for controlling the production and logistics subsystems (subsystem components) of a company. The declared universal character of the model allows a systematic consideration of both production components, including constraints associated with how raw materials and components are converted into goods for sale, and resource-based and logical constraints on input–output material flows. The model and the generated control problems are developed within a single approach allowing the implementation of logical conditions of any complexity and the formulation of the corresponding formal optimization problems. An explanation is provided for the meaning behind the criteria and constraints. An approximate polynomial algorithm is proposed for solving the formulated mixed programming optimization problems of actual dimension. The results are presented of testing the algorithm for problem instances over a wide range of dimensions.

Keywords: Discrete optimization problems · Mixed integer linear programming · Production, supply, and sales control · Discount functions · Efficient algorithm.

1 Introduction

The aim of this work is to solve one of the problems associated with control over production and economic systems and processes. Within its framework, we developed a model and an algorithm, based on mathematical programming methods, for synthesizing optimal solutions. Studies like this one most often focus on specific topics (problems): location, supplier selection [1], job assignment, inventory management, supply chain management, logistics [2, 3], and production [4]. In this work, we used a comprehensive system approach to optimize the control over the product line and material flows of an industrial company [5].

The composition of the product line depends on the specific weight of each product type in the total share of production and its profitability. A large product line allows

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the company to satisfy the various demands of customers and, thus, increase the output and sales. To maximize profits, however, managers must make sure that the product line composition is rational. They should assess the relevance of the product program in terms of economic efficiency as early as during the development of the program. It should be noted that there is no generally accepted methodology for determining an optimal product line for an industrial company. We analyzed the literature on this subject, from which we elicited a few approaches to product line determination and optimization. One can speak only of calculation systems/techniques designed and applied by industrial companies or researchers on a case-by-case basis, depending on a specific problem. Therefore, it would be irrational to widely apply these individual techniques.

At present, optimization problems are widely used in the various areas of production [6]. In [7], e.g., a process is described for finding a solution to the problem of multi-objective optimization of material traffic in a logistics network by means of a control system based on fuzzy logic as well as the simulated annealing methodology and a genetic algorithm.

In [8], the authors point out the relevance of studying supply chain optimization—in today's competitive and flexible environment, companies need effective planning that is based primarily on modern technology and calculations. One such technology is dynamic modeling tools, i.e., discrete-event simulation (DES).

The multi-objective optimization problem as applied to supplier selection and the order release mechanism has long been the focus of research for a team of scientists from Youngstown State University in the United States [9, 10]. They consider one of the alternative decision support systems with several criteria, i.e., visual interactive goal programming (VIG).

Researchers from Sweden [11] focus on production logistics optimization, which is also relevant for Russian companies. They discuss the results of the combined use of DES and simulation-based multi-objective optimization (SBO) for analysis and improvement of logistics and production systems.

2 Conceptual Problem Statement

Control actions: selection of suppliers, determination of amounts of procurement for all items in the product line, transportation, production, storage, and sales [5, 12, 13].

Production and economic activity features considered in the model: the high unit price for all items in the product line (e.g., electronic chips, plant seeds, or jewelry; this condition has no substantial effect on the structure of the formal model); relatively small supply by volume; in-house production is considered in the general scheme as in-house supply. Transportation costs are considered insignificant. Remoteness of suppliers affects only the time of delivery, which is compensated by a necessary amount of stocks in the warehouse. Supply conditions can be considered significant if they are characterized by wholesale discounts, whose dependence on the amounts of supply by value is shown in Fig. 1.

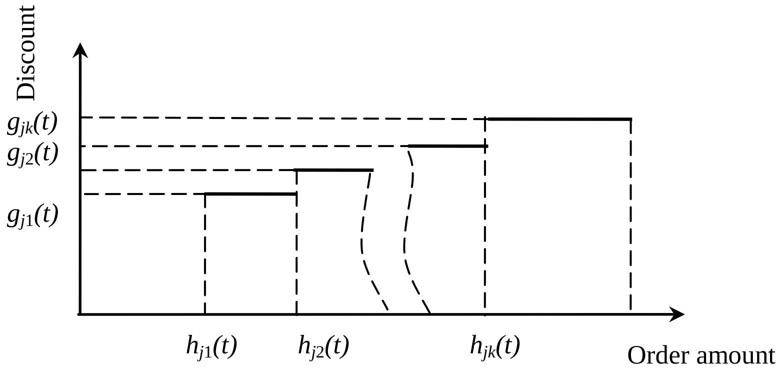

Fig. 1. Product supply conditions.

Here and below, wavy dashed lines show breaks in the plots.

The dependence of the supplier prices on sales is presented in Fig. 2.

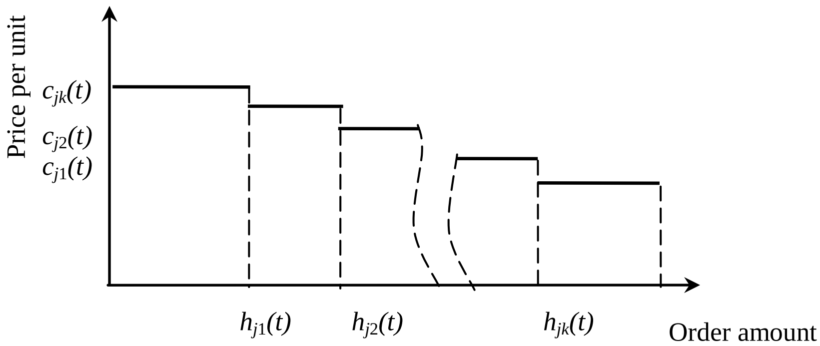

Fig. 2. Dependence of the unit price on the order amount.

The most important factor in the model is demand. In the worst-case scenario, there is only an average demand forecast estimate; in the best-case one, there is a forecast of the demand function for all the items in the product line. The demand function for each product item may look as in Fig. 3.

Another feature is the presence of several consumers groups (wholesale and retail customers, persons entitled to privileges, and holders of discount cards).

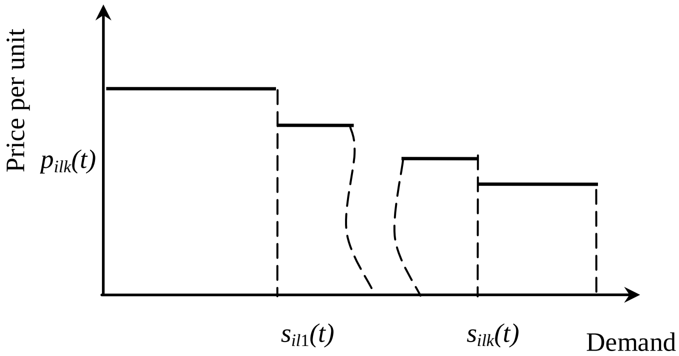

Fig. 3. Product supply conditions.

Considering the above circumstances, the control problem can be formulated as follows.

It is necessary to devise such a procurement strategy (select suppliers and supply amounts, in view of the discounts) and such a sales price policy by consumer group that maximize the criterion (the net income or working capital at the end of the planning period) under constraints on the working capital at the beginning of the period and on the warehouse capacity. The term procurement strategy means a set of planned amounts of procurement for the entire product line, including the selected prices and discounts from all potential suppliers; the amounts are determined for each time interval within the planning period. The term sales strategy means a set of planned amounts of sales for the entire product line to all consumers groups; the amounts are determined from demand data for each time interval within the planning period.

The constraints of the problem are logical conditions that consider changes over time in the discounts associated with procurement and sales [5] as well as in consumer demand and in the company's warehouse and production capacities and financial capabilities [12].

It should also be noted that the production cycle in the case under consideration is much shorter than any interval of the planning period.

3 Formal Statement

We use the following notation:

t is the number of the time interval used as a measure of discreteness when determining the simulation time (hereinafter, the month number);

j is the supplier number ($j=\overline{1,J}$); i is the product number in the supply product line ($i=\overline{1,I}$); l is the consumer type index ($l=\overline{1,L}$); k is the number of the interval on the discount ($k=\overline{1,K}$) and demand ($k=\overline{1,K'}$) scales;

$y_{ij}(t)$ is the amount of procurement of product i by volume from supplier j in month t;

$O_i(t)$ is the stock of product i in the warehouse at the beginning of month t;

$C_{ij}(t)$ is the base wholesale price of product i from supplier j in month t;

$d_j(t)$ is the amount of procurement by value from supplier j in month t at the base price (without discounts);

$h_{jk}(t)$ is the right boundary of interval k on the scale of discounts given by supplier j in month t;

$g_{jk}(t)$ is the discount given by supplier j in month t in interval k on the corresponding scale (in percentage);

$w_{jk}(t)$ is an indicator that a given amount of procurement falls within interval k on the scale of the discounts given by supplier j in month t;

$x_{ilk}(t)$ is the amount of sales of product i by volume to a consumer of type l in month t in interval k on the demand-function scale;

$p_{ilk}(t)$ is the unit price of product i for a consumer of type l in month t in interval z of the demand function;

$Q(t)$ is the size of working capital in month t;

$N(t)$ is the wages and overheads in month t;

$s_{ilk}(t)$ is the right boundary of interval k on the scale of the demand function for product i by a consumer of type l in month t.

A mathematical economic model (MEM) for optimal control over the supply and sales of inhomogeneous products manufactured by a company is as follows:

$$\sum_{i=1}^{I} C_{ij}(t) y_{ij}(t) = d_j(t), \quad j=\overline{1,J}, \; t=\overline{1,T}; \tag{1}$$

$$d_j(t) - h_{jk}(t) w_{jk}(t) \ge 0, \quad j=\overline{1,J}, \; t=\overline{1,T}; \tag{2}$$

$$0 \le w_{jk}(t) \le 1, \; w_{jk}(t) \text{ are integer numbers;} \tag{3}$$

$$y_{ij}(t) \ge 0, \; i=\overline{1,I} \;\; j=\overline{1,J}, \; t=\overline{1,T}, \; k=\overline{1,K}; \tag{4}$$

$$\sum_{j=1}^{J} [d_j(t) - d_j(t) \sum_{k=1}^{K} g_{jk}(t) w_{jk}(t)] \le Q(t), \; t=\overline{1,T}, \tag{5}$$

$$\text{where } g_{jk}(t) = \begin{cases} g_{j1}(t) \text{ if } d_j(t) \le h_{j1}(t), \\ g_{j2}(t) \text{ if } h_{j1}(t) < d_j(t) \le h_{j2}(t), \\ \dots \\ g_{jK}(t) \text{ if } d_j(t) > h_{jK}(t), \end{cases} \quad j=\overline{1,J}, \; t=\overline{1,T}; \tag{6}$$

$$x_{il1}(t) \le s_{il1}(t),\ i = \overline{1,I},\ l = \overline{1,L},\ t = \overline{1,T}; \tag{7}$$

$$x_{ilk}(t) \le s_{ilk}(t) - \sum_{k'=1}^{k-1} x_{ilk'}(t),\ i = \overline{1,I},\ l = \overline{1,L},\ k = \overline{1,K},\ t = \overline{1,T}; \tag{8}$$

$$\sum_{j=1}^{J} y_{ij}(t) + O_i(t-1) \ge \sum_{l=1}^{L}\sum_{k=1}^{K} x_{ilk}(t),\ i = \overline{1,I},\ t = \overline{1,T}; \tag{9}$$

$$O_i(t) = \sum_{j=1}^{J} y_{ij}(t) + O_i(t-1) - \sum_{l=1}^{L}\sum_{k=1}^{K} x_{ilk}(t),\ i = \overline{1,I},\ t = \overline{1,T}; \tag{10}$$

$$Q(t+1) = \sum_{i=1}^{I}\sum_{l=1}^{L}\sum_{k=1}^{K} p_{ilk}(t)x_{ilk}(t) - N(t) - \sum_{j=1}^{J}[d_j(t) - d_j(t)\sum_{k=1}^{K} g_{jk}(t)w_{jk}(t)],\ t = \overline{1,T}; \tag{11}$$

$$\sum_{t=2}^{T} \alpha(t)Q(t) \to \max \quad \text{provided that } 0 \le \alpha(t) \le 1, \sum_{t=2}^{T} \alpha(t) = 1; \tag{12}$$

$$Q(T) \to \max. \tag{13}$$

Relations (1) define the amount of procurement by value, ignoring the discounts, in month t from supplier *j*; relations (2) and (3) are logical constraints on the presence of discounts and on their size; (4) are constraints on the amount of procurement by value, considering the discounts, in month t from all the suppliers; (5) and (6) are demand constraints for each product for all types of consumers in month t. Relations (7) are logical constraints: the total amounts of procurement and stock in the warehouse for each product item in each month must not be lower than the corresponding amounts of sales. Relations (8) define the time changes in the warehouse stock for the entire product line; (9) define the time changes in net income; (10) is a criterial indicator of efficiency, meaning the time-weighted average of net income; (11) is a special case: the net income at the end of the planning period.

Since the problem under consideration includes the manufacturing component of the process, the above constraints can be supplemented by another one, i.e., on the ways to transform raw materials and components Y into goods for sale X:

$$X = A \times Y, \tag{14}$$

where *A* is the tensor of technological coefficients. It should be noted that although we calculate several output values (considering consumer types and discount scales) for each output good, the calculations for all these values use the same coefficients of the *A* tensor for this good. This is reflected in the following group of constraints:

$$\sum_{k=1}^{K'}\sum_{l=1}^{L} x_{ilk}(t) = \sum_{v=1}^{I}\left[A_{vi}(t)\sum_{j=1}^{J} y_{ij}(t)\right], i = \overline{1,I}, t = \overline{1,T}. \tag{15}$$

4 Estimating the Potential Complexity of Solving the Optimization Problem Instances

We assume that $a_{ij} \in A, \forall i = \overline{1.I}, j = \overline{1, J}$ is an element of a continuous set A. We use the following notation: $M(a_{ij}) = I \times J$ is the number of elements in the set A; M_{cont} is the number of continuous variables; M_{int} is the number of integer variables; and M_{constr} is the number of constraints in the model.

Let us consider a typical example of applying model (1)–(13) with the following parameters:

$I = 2000$ is the product line; $J = 10$ is the number of suppliers; $T = 3$ is the planning period; $K = 3$ is the number of intervals on the discount scale; $K' = 3$ is the number of intervals on the demand scale; and $L = 2$ is the number of types of consumers.

Then, if we leave out the constraints on continuous variables, we have

$M(y_{ij}(t)) = 60000$, $M(x_{ilk}(t)) = 36000$, $M(w_{jk}(t)) = 90$, $M_{\text{cont}} = M(y_{ij}(t)) + M(x_{ilk}(t)) = 96000, M_{\text{int}} = M(w_{jk}(t)) = 90, M_{constr} =$

$= 10 \cdot 3 + 10 \cdot 3 + 2000 \cdot 10 \cdot 3 + 3 + 2000 \cdot 2 \cdot 3 + 2000 \cdot 2 \cdot 3 \cdot 3 + 2000 \cdot 3 + 2000 \cdot 3 + 2000 \cdot 3 = 126063$.

The number M_{constr} is formed by those constraints that include the solution variables: (1), (2), and (3) for procurement-related variables; (4)–(8) and (13).

$M(y_{ij}(t))$ is the maximum possible estimate. If there is no complete intersection of the suppliers' product lines, the estimate will be lower.

Thus, an order-of-magnitude estimate for the number of dimensions and, hence, for the complexity of a control problem with parameters as close as possible to actual ones is as follows: 10^4 continuous variables and 10^2 integer variables. Moreover, the model contains nonlinear constraints (4) and (9) and a nonlinear objective function (10)–(11).

It also follows directly from the problem statement that the problem belongs to the class of NLP and MIP with potential NP-hardness.

5 Approximate Algorithm for Solving the Problem of Optimal Control over Supply, Production, and Sales

As noted above, if we ignore the specific features of the problem statement, problem (1)–(13) of any actual dimension is, at given parameters of computational complexity, formally unsolvable by known methods. To solve this problem, we construct an algorithm best tailored to the specific features of the problem. Note that all the discount functions $g_{jk}(t)$ are nondecreasing ones; hence, all the functions of wholesale prices and demand are nonincreasing ones. In view of these circumstances, we propose the following algorithm to search for an optimal solution of problem (1)–(13):

Preliminary Step. We define the relaxed problem for (1)–(13) as follows. We select any $\tilde{g}_j(t) \in \{g_{jk}(t)\}$, $j=\overline{1,J}$, $t=\overline{1,T}$, and form on the basis of problem (1)–(13) a linear subproblem:

$\sum_{i=1}^{I} C_{ij}(t)y_{ij}(t) = d_j(t)$, $j=\overline{1,J}$, $t=\overline{1,T}$, $\sum_{j=1}^{J}[d_j(t)-d_j(t)\tilde{g}_j(t)] \le Q(t)$, $t=\overline{1,T}$, or

$$\sum_{j=1}^{J}\sum_{i=1}^{I} C_{ij}(t)y_{ij}(t)[1-\tilde{g}_j(t)] \le Q(t)\,,\ t=\overline{1,T}\ ; \tag{16}$$

$$y_{ij}(t) \ge 0\,,\ i=\overline{1,I}\,,\ j=\overline{1,J}\,, t=\overline{1,T}\ ; \tag{17}$$

$$x_{il1}(t) \le s_{il1}(t)\,,\ i=\overline{1,I}\,, l=\overline{1,L}\,, t=\overline{1,T}\ ; \tag{18}$$

$$x_{ilk}(t) \le s_{ilk}(t) - \sum_{k'=1}^{k-1} x_{ilk'}(t)\,,\ i=\overline{1,I}\,, l=\overline{1,L}\,,\ k=\overline{1,K}\,, t=\overline{1,T}\ ; \tag{19}$$

$$\sum_{j=1}^{J} y_{ij}(t) + O_i(t-1) \ge \sum_{l=1}^{L}\sum_{k=1}^{K} x_{ilk}(t)\,,\ i=\overline{1,I}\,,\ t=\overline{1,T}\ ; \tag{20}$$

$$O_i(t) = \sum_{j=1}^{J} y_{ij}(t) + O_i(t-1) - \sum_{l=1}^{L}\sum_{k=1}^{K} x_{ilk}(t)\,, i=\overline{1,I}\,,\ t=\overline{1,T}\ ; \tag{21}$$

$$\sum_{k=1}^{K'}\sum_{l=1}^{L} x_{ilk}(t) = \sum_{v=1}^{I}\left[A_{vi}(t)\sum_{j=1}^{J} y_{ij}(t)\right], i=\overline{1,I}, t=\overline{1,T}\ ; \tag{22}$$

$$Q(t+1) = \sum_{i=1}^{I}\sum_{l=1}^{L}\sum_{k=1}^{K} p_{ilk}(t)x_{ilk}(t) - N(t) - \sum_{i=1}^{I} C_{ij}(t)y_{ij}(t)[1-\tilde{g}_j(t)]\,,\ t=\overline{1,T}\ ; \tag{23}$$

$$z = \sum_{t=2}^{T}\alpha(t)Q(t) \to \max \ \text{ provided that } \ 0 \le \alpha(t) \le 1, \sum_{t=2}^{T}\alpha(t) = 1\text{, or}$$

$$Q(T) \to \max\ . \tag{24}$$

We now add new notation to that introduced above. Let n be the number of the step in the algorithm. We denote as Y^n, X^n and z^n the solution of the relaxation problem at step n (the amounts of procurement and sales and the value of the efficiency criterion). We denote as G^n the set of intervals of discounts at step n ($\|\tilde{g}_j(t)\|$). Below we give a stepwise representation of the algorithm for solving the problem.

Step One. We assume that $\tilde{g}_j(t) = \max_k\{g_{jk}(t)\} = g_{jK}(t)$, $j=\overline{1,J}$, $t=\overline{1,T}$ and make up the relaxed subproblem (14)–(22). We denote its solution as Y^0, X^0, z^0. ($Y^0 = \|y_{ij}^0(t)\|$, $X^0 = \|x_{ilk}^0(t)\|$, $z^0 = z(X^0, Y^0)$) We determine the matrix identity: $\|\tilde{g}_j(t)\| = G^0$.

Step n. Based on the solution obtained at the previous step, i.e., $Y^{n-1}, X^{n-1}, z^{n-1}$ at G^{n-1}, we determine the new values of $\left\|\tilde{g}_j(t)\right\|$:

$$\tilde{g}_j(t) = \begin{cases} g_j^{n-1}(t) & \text{if } y_{ij}^{n-1}(t) = 0 \\ g_{jk}^{+}(t) & \text{if } y_{ij}^{n-1}(t) > 0 \end{cases}, \text{ where } g_{jk}^{+}(t) = \begin{cases} g_{j1}(t) \text{ if } d_j(\text{t}) \le h_{j1}(t), \\ g_{j2}(t) \text{ if } h_{j1}(t) < d_j(\text{t}) \le h_{j2}(t), \\ \dots \\ g_{jK}(t) \text{ if } d_j(\text{t}) > h_{jK}(t), \end{cases} \text{ and}$$

$$d_j(t) = \sum_{i=1}^{I} C_{ij}(t) y_{ij}^{n-1}(t), \ j = \overline{1,J}, \ t = \overline{1,T}.$$

Using the implementation of the barrier algorithm in the IBM ILOG CPLEX optimization studio [13], the main computing tool in the software implementation of the algorithm, we solve problem (14)–(22), find new values of Y^n, X^n, z^n, and check them for optimality. If $\left|z^n - z^{n-1}\right| \le \varepsilon$ is a small number setting the calculation accuracy), then we have obtained at this step an optimal solution of (1)–(13). If the condition is not satisfied, we proceed to the next step (n+1), determining the new values of $\left\|\tilde{g}_j(t)\right\|$ from Y^n.

It is obvious that the algorithm converges in a finite number of steps, which cannot be greater than $J \cdot K \cdot T$. This is due to the specific features of the discount functions $g_{jk}(t)$. In our example, $J \cdot K \cdot T$ = 90. However, a statistical estimate for the number of steps in this example for varying initial data is 5.

Thus, the proposed algorithm converts problem (1)–(13) into a polynomially solvable one with respect to dimension. If we use this algorithm, problem (1)–(13) falls into another class of (linear) models with an ordinal number of continuous variables of 10^4 and a complete absence of integer variables [13].

6 Results and Discussion

The universal character of the model, the algorithm, and the implementation software with respect to the types of enterprises is achieved through the tensor of technological coefficients, which determines the ways of converting raw materials and components into goods for sale and participates in a group of constraints (12)–(13) of the problem. The technological coefficients in the tests are nonnegative. They were generated in the range from 0 to 1 for a general instance of the problem of managing a trading and manufacturing company.

Table 1 shows the input parameters and the program results for each of the tests, which are displayed in the table rows. The right-hand side of the table contains the input dimensions, i.e., the following numbers for a given case (test): items in the suppliers' product line (I), consumer-type indices (L), suppliers (J), intervals on the discount (K) and demand (K1) scales, and time intervals (T). The second part of Table 1 shows the resulting indicators, such as the time of execution of the program (in seconds and fractions of a second), the number of steps in which the problem was solved (q), and the number of constraints in the problem.

The columns Number of Continuous Variables and Number of Boolean Variables show the number of variables that participate in solving the problem. These include all the tensor components $y_{ij}(t)$, $x_{ilk}(t)$, and $w_{jk}(t)$, considering their differences for each of the time intervals.

The column Number of Constraints shows the number of problem constraints, which depends on the input values of the variables. The number of constraints was calculated in the same way as the indicator M_{constr} in the section Estimating the Complexity of the Model, i.e., by considering constraints (1)–(3) for the procurement-related variables, (4)–(8), and (13).

Table 1. Results of testing the program given the presence of in-house production

No.	I (product types)	L (consumer types)	J (suppliers)	K (intervals on the discount scale)	K1 (intervals on the demand scale)	T (months)	Computing time (seconds)	q (steps)	Number of continuous variables	Number of Boolean variables	Number of constraints
1	10	5	10	4	3	6	4.25	5	1500	240	2046
2	10	5	10	5	4	6	4.77	5	1800	300	1656
3	7	4	4	4	3	6	2.59	3	672	96	1020
4	7	4	4	5	4	6	2.8	3	840	120	1188
5	6	3	3	4	3	6	2.69	3	432	72	690
6	6	3	3	5	4	6	3.28	4	540	90	798
7	10	5	10	3	2	6	4.78	5	1200	180	1806

This testing section shows three blocks of tests, each including the same I, L, and J indicators and two different tests for different K and K1. The planning period was the same for all the tests in this section. One can see how the time increases linearly for tests of higher dimension, i.e., with larger K and K1 in the rows with the same I, L, and J, which confirms the efficiency of the algorithm. The number of steps in the tests of higher dimension is greater than or equal to that in the corresponding pairwise tests of lower dimension.

7 Conclusions

The initial problem of control over the external material flows of a company was examined and supplemented with a production component. A program was developed that implements the modified algorithm, and the relevant tests were performed. As a result, a new decision support tool was obtained.

Thus, this program can be successfully applied to problems of actual dimension that arise in the production sector, in terms of applying MEMs to company logistics, and can provide support of decision-making in the planning of procurement, production, and sales, from the perspective of maximization of working capital balances. According to expert estimates, the potential for improving the performance in the search for the best solutions to logistics problems is on average 30% or higher [14, 15].

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