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In 2020, the International Center for Periodicals (ISSN International Center, Paris) included the Electronic Scientific and Practical Edition "Intellectualization of Supply Chain Management" in the international register of periodicals and provided it with a numerical code of international identification: ISSN 2708-3195 (Online).

Recommended for dissemination on the Internet by the Academic Council of the Department of Logistics NAU (No. 7 of February 26, 2020). Released 6 times a year. Editions references are required. The view of the editorial board does not always coincide with that of the authors.

DOI: https://doi.org/10.46783/smart-scm/2020-3
e-mail: support@smart-scm.org

t.me/smart_scm
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тел.: (063) 593-30-41
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INTELLECTUALIZATION OF A METHOD FOR SOLVING A LOGISTICS PROBLEM TO OPTIMIZE COSTS WITHIN THE FRAMEWORK OF LEAN PRODUCTION TECHNOLOGY

Eugene Fedorov, Peter Nikolyuk, Olga Nechporenko, Esta Chioma. “Intellectualization of a method for solving a logistics problem to optimize costs within the framework of Lean Production technology”. In the article, within the framework of intellectualization of the Lean Production technology, it is proposed to optimize the costs arising from the insufficient efficiency of placing goods in the warehouse by creating an optimization method based on the immune metaheuristics of the T-cell model, which allows solving the knapsack constrained optimization problem. The proposed metaheuristic method does not require specifying the probability of mutation, the number of mutations, the number of selected new cells and allows using only binary potential solutions, which makes discrete optimization possible and reduces computational complexity by preventing permanent transformations of real potential solutions into intermediate binary ones.
and vice versa. An immune metaheuristic algorithm based on the T-cell model has been created, intended for implementation on the GPU using the CUDA parallel information processing technology. The proposed optimization method based on immune metaheuristics can be used to intellectualize the Lean Production technology. The prospects for further researches are to test the proposed methods on a wider set of test databases.

**Keywords:** lean manufacturing, immune metaheuristics, T-cell model, conditional optimization, knapsack problem.

Introduction. At present many worldwide companies are optimizing their business processes based on Lean Production technology. The concept of Lean Production is that it clearly identifies seven groups of costs that do not create value for final buyers, and therefore, the primary efforts of any company should be directed to minimizing these costs. However, the problem of finding models to minimize these costs is quite...
complicated and requires searching for the new solutions. As a result, the relevance of the development of methods for the intellectualization of Lean Production technology, which is based on the solution of optimization problems, significantly increases.

**Literature and research review.** Highly computationally complex optimization methods that find an accurate solution. Optimization methods that find an approximate solution through directional search have a high probability of hitting a local extremum. Random search methods do not guarantee convergence. Consequently, there is a problem of insufficient efficiency of optimization methods, which needs to be addressed.

Metaheuristics (or modern heuristics) [2-5] are used to find an accelerate quasi-optimal solution optimization problems and reduce the probability of hitting a local extremum. Metaheuristics empowered of heuristics by combining heuristic methods based on a high-level strategy [6-9].

The current metaheuristics have one or more of the following disadvantages:

- there is only an abstract description of the method or the description of the method is focused on solving only a certain problem [10];
- the influence of the iteration number on the process of finding a solution is not taken into account [11];
- the convergence of the method is not guaranteed [12];
- it is not possible to use non-binary potential solutions [13];
- the procedure for determining the values of parameters is not automated [14];
- it is not possible to solve the problems of conditional optimization [15];
- the lack of accuracy of the method [16].

In this regard, the problem of constructing effective metaheuristic optimization methods arises [17].

One of the popular metaheuristics are immune metaheuristics [18, 19], among which the T-cell model [20] can be distinguished, which allows solving constrained optimization problems.

**Aims and Objectives.** The aim of the work is to optimize the costs arising from the insufficient efficiency of placing goods in the warehouse by creating an optimization method based on immune metaheuristics that solves the knapsack problem.

To achieve the goal, the following tasks were put and decided:

1. Conduct an analysis of existing optimization methods aimed at optimizing costs within the framework of lean manufacturing technology.
2. Create an immune metaheuristic method based on the T-cell model for solving the knapsack problem.
3. Create an algorithm of the immune metaheuristic method based on the T-cell model, intended for implementation on the GPU using the CUDA technology.
4. Conduct a numerical study.

**Results, analysis, and discussion.** Optimization of costs associated with inefficient placement of goods in a warehouse can be reduced to the problem of a knapsack. To solve this problem, the work proposes an immune metaheuristic - a modified model of T cells that uses imitation of annealing.

As a function of the goal $F$, it is proposed to use the inverse function of income

$$F(x) = \left( \sum_{j=1}^{M} v_j x_j \right)^{-1} \rightarrow \min_x$$

where $v_j$ is the income from the goods of the $j$-th type, defined,

$w_j$ – weight of goods of the $j$-th type, defined,

$x_j$ – goods presence of the $j$-th type (corresponds to the T-cell),

$M$ – the number of types of goods.
As a limit, it is proposed to use the following function:

1. Cells initialization

2. Creation of a subpopulation of new cells

3. Calculating the dynamic tolerance value for a subpopulation of new cells

4. Creation of a subpopulation of executive cells

5. Modification of a subpopulation of executive cells based on mutation

6. Calculation of the dynamic tolerance value for a subpopulation of executive cells

7. Creation of a subpopulation of memory cells

8. Modification of a subpopulation of memory cells based on mutation

9. Streamlining the subpopulation of memory cells

10. Determining of the global best cell

11. Stop condition
Figure 1 – The structure of the proposed immune metaheuristic method for solving the knapsack problem

\[ g(x) = \max \left\{ 0, \sum_{j=1}^{M} w_j x_j - W \right\} \]

where \( W \) – is the maximum total weight of all goods, defined.

The structure of the proposed immune metaheuristic method is shown in Fig. 1.

The proposed metaheuristic method makes possible to find the quasi-optimal number of placed goods and consists of the following blocks:

Block 1 - Initialization:
- setting the number of the current iteration \( n \) to one;
- setting the number of iterations \( N \);
- setting the cell length \( M \);
- setting the size of the subpopulation of new cells \( L_v \);
- setting the number of selected new cells, taking into account the restrictions \( L_{1v} \) as \( L_{1v} = L_v / 4 \);
- setting the number of selected new cells without taking into account the restrictions \( L_{2v} \) as \( L_{2v} = L_v / 4 \);
- setting the number of mutations of each executive cell \( N_E \) as \( N_E = N \);
- setting the size of the subpopulation of memory cells \( L_M \) as \( L_M = L_v / 4 \);
- setting the number of mutations of each memory cell \( N_M \) as \( N_M = N \);
- setting a static tolerance \( \Delta_M \) for a subpopulation of memory cells;
- setting the probability of mutation of executive cells as \( p^E = \frac{1}{M} \);

- setting the probability of mutation of memory cells as \( p^M = \frac{1}{M} \);
- randomly create the best cell \( x^* \)
  \[ x^* = (x_1^*, \ldots, x_M^*) \]
  \[ x_j^* = \begin{cases} 1, & U(0,1) < 0.5 \\ 0, & U(0,1) \geq 0.5 \end{cases} \]

where \( U(0,1) \) – is a function that returns a uniformly distributed random number in the range of \([0,1]\).

Block 2 – Creation of a subpopulation of new cells \( P^V \)
\[ P^V = \{ (x_k, s_k) \} , \quad k \in 1, L_v \]
\[ x_k = (x_{k1}, \ldots, x_{kM}) \]
\[ x_{kj} = \begin{cases} 1, & U(0,1) < 0.5 \\ 0, & U(0,1) \geq 0.5 \end{cases} \]
\[ s_k = \max \{ 0, g(x_k) \} \]

Block 3 – Calculation of the dynamic tolerance value \( \Delta_v \) for a subpopulation \( P^V \)
\[ \Delta_v = \frac{1}{L_v} \sum_{k=1}^{L_v} s_k \]
If \( \Delta_v < \Delta_M \), then \( \Delta_v = 0.1 \)

Block 4 – Creation of a subpopulation of executive cells \( P^E \) with capacity \( L_E \)
4.1. Dividing a subpopulation of new cells \( P^V \) into a subset \( P_1^V = \{ (x_{1k}, s_{1k}) \} \)
containing cells for which \( s_{1k} < \Delta_v \), and a subset \( P_2^V = \{ (x_{2k}, s_{2k}) \} \)
containing cells for which \( s_{2k} \geq \Delta_v \).

4.2. Ordering the subset \( P_1^V \) by target function, i.e.
\[ F(x_{1k}) < F(x_{1_{k+1}}) \]
4.3. Ordering the set $P_2^V$ by the sum of the values of all bounding functions, i.e. $s_2^k < s_2^{k+1}$

4.4. $L_1^V$ of the first cells from an ordered set $P_1^V$ and $L_2^V$, the first cells from an ordered set $P_2^V$ forms a subpopulation of executive cells $P^E = \{(x_i, s_i)\}$ with capacity $L_E = L_1^V + L_2^V$, while the first there are cells from the set $P_1^V$

Block 5 – Modification of a subpopulation of executive cells $P^E$ based on mutation

For each $i$ - th cell is performed $N_E$, once as the following operations are performed:

- mutation $r = U(0,1)$

$$\tilde{x}_{ij} = \begin{cases} 1, & (r < p^E \land x_{ij} = 0) \lor (r \geq p^E \land x_{ij} = 1) \\ 0, & (r < p^E \land x_{ij} = 1) \lor (r \geq p^E \land x_{ij} = 0) \end{cases}, \ j \in 1, M$$

where $\text{round}(\cdot)$ – is the function that rounds the number to the nearest integer.

- calculating the value of the constraint function

$$\hat{s}_i = \max \{0, g(\tilde{x}_i)\}$$

- replacement by a mutant cell if the condition is met

If $\hat{s}_i < s_i$ or $\hat{s}_i = s_i \land F(\tilde{x}_i) \leq F(x_i)$,

then $x_i = \tilde{x}_i$, $s_i = \hat{s}_i$

Block 6 - Calculate the value of the dynamic tolerance $\Delta_E$ for a subpopulation $P^E$

$$\Delta_E = \frac{1}{L_E} \sum_{k=1}^{L_E} s_k$$

If $\Delta_E < \Delta_M$, then $\Delta_E = \Delta_M$

Block 7 - Creation of a subpopulation of memory cells $P^M$ with capacity $L_M$

7.1. Dividing the subpopulation of executive cells $P^E$ into a subset $P_1^E = \{(x_{1k}, s_{1k})\}$, containing cells for which $s_{1k} < \Delta_E$, and subset $P_2^E = \{(x_{2k}, s_{2k})\}$, containing cells for which $s_{2k} \geq \Delta_E$

7.2. Ordering the subset $P_1^E$ by target function, i.e. $F(x_{1k}) < F(x_{1k+1})$

7.3. Ordering the set $P_2^E$ by the sum of the values of all bounding functions, i.e. $s_{2k} < s_{2k+1}$

7.4. If $n = 1$, then $L_M$ the first cells from the ordered union $P_1^E \cup P_2^E$ form a subpopulation of executive cells $P^M = \{(x_i, s_i)\}$

If $n > 1$, then $L_M/2$ the first cells from the ordered union $P_1^E \cup P_2^E$ are replaced $L_M/2$ by the worst (last) cells, a subpopulation of executive cells $P^M$

Block 8 - Modification of a subpopulation of memory cells $P^M$ based on mutation

For each $i$ - th cell is performed $N_M$, once as the following operations are performed:

- mutation $r = U(0,1)$,
\[ \tilde{x}_{ij} = \begin{cases} 1, & (r < p^M \wedge x_{ij} = 0) \vee (r \geq p^M \wedge x_{ij} = 1) \\ 0, & (r < p^M \wedge x_{ij} = 1) \vee (r \geq p^M \wedge x_{ij} = 0) \end{cases}, \quad j \in 1, M \]

- calculating the value of the constraint function
  \[ \tilde{s}_i = \max \{0, g_2(\tilde{x}_i)\} \]
- replacement by a mutant cell if the condition is met
  \[ x_i = \tilde{x}_i, \quad s_i = \tilde{s}_i \]

**Block 9** - Ordering the subpopulation of memory cells \( P^M \)

Dividing the subpopulation of memory cells \( P^M \) into a subset \( P^M_1 = \{(x_{1k}, s_{1k})\} \)
containing cells for which \( s_{1k} < \Delta_M \), and a subset \( P^M_2 = \{(x_{2k}, s_{2k})\} \) containing cells for which \( s_{2k} \geq \Delta_M \).

9.2. Ordering the subset \( P^M_1 \) by target function, i.e.
\[ F(x_{1k}) < F(x_{1k+1}) \]
9.3. Ordering the set \( P^M_2 \) by the value of the bounding function, i.e.
\[ s_{2k} < s_{2k+1} \]
9.4. \( P^M = P^M_1 \cup P^M_2 = \{(x_i, s_i)\} \)

**Block 10** – Determining of the global best cell
If \( F(x_{1}) < F(x^*) \), then \( x^* = x_{1} \)

**Block 11** – Stop Condition
If \( n < N \), then increase the iteration number \( n \) by one and go to block 2.

For the proposed method, using the example of optimization of costs arising from insufficient efficiency of placing goods in a warehouse, an algorithm is considered intended for implementation on a GPU using the technology of parallel processing of information CUDA and shown in Fig. 2. This block diagram functions as follows.

**Step 1** – Operator’s input of the number of iterations \( N \), the cell length \( M \), the size of the subpopulation of new cells \( L^v \), the number of selected new cells taking into account the limitations \( L^1 \), the number of selected new cells without taking into account the limitations \( L^2 \), the number of mutations of each executive cell \( N^E \), the size of the subpopulation of memory cells \( L^M \), the number of mutations of each memory cell \( N^M \), static tolerance \( \Delta^M \) for a subpopulation of memory cells, the probability of mutation of executive cells \( p^E \), setting the probability of mutation of memory cells as \( p^M \).

**Step 2** – Randomly create the best cell \( x^* \)

**Step 3** – The creation of a subpopulation of new cells \( P^v \) using GPU threads \( L^v \) that are grouped into 1 block. Each thread randomly creates a cell \( x^*_k \) and calculates the value of the bounding function for this cell \( \tilde{s}_k \)

**Step 4** – Computation based on reduction of the dynamic tolerance \( \Delta^v \) value for the subpopulation \( P^v \) across all cells using GPU threads \( L^v \), which are grouped into 1 block. If \( \Delta^v < \Delta^M \), then \( \Delta^v = 0.1 \)

**Step 5** – Dividing the subpopulation of new cells \( P^v \) into a subset \( P^v_1 = \{(x_{1k}, s_{sk})\} \)
containing cells for which \( s_{1k} < \Delta^v \), and a subset \( P^v_2 = \{(x_{2k}, s_{2k})\} \) containing cells for which \( s_{2k} \geq \Delta^v \).

**Step 6** – Ordering the subset \( P^v_1 \) by target function, i.e. \( F(x_{1k}) < F(x_{1k+1}) \) using
GPU threads \(|P_1^V|\) which are grouped into 1 block

Step 7 – Ordering the subset \(P^2_V\) by the sum of the values of all bounding functions, i.e. \(s_k < s_{k+1}\) using GPU threads \(|P^2_V|\) which are grouped into 1 block

Step 8 – \(L_V\) first cells from the ordered set \(P_1^V\) and \(L_{2V}\) first cells from the ordered set \(P_2^V\) form a subpopulation of executive cells \(P^E = \{(x_i, s_i)\}\) with capacity \(L_E = L_1V + L_2V\), and the first cells from the set \(P_1^V\)

Figure 2 – Block diagram of the algorithm of the proposed immune metaheuristic method
Step 9 – Modification of a subpopulation of executive cells $P^E$ based on mutation using GPU threads $L_E$ that are grouped into 1 block. Each thread $N_E$ once mutates a cell $x_i$ and calculates the value of the limiting function for this cell $s_i$.

Step 10 – Reduction computation of the dynamic tolerance value $\Delta_E$ for the subpopulation $P^E$ across all cells using GPU threads $L_E$ that are grouped into 1 block. If $\Delta_E < \Delta_M$, then $\Delta_E = \Delta_M$.

Step 11 – Dividing the subpopulation of executive cells $P^E$ into a subset $P_1^E = \{(x_1^k, s_1^k)\}$ containing cells for which $s_1^k < \Delta_E$, and a subset $P_2^E = \{(x_2^k, s_2^k)\}$ containing cells for which $s_2^k \geq \Delta_E$.

Step 12 – Ordering the subset $P_1^E$ by target function i.e. $F(x_1^k) < F(x_1^{k+1})$ using GPU threads $|P_1^E|$ which are grouped into 1 block.

Step 13 – Ordering the set $P_2^E$ by the sum of the values of all bounding functions, i.e. $s_2^k < s_2^{k+1}$ using GPU threads $|P_2^E|$ which are grouped into 1 block.

Step 14 – If $n = 1$, then $L_M$ the first cells from the ordered union $P_1^E \cup P_2^E$ form a subpopulation of executive cells $P^M = \{(x_i, s_i)\}$, otherwise $L_M / 2$ first cells from the ordered union $P_1^E \cup P_2^E$ are replaced $L_M / 2$ the worst (last) cells, a subpopulation of executive cells $P^M$.

Step 15 – Modification of a subpopulation of memory cells $P^M$ based on the mutation using GPU threads $L_M$, which are grouped into 1 block. Each thread $N_M$ once mutates a cell $x_i$ and calculates the value of the limiting function for this cell $s_i$.

Step 16 – Dividing the subpopulation of memory cells $P^M$ into a subset $P_1^M = \{(x_1^k, s_1^k)\}$ containing cells for which $s_1^k < \Delta_M$, and a subset $P_2^M = \{(x_2^k, s_2^k)\}$ containing cells for which $s_2^k \geq \Delta_M$.

Step 17 – Ordering the subset $P_1^M$ by target function i.e. $F(x_1^k) < F(x_1^{k+1})$ using GPU threads $|P_1^M|$ which are grouped into 1 block.

Step 18 – Ordering the set $P_2^M$ by the value of the bounding function, i.e. $s_2^k < s_2^{k+1}$ using GPU threads $|P_2^M|$ which are grouped into 1 block.

Step 19 – Ordered sets $P_1^V$ and $P_2^V$ form a new subpopulation of memory cells $P^M$, i.e. $P^M = P_1^M \cup P_2^M = \{(x_i, s_i)\}$.

Step 20 – Determining the global best cell according to the following rule:

If $F(x_1) < F(x^*)$, then $x^* = x_1$.

Step 21 – Stop Condition.

If $n < N$, then increase the iteration number by one and go to step 4.

Step 22 – Writing the obtained global best position to the database.

In the work, the number of iterations $N = 100$, the size of the subpopulation of new cells $L_V = 100$, the number of selected new cells taking into account the constraints $L_1_V = L_V / 4 = 25$, the number of selected new cells without taking into account the constraints $L_2_V = L_V / 4 = 25$, the number of mutations of each executive cell $N_E = N = 100$, the size of the memory cell
subpopulation $L_M = \frac{L}{4} = 25$, the number of mutations of each memory cell $N_M = N = 100$, the static tolerance $\Delta_M = 0.0001$ for the memory cell subpopulation.

For the knapsack problem, the search for a solution was carried out on the standard KNAPSACK_01 databases. For the proposed method, a root-mean-square error of 0.02 was obtained.

The traditional method for optimizing a T-cell model requires:
- setting the probability of mutation, the number of mutations, the number of selected new cells;
- real potential solutions, which makes discrete optimization impossible;
- constant transformations of real potential solutions into intermediate binary ones and vice versa.

The proposed method eliminates these disadvantages.

Conclusions.

1. To minimize losses that do not create consumer value and are the basis of Lean Production technology, an immune metaheuristic method based on the T-cell model was developed to solve the knapsack problem. The use of this method is aimed at minimizing costs arising from insufficient efficiency of the placement of goods in the warehouse.

2. The proposed metaheuristic method does not require setting the probability of mutation, the number of mutations, the number of selected new cells and allows using only binary potential solutions, which makes discrete optimization possible and reduces computational complexity by preventing constant transformations of real potential solutions into intermediate binary ones and back.

3. There was created an immune metaheuristic algorithm based on the T-cell model, intended for implementation on a GPU using the CUDA parallel processing technology.

4. The proposed optimization method based on immune metaheuristics can be used to intellectualize the Lean Production technology. Prospects for further research are in testing the proposed methods on a wider set of test databases.

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