Available online at www.sciencedirect.com

ScienceDirect

IFAC PapersOnLine 54-1 (2021) 472–477

Developing and testing cutting map design of rectangular sheets through the "useless material" criterion

Dmitry A. Denisevich*, Anatoly I. Yakimov, Alla Yu. Vladova*****

**Belarusian-Russian University, 43 Mira Ave, Mogilev 212000, Belarus (e-mail: denis1351@yandex.ru)*

***Automated Control Systems Department, Belarusian-Russian University, Mogilev, Belarus (e-mail: ykm@tut.by)*

****V.A. Trapeznikov Institute of Control Sciences, 65 Profsoyuznaya, Moscow 117997, Russia (e-mail: vladova@ipu.ru)*

Abstract: The article is devoted to the design and development of an application for forming cutting maps and calculating the "useless material" criterion when cutting sheet materials into rectangular products. The created application performs a wide variety of calculations, for example, a total area of a workpiece, free space, cutting time, etc. The proposed application provides designers with a graphical model editor, and a model to text transformation, to generate the source code templates using javascript language.

Keywords: rational material cutting, construction of cutting maps, "useless material" criterion, application for designing cutting maps

INTRODUCTION

There are plenty of physical models and, corresponding to it, the mathematical models of the analyzed steel sheet being cut were elaborated. In (Kaczmarczyk and Grajcar, 2018) the relationship between the cutting depth and the values of reduced Huber–Mises stresses as well as the mechanism of sheet separation were presented. The numerical simulations were conducted using the finite element method and the computer system LS-DYNA. The results of numerical computations are juxtaposed as graphs, tables, and contour maps of sheet deformation as well as reduced Huber–Mises strains and stresses for selected time instants.

In (Celli P. et al., 2018) authors demonstrate that a non-periodic cut pattern can cause a sheet to buckle into three-dimensional shapes, such as domes or patterns of wrinkles, when pulled at specific boundary points. These global buckling modes are observed in experiments and rationalized by an in-plane kinematic analysis that highlights the role of the geometric frustration arising from non-periodicity.

(Yunqing, Dezhong & Jinling, 2013) presents an improved hierarchical genetic algorithm for sheet cutting problem which involves n cutting patterns for m non-identical parallel machines with process constraints has been proposed in the integrated cutting stock model. Furthermore, to speed up convergence rates and resolve local convergence issues, a kind of adaptive crossover probability and mutation probability is used.

The results show in (Song, C. et al., 2020) that compared with other methods, the optimal sheet-cutting strategy based on an improved real-coded genetic algorithm reduces the computational complexity and maintains high stability under the premise of high utilization, which is more appropriate for systems with various product types and quantity constraints.

One of the main tasks of the industry is to reduce production costs, including through the optimal use of materials and resources. Many industries require cutting sheet material. Wood, plastic, metal, glass, and other industrial materials go into production as whole units (objects). These materials must be cut out into pieces of certain sizes and shapes, while a significant part of the material goes to waste that is not used in production. The amount of waste makes up a substantial percentage, significantly affecting the overall budget of enterprises, because, in addition to direct costs for expensive materials, there are also minor ones, such as transportation, storage, and disposal.

This software toolkit aims at developing an application for computer-aided design of cutting maps and calculation of the "useless material" criterion. Based on the results of calculating the criterion, it is possible to analyze the effectiveness of the selected algorithm for building a cutting map.

The application is implemented using the JavaScript language. When developing the interface, the REACT library is used. The advantage of this presentation is that users do not depend on a specific operating system and also this application meets the requirements of data reliability and integrity.

1. DESIGN AND DEVELOPMENT OF APPLICATIONS

Application development is aimed at enterprises that manufacture products from sheet material in conditions with a single or small-scale type of production and is intended for design engineers, foremen of production sites for cutting sheet materials.

We described the stages of application development in a functional production model that has been built using the IDEF0 methodology (Fig. 1).

10.1016/j.ifacol.2021.08.165

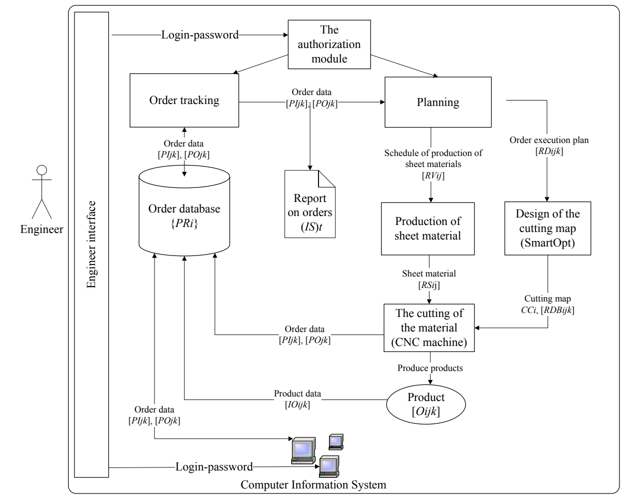
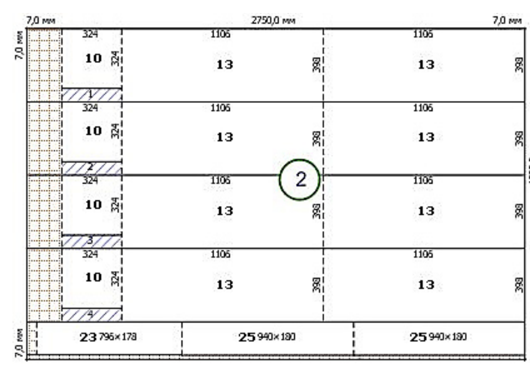


Fig. 1. Functional production model

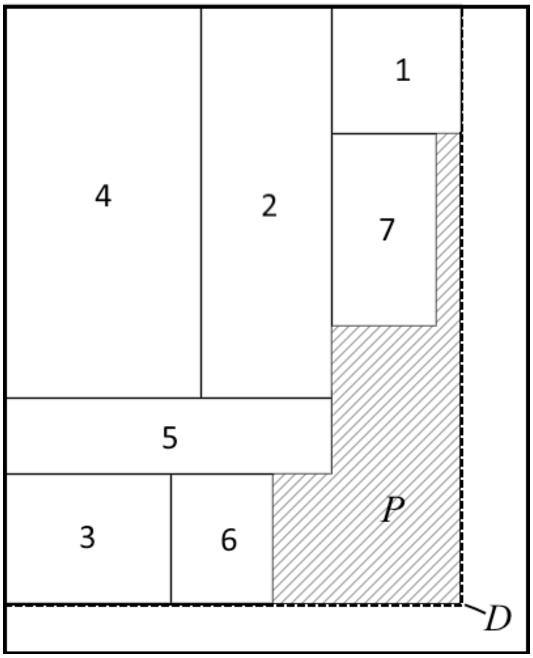
The following variables are used to describe the functional production model:
$\{PRi\}$ – multiple orders for product delivery.
$(IS)t$ – order report for the time period t;
$\{RVij\}$ – matrix of requirements for the i-th resource in the j-th planning interval for the implementation of the production schedule;
$[PSij]$ – matrix of manufactured products of the i-th type in the j-th period;
$[Oijk]$ – matrix of products of the i-th type in the j-th planning interval for k requests;
$[RVij]$ – matrix of requirements for the i-th resource in the j-th planning interval for the implementation of the schedule for sheet material production;
$[PIjk]$, $[POjk]$ – matrices of completed and non-completed requests for production in the j-th planning interval for k-th requests;
$[RDijk]$ – matrix of the volume of orders of the i-th type of resource in the j-th planning interval for k-th requests;
$[RSij]$ – matrix of the volume of sheet material of the i-th type in the j-th period;
$[SDij]$ – matrix of the production volume of the i-th type of material in the j-th planning interval;
$[IOijk]$ – matrix of output volume of the i-th type in the j-th planning interval for k-th orders;
SmartOpt is an application that designs cutting maps according to the order fulfillment plan for products of the i-th type (determines the composition and quantity of products);
$[RDBijk]$ – matrix of orders of the i-th type in the j-th planning interval for k-th orders;
CCi – cutting map showing the location of product orders of the i-th type on the sheet material.
In the process "Accounting of orders", employees accept orders $\{PRi\}$, draw up contracts and discuss deadlines for work. The output of the process is the order report $(IS)t$ and order data $[PIjk]$, $[POjk]$. Based on the input and output data, the Manager creates a portfolio of orders and looks through reports on orders (IS) for the period of time t.
The process "Planning" is based on orders $\{PRi\}$ and order data $[PIjk]$, $[POjk]$. The output of the business process is an order fulfillment plan $[RDijk]$ and a schedule for sheet material production $[SDij]$. As a result, the output data go to the next process "Sheet material production" to agree on the manufacture of $[Oijk]$ products of a certain type according to the order reports $(IS)t$.
In the process "Sheet material production" the input data are $\{RVij\}$ resources. The process is regulated using a schedule plan for sheet material production $[RVij]$. The output data are sheet material $[RSij]$, which type is determined according to the production schedule $[RVij]$.
In the process "Designing a cutting map" the input data are sheet material $[RSij]$, $[RDijk]$. The output is a CCi cutting map based on the order fulfillment plan $[SDij]$ using the cutting map design application SmartOpt.
In the process of "Material cutting" the CCi cutting map is used as input data. The output data are $[Oijk]$ products manufactured according to the generated shift assignment, which is often regulated by special technical documentation in the form of CCi cutting cards.
The cutting map shows exactly how to cut the sheet material and what products will be obtained in this case. This document is issued in a special format for the cutting section. It is used for cutting or, in the case of using an electronically controlled machine, to control the correctness of cutting (Starikov & Elmurodov, 2018). An example of a cutting map is shown in figure 2.



1 – data of the cutting map; 2 – data of the ordered products.
Fig. 2. Example of a cutting map

1. MAIN FEATURES OF THE APP

To implement the process of "Designing a cutting map" (see figure 1), an application consisting of the following functionality has been developed. This application:
– builds cutting maps based on the specified initial data according to the selected algorithm for construction;
– calculates the area of sheet material, the total area of products, the free area as the difference between the area of sheet material and the total area of products, the time spent building the solution, and the "useless material" criterion.
The "useless material" criterion P is the difference between the area of the rectangle covering all the products on the sheet material and the sum of the product areas (Rodríguez, 2015) (Fig. 3).
Let $N = \{N_1, N_2, ..., N_n \mid n = |N|\}$ – be the set of products to be made from sheet material with area S. Each product N_i, $i = 1,\dots, |N|$ has width W_i, length L_i, square $s_i = W_i \cdot L_i$,
$0 < s_i \le S$, $i = 1,\dots,|N|$.



P – "useless material"; D – rectangle covering all products on the sheet material
Fig. 3. Cutting map for sheet material

However, many products have a limited area:

$$\sum_{i=1}^{|N|} s_i \cdot x_i \le D,\ \ i = 1,...,|N|, \tag{1}$$

where D is the area of the rectangle covering all the products on the sheet material (see Fig. 3). Then the "useless area" criterion P is calculated using the formula:

$$P = (D - \sum_{i=1}^{|N|} s_i \cdot x_i \le D) \to \min,\ \ i = 1,...,|N|. \tag{2}$$

2. ALGORITHMS FOR DESIGNING CUTTING MAPS IN THE APP

The algorithm "First suitable". Following the algorithm "First suitable", items are added to the cutting map according to the following rule: the first item is added to the sheet material from the lower-left corner. In step k, an attempt is made to add the N_i item to the sheet material from the lower right corner of the N_{i-1} item. If the product fits the width of the sheet, then it is added, otherwise, the item is added along the length of the sheet from the upper left corner of the product N_{i-1}. If the product does not fit the width and length of the sheet material, it is added to the list of unsuitable products (Koshlakov, 2018).
Let $N = \{N_1, N_2, ..., N_n \mid n = |N|\}$ – be the set of products to be made from sheet material with width W_s, length L_s, and area $S = W_s \cdot L_s$. Each product N_i, $i = 1,\dots, |N|$ has width W_i, length L_i, area $s_i = W_i \cdot L_i$, $0 < s_i \le S$, $i = 1,...,|N|$.
Many products have a limited area:

$$\sum_{i=1}^{|N|} s_i \cdot x_i \le S, \tag{3}$$

where x_i – is the number of products of the i-th type, $i = 1,...,|N|$, placed on the sheet material.
The formalization of the algorithm is presented as:

$$CC_i:\ W_1, L_1 \begin{cases} W_1 \le W_s, \\ L_1 \le L_s \end{cases} \begin{cases} N_1 \in S \\ \text{else } N_1 \in I \end{cases} \begin{cases} W_i, L_i \\ i = 2...|N| \end{cases} \begin{cases} W_i \le W_s - W_{i-1}; \\ L_i \le L_s - L_{i-1} \end{cases} \begin{cases} N_i \in S \\ \text{else } N_i \in I \end{cases}$$

The algorithm *"First suitable with ordering"*. According to the algorithm *"First suitable with ordering"*, products are sorted in descending order of their area. The steps for solving the problem coincide with the execution of the algorithm *"First suitable"*. Adding items to the cutting map starts with the largest item by area.
The formalization of the algorithm is presented as:

$$CC_i:\ \text{sort}(s_i) \{ W_1, L_1 \begin{cases} W_1 \le W_s, \\ L_1 \le L_s \end{cases} \begin{cases} N_1 \in S \\ \text{else } N_1 \in I \end{cases} \begin{cases} W_i, L_i \\ i = 2...|N| \end{cases} \begin{cases} W_i \le W_s - W_{i-1}; \\ L_i \le L_s - L_{i-1} \end{cases} \begin{cases} N_i \in S \\ \text{else } N_i \in I \end{cases}$$

Among the existing metaheuristicthe, *the genetic algorithm* is considered as one of the most popular that has been used in practically all optimization, design, and application areas (Albadr M. A. et al., 2019). A genetic algorithm is an algorithm that is used to solve optimization and modeling problems by a random selection of a population, individuals in a population, and chromosomes. The optimal solution of this algorithm is based on a combination (genes crossing) and parameter variation (mutation) using mechanisms similar to natural selection in nature (Albadr M. A. et al., 2020). Let's consider the representation of the genetic algorithm as a solution to the problem of designing a cutting map. The following characteristics are determined for the genetic algorithm: $N = \{N_1, N_2, ..., N_n \mid n = |N|\}$ – population, for finding the solution; Individual N_i, $i = 1,\dots, |N|$ contains a chromosome that consists of genes that have width W_j, length L_j; Genes are built based on a pair (pairs) of products and an operator H or V, which determines the location of two products (several pairs of products) horizontally or vertically facing the operator (Fig. 4):

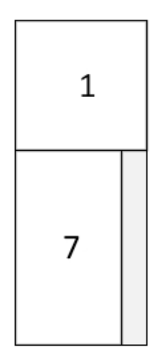


Fig. 4. The phenotype of the "1 7 V" chromosome

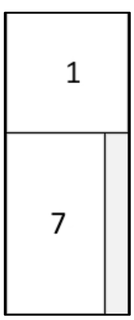
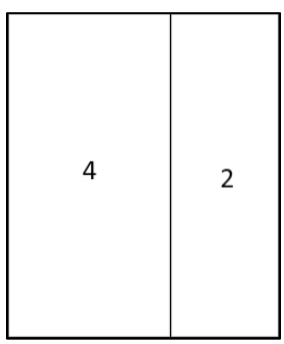
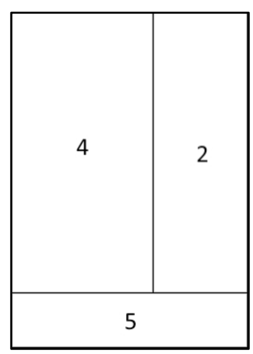
Accordingly, the length L_j and the width W_j of a chromosome consisting of a single gene formed from products numbered 1 and 7 are found by the formulas (4)-(5):

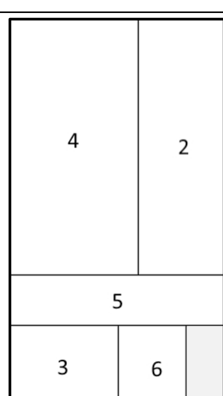
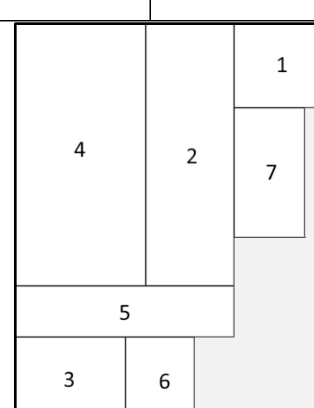
$$L_j = \max(L_1, L_7)\,, \tag{4}$$

$$W_j = W_1 + W_7\,. \tag{5}$$

where max is a function that returns the maximum number. Let's assume that the optimal solution in the population is N_i individual with the chromosome "7 1 *V 4 2 H 5 V* 3 6 *H V H*", then the interpretation of the individual means obtaining a phenotype from the genotype, that is, determining the position and location of all products from the active chromosome on the sheet material (Table 1).

Table 1. The interpretation of the chromosome "7 1 *V 4 2 H 5 V* 3 6 *H V H*"

	Genes			
Product number				6
		2	5	3
	1	4	4,2	4,2,5
	7	7,1	7,1	7,1
Operator	*V*	*H*	*V*	*H*
Phenotype				

	Genes		
Product number	3,6		
	4,2,5	4,2,5,3,6	
	7,1	7,1	7,1,4,2,5,3,6
Operator	*V*	*H*	
Phenotype			

The idea of decoding a chromosome is implemented using a stack:

Step 1. The last two elements of the stack are read.
Step 2. The last two elements are added and removed from the stack.
Step 3. The combined part resulting from the addition is logged to the stack.
Step 4. Return to step 1 until there is only one item on the stack.
Step 5. The last element remaining in the stack corresponds to the projected cutting map (Fig. 5).

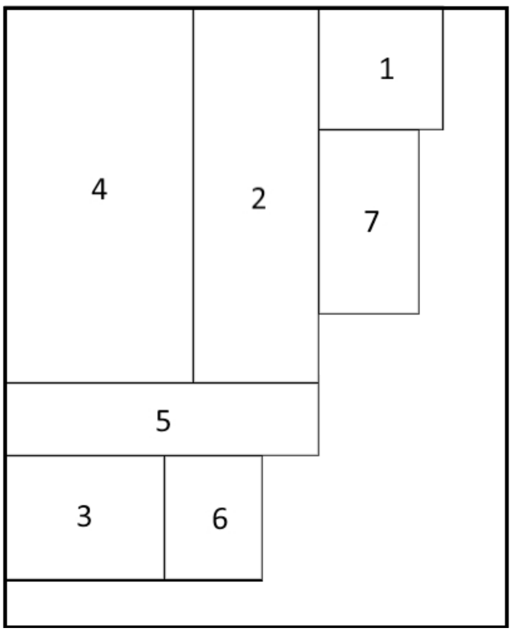


Fig. 5. The result of designing the cutting map using the genetic algorithm

In the cutting area, the elements are products. They consist of two interconnected genes, the first of which includes the size of the product, the second – the parameter of interconnection with the neighboring product.

3. TESTING AND RESULTS

The SmartOpt application implements 3 algorithms that are used to search for the optimal solution for cutting sheet material, to calculate the "useless material" criterion, and the time to build the solution.
If there is a construction of multiple solution results, it is possible to clear the previous cutting map without refreshing the application page in the web browser, which in turn saves the list of products with the specified parameters. The area is restored to its original form by the function "Clear" (Fig. 6).

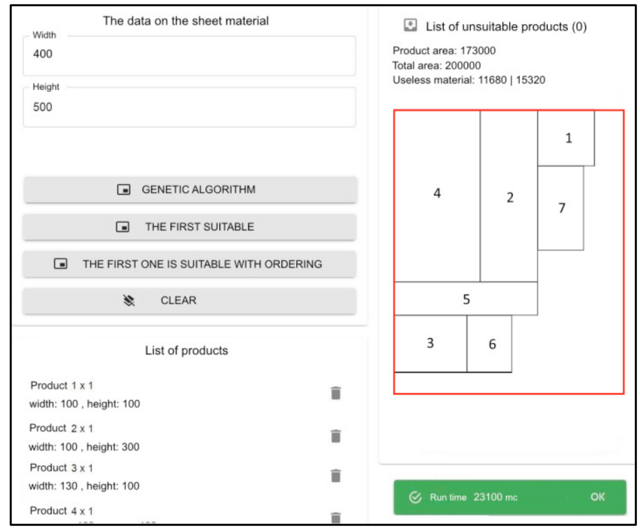


Fig. 6. A copy of the application screen for designing a cutting map using the "Genetic algorithm"

Input data diagnostics have several levels. The main level is the input level of the initial data. A corresponding message is issued for each case of violation.
The left part of the window (see Fig. 6) contains the necessary fields for entering parameters (width and length) of sheet material and products. If two identical products are ordered, it is possible to specify their quantity to be placed on the sheet material. The dimensions of the ordered products and sheet material are represented as integers. The cutting maps obtained using the three presented algorithms allow us to analyze the solution of the cutting problem by the "useless material" criterion (P, м^2) and the time (T, с) of its solution.
To test the application, it is accepted to design cutting maps using the algorithms "First suitable", "First suitable with ordering", and "Genetic algorithm". The initial data can be any number of products, the area of which does not exceed the area of the sheet material. The data for testing is described in table 2.

Table 2. Initial data for testing

Test 1				Test 2			
№ item (number)	W_i, m	L_i, m	s_i, m^2	№ item (number)	W_i, m	L_i, m	s_i, m^2
1-2 (2)	1,0	1,5	1,5	1-5 (5)	0,4	0,5	0,2
3 (1)	0,7	1,5	1,05	6-10 (5)	0,4	0,5	0,2
4 (1)	0,8	1,5	1,2	11-12 (2)	1,0	1,0	1,0
5 (1)	1,2	1,0	1,2	13 (1)	1,5	0,7	1,05
6 (1)	0,8	1,0	0,8	14 (1)	1,0	1,3	1,3
7 (1)	1,0	1,0	1,0	15 (1)	0,7	1,3	0,91

The test results are shown in table 3.

Table 3. Test results

Algorithm	Test 1		Test 2	
	T, s	P, m^2	T, s	P, m^2
The first suitable	0,006	1,75	0,006	0,74
The first suitable with ordering	0,006	1,75	0,006	1,74
Genetic algorithm	7,99	1,12	76,072	1,44

The application is implemented in JavaScript using the React.js library. React is an open JavaScript library for creating interfaces, which is designed to solve the problems of partial updating of web page content that is encountered in the development of single-page applications The advantage of using it is the simplicity of interface development, where there is no need to update the entire page for any user action (Mardan, 2019). Testing was performed on a computer with an Intel Core i5 3230M 2.6 GHz processor and 6 GB of RAM. User interaction with the app was implemented through the browser.

4. DISCUSSION OF RESULTS

In the first test, the algorithms "First suitable" and "First suitable with ordering" placed items on the sheet material in equal times. In this case, the area D (see Fig. 3) coincides with the area S of the sheet material:

$$S - \sum_{i=1}^{7} s_i = 1{,}75 \text{ м}^2.$$

The genetic algorithm fits products more tightly and $D < S$. At the same time, it is significantly inferior to other algorithms in time (T = 7,99 s).

When studying algorithms for rational cutting of sheet material, it was shown that the genetic algorithm is inferior in terms of speed to the studied algorithms "First suitable", "First suitable with ordering" and surpasses them by the "useless material" criterion (Demidenko, Yakimov and Denisevich, 2020). However, in the second test, the result of the algorithm "First suitable" according to the "useless material" criterion (P = 0,74 m^2) turned out to be the best among the studied algorithms.

The explanation for this result is the order in which items are added to the algorithm "First suitable". The genetic algorithm showed a value according to the "useless material" criterion (P = 1.44 m^2) and a worse result in time compared to the first testing (T = 76.072 s).

CONCLUSION

An application has been developed for designing cutting maps and calculating the criteria (T, s) of the solution of construction time, (P, m^2) "useless material" criterion using the algorithms "First suitable", "First suitable with ordering", "Genetic algorithm". The application of several algorithms for solving the problem of cutting sheet materials in the application is practically justified since with a certain order of adding products, the algorithm "First suitable" shows the best result in comparison with the "Genetic algorithm" according to the "useless material" criterion. The idea of using a genetic algorithm reduces the complexity of the operation, and it also has a good solution convergence for large-scale engineering problems, and a satisfactory solution is obtained. In further studies, the product parameters can be extended to characterize the cutting angle of products of various shapes on sheet material, which can be applied to more situations.

REFERENCES

Albadr M. A., Tiun S., Ayob M., AL-Dhief F. (2020). Genetic Algorithm Based on Natural Selection Theory for Optimization Problems. Symmetry. 12(11): 1758. https://doi.org/10.3390/sym12111758.

Albadr M. A., Tiun S., Ayob M. et al. (2019). Spoken language identification based on optimised genetic algorithm-extreme learning machine approach. Int J Speech Technol 22, 711–727. https://doi.org/10.1007/s10772-019-09621-w.

Celli P., McMahan C., Ramirez B., Bauhofer A., Naify C., Hofmann D., Audoly B. and Daraio C. (2018). Shape-morphing architected sheets with non-periodic cut patterns. Soft Matter, no 14, pp. 9744–9749. https://doi.org/10.1039/c8sm02082e.

Demidenko O. M., Yakimov E. A., Denisevich D. A. (2020). Research of algorithms for rational cutting of sheet material. Problems of physics, mathematics and engineering, no 1 (42), pp. 91–94.

Kaczmarczyk J., Grajcar A. (2018). Numerical Simulation and Experimental Investigation of Cold-Rolled Steel Cutting. Materials, no 11, 1263. https://doi:10.3390/ma11071263.

Koshlakov N. V. (2018). The problem of geometric coverage. Polytechnic youth magazine. Bauman Moscow state technical University, no 1, p. 4.

Mardan A. (2019). React quickly. Web applications on React, JSX, Redux and GraphQL. Peter : programmer's Library, 560 p.

Rodríguez I. S. (2015). Aplicación de Algoritmos Genéticos para la optimización del corte de material. Escola Tècnica Superior d'Enginyeria Informàtica Universitat Politècnica de València. Trabajo Fin de Grado. Grado en Ingeniería Informática, p. 14.

Song C., Gong K., Bu J., and Huang L. (2020). Research on Stability of Optimal Sheet-cutting Strategy Based on Improved Real-Coded Genetic Algorithm, in E3S Web of Conferences, vol. 162. doi:10.1051/e3sconf/202016203007.

Starikov A. V., Elmurodov S. U. (2018). Possibilities of automation of cutting of sheet and plate materials in the conditions of order-based production of cabinet furniture. Actual directions of scientific research of the XXI century: theory and practice, vol. 6, no 5 (41), pp. 350–354.

Yunqing Rao, Dezhong Qi, Jinling Li. (2013). An Improved Hierarchical Genetic Algorithm for Sheet Cutting Scheduling with Process Constraints. The Scientific World Journal, vol. 2013, 10 p., https://doi.org/10.1155/2013/202683.