Research article
DOI: https://doi.org/10.48554/SDEE.2022.4.5

Development of Methodological Provisions for Rational Material Cutting in Lean Manufacturing at Mechanical Engineering Enterprises

Artem Smirnov[1,2*], Vladimir Kobzev[1*], Cholpon Nuralieva[3]

[1] Peter the Great St. Petersburg Polytechnic University, Saint-Petersburg, Russia
[2] Vologda State University, Vologda, Russia
[3] Kyrgyz-Russian Slavic University named after B.N. Yeltsin
Corresponding author: smirnov.artem.a@yandex.ru

Abstract

In the market economy, mechanical engineering enterprises require continuous improvement of business processes to ensure their competitiveness and sustainable development. Improving business processes based on lean manufacturing and management accounting allows for gaining competitive advantages in the value-creating flow for the consumer and increasing the economic efficiency of the enterprise's operations. This study takes into account the need to improve the management of material resources being cut at mechanical engineering enterprises with single and serial production types. The main direction for improving the cutting process of industrial materials is to increase their utilisation rate through the use of rational cutting methods. However, this study identifies unresolved problems in theory and practice related to managing business and non-business material resources obtained after cutting, which affect the elimination of material and time losses arising in the process of cutting. Among the main study results are advanced terminological apparatus in the field of cutting industrial materials, advanced techniques for sorting material resources obtained after cutting and methodological provisions for their valuation, methodological approach to assessing economic efficiency of the sorting decision, and software package prototype with elements of the decision-making support system for sorting materials obtained after cutting. The implications of these results are discussed, and directions for future research are suggested.

Keywords: lean manufacturing, managerial accounting, material resource management, mechanical engineering enterprises, development of rational material cutting, business material resources, sorting technique

Citation: Smirnov, A., Kobzev, V., Nuralieva, Ch., 2022. Development of methodological provisions for rational material cutting in lean manufacturing at mechanical engineering enterprises. Sustainable Development and Engineering Economics 4, 5. https://doi.org/10.48554/SDEE.2022.4.5

Научная статья

УДК 658.5

DOI: https://doi.org/10.48554/SDEE.2022.4.5

Развитие методических положений рационального раскроя материалов в бережливом производстве на предприятиях машиностроения

Артем Смирнов[1,2*], Владимир Кобзев[1], Чолпон Нуралиева[3]

[1] Санкт-Петербургский политехнический университет Петра Великого, Санкт-Петербург, Россия
[2] Вологодский государственный университет, Вологда, Россия
[3] Кыргызско-Российский Славянский университет им. Б.Н. Ельцина, Бишкек, Кыргызская Республика
Автор, ответственный за переписку: smirnov.artem.a@yandex.ru

Аннотация

В условиях рыночной экономики на предприятиях машиностроения для обеспечения конкурентоспособности и устойчивого развития требуется непрерывное совершенствование бизнес-процессов. Совершенствование бизнес-процессов на основе бережливого производства и управленческого учета позволяет получить конкурентные преимущества в потоке создания ценности для потребителя и повысить экономическую эффективность операционной деятельности предприятия. В исследовании принята во внимание необходимость совершенствования управления материальными ресурсами при их раскрое на предприятиях машиностроения с единичными и серийным типами производства. Основным направлением совершенствования раскроя промышленных материалов является увеличение коэффициента их использования через применение рациональных методов раскроя. Однако в ходе работы выявлены нерешенные в теории и практике проблемы, связанные с управлением деловыми и неделовыми материальными ресурсами, полученными после раскроя, которые влияют на устранение возникающих материальных и временных потерь в процессе раскроя Также основными результатами исследования являются: развитый терминологический аппарат в области раскроя промышленных материалов; разработанные методика сортировки материальных ресурсов, полученных после раскроя, и методические положения их стоимостной оценки; предложены методический подход к оценке экономической эффективности принимаемого решения по сортировке и прототип программного комплекса с элементами системы поддержки принятия решений по сортировке материалов, полученных после раскроя. В статье проведен анализ полученных результатов и определены направления дальнейших исследований.

Ключевые слова: бережливое производство, управленческий учет, управление материальными ресурсами, предприятия машиностроения, развитие рационального раскроя материалов, деловые материальные ресурсы, методика сортировки

Цитирование: Смирнов, А., Кобзев, В., Нуралиева, Ч., 2022. Развитие методических положений рационального раскроя материалов в бережливом производстве на предприятиях машиностроения. Sustainable Development and Engineering Economics 4, 5. https://doi.org/10.48554/SDEE.2022.4.5

1. Introduction

Mechanical engineering enterprises with single or serial types of production, using lean manufacturing tools as one of the directions of their development, were chosen as the study objects. The relevance of the study is grounded in its focus on the concept of lean manufacturing aimed at eliminating all types of losses while improving processes in the organisation, which ensures an increase in the economic efficiency of production and in the consumer properties of products, and the emergence of competitive advantages as a result. The solution to multiple problems in modern science and technology development requires an interdisciplinary approach that provides synergistic effects. The current practice of implementing lean manufacturing confirms the need to consider the identified problems from different perspectives.

Shichkov et al. (2016, 2019) confirmed that the study of the problems applied in the field of production organisation, managerial accounting and innovation management ensures the development of the theoretical aspects of industrial economics. Managerial accounting should include the adoption of prompt and reasonable managerial decisions, so it is advisable to consider its competent combination with lean manufacturing. Suloeva et al. (2017) emphasised that in the overall mechanical engineering enterprise management system, special attention should be paid to cost management, since achieving the required consumer product properties and competitive advantages can be guaranteed by increasing the economic efficiency of production processes.

In the field of lean manufacturing, Turovets et al. (2016), for example, substantiated the need to consider the specifics of the object of study, which can improve business processes. The development of lean manufacturing tools is driven by their validation by many manufacturing enterprises (Safronova et al., 2020). Business processes associated with material resources management at mechanical engineering enterprises require constant managers' attention, since these are material resources that form the largest share of costs, and the technology of their processing and organisational and economic management mechanisms determine the economic efficiency of their activities. The task of increasing the utilisation rate of industrial materials in order to reduce material costs, optimise costs of improving product consumer properties, and increase net income is set when organising the process of material cutting, which is a significant share in operating costs at many mechanical engineering enterprises.

The main direction of increasing the utilisation rate of industrial materials is the promotion of rational cutting algorithms, which are widely considered by national and international researchers. The issues of rational cutting are handled by the Euro Special Interest Group on Cutting and Packing (ESICUP), the Ufa School of Science, etc. The analysis of the scientific and practical literature on the issues of rational cutting led to the following conclusions:

Scientific and practical studies consider the issues of developing rational cutting techniques that provide optimal blank location on a given material resource and optimal material resource choice for making blanks from it to increase the material utilisation rate.

The issue of the reasonable sorting of material resources into business and non-business resources obtained after cutting at mechanical engineering enterprises has not been addressed. The relevance of this issue is confirmed by the fact that reasonable sorting of material resources after cutting reduces the cost of storage and transportation of non-business materials, which, under empirical sorting, could be classified as business materials, and will increase the material utilisation rate during manufacturing products made from business material resources, which, under empirical sorting, could be classified as non-business materials. This task is especially relevant for mechanical engineering enterprises with single or serial production types, since the range and completeness of blanks and material resources obtained after cutting vary depending on the consumer properties of the product.

Thus, to address these gaps, this study focuses on managerial relations that arise in the process of providing lean production with material resources when cutting materials in mechanical engineering enterprises with single or serial production types. The purpose of this study is to develop methodological provisions for improving the tools to manage material resources in lean manufacturing when cutting materials in mechanical engineering enterprises with single or serial production types. Methodological provisions are understood in the study as a set of tools (e.g. terminology, techniques, methodological approaches) that help to achieve the main goal (e.g. improving the process under study, existing technologies). The study is aimed at:

Assessing theoretical and practical aspects of rational material cutting.

Forming a terminological apparatus in the field of material cutting.

Developing a methodology for classifying material resources as business and non-business after cutting and practical recommendations for the methodology application.

Developing methodological provisions to determine the possible price of material resources obtained after cutting.

Developing a methodological approach to assess the economic efficiency of the sorting process during decision making.

Developing the prototype software package with elements of decision support for sorting material resources.

2. Literature review

A central issue in the rational cutting of industrial materials, according to the scientific and practical literature, is the 'cutting and packing problem'. The solution to this problem is aimed at reducing the cost of resources (Valiakhmetova et al., 2014). One-dimensional (1D), two-dimensional (2D), and three-dimensional (3D) cutting and packing problems are distinguished based on the geometry of the initial resource. In addressing these problems, researchers have identified nesting problems arising from placing parts of the complex geometry in specified areas of the material resource. In solving these issues, particular attention is paid to informational problems of shape setting, accounting, and ensuring their non-intersection. Within the framework of 3D packing problems, objects are rectangular parallelepipeds placed either in a rectangular container with one unfixed face, or in several containers with given linear dimensions. Table 1 shows the main varieties of one-dimensional and two-dimensional problems within the framework of the general cutting and packing problem (Filippova et al., 2013).

Table 1. Basic one-dimensional and two-dimensional problems of cutting and packing

Problem name	Content
1D cutting and packing problems	
Knapsack packing (KP)	The dimensions (e.g. weight, length) and the values (price, other estimate) of certain elements are known, and the capacity of the knapsack is also known. A combination of elements that allows the cost of the knapsack to reach its maximum is identified.
1D cutting stock (1DCS)	The strip must be cut into blanks of certain sizes with the lowest cost of the source material.
Multi cutting stock (MCS)	A more complex version of the previous problem of cutting material of various lengths.
1D bin packing (1DBP)	A special case of the one-dimensional cutting problem in which each blank is required in a single copy.
2D cutting and packing problems	

2D strip packing (2DSP)	One of the strip dimensions (e.g. width) is specified, the second dimension (e.g. length) is variable. A package must fit within a strip of a minimum length.
2D bin packing (2DBP)	Both dimensions (width, length) are set. The minimum number of containers in which all rectangular elements are packed must be specified.
2D area packing (2DAP, quadrant)	Both dimensions (width, length) are variable for a rectangular object. A pack of elements must fit into an angle formed by coordinate axes that coincide with the width and length of the area for which the area of the envelope element of the rectangle reaches its minimum.
Guillotine cutting	Only through cuts of the source material are possible; Generalises the 1DCS problem to a two-dimensional version.
2D guillotine strip cutting (2DGSC)	A guillotine roll must be cut into specified rectangular elements that will provide the minimum length of the used part of a strip.
2D guillotine bin cutting (2DGBC)	A set of guillotine cuts must be identified to ensure the minimum consumption of sheets.

Table 2 reflects the research directions in the field of solving problems of cutting industrial materials.

Table 2. Research in the field of solving problems of cutting and packing

Authors	Main research directions in solving problems of cutting industrial materials
L.V. Kantorovich and V.A. Zalgaller	Soviet scientists, founders of solving the problems of rational cutting of industrial materials. L.V. Kantorovich proposed the method of resolving indices, which was finalised in practice by V.A. Zalgaller, who proposed his method for selecting integer indices. The researchers described the developed techniques, which were practically tested at the Leningrad Carriage Works in 1948–1949 in their Rational Cutting of Industrial Materials book. The first edition was published in 1951. In this paper, the authors mainly considered techniques for solving problems of rational (with the highest material utilisation factor) cutting of linear materials (long products, pipes, bars) and sheet materials (rolled sheets, plywood, glass) into blanks of simple shapes. It should be noted that the issues of cutting sheet material into curvilinear elements have not been studied. (Kantorovich and Zalgaller, 1971)
E.A. Mukhacheva	The Ufa Scientific School was found based on the cutting and packing studies by E. A. Mukhacheva (a student of G. Sh. Rubenstein, who worked with L. V. Kantorovich. Her paper, Rational Cutting of Industrial Materials. Application in Automated Control Systems, which was published in 1984, reflects the theory and practice of rectangular cutting within the framework of a computer-aided design system for the technological preparation of cutting in cold stamping production. The main attention was paid to the theory and practice of rational cutting of rectangular sheets into rectangular blanks. (Mukhacheva, 1984)
V.M.Kartak	Development of the 'branches and boundaries' technique for solving packing problems by introducing iteration reduction procedures; study of the problems of linear cutting, packing, and assessing packing density of rectangles in a semi-infinite strip. (Kartak, 2009, 2019)

M.A. Mesyagutov	An exact technique of solving the problem of one-dimensional continued packing was proposed, based on dominance criteria and cut-off rules to reduce the process of iteration (Filippova et al., 2013)
Yu.I. Valiakhmetova	Research of layer-by-layer algorithms for solving problems of rectangular guillotine cutting of sheet materials; development of the concept of hyperheuristic algorithms for solving optimisation problems (Valiakhmetova et al., 2012, 2013, 2014)
A.S. Filippova	Research is aimed at developing solutions to orthogonal packing problems (Filippova et al., 2013)
A.A. Petunin	A scheme is proposed for automatic selection of the optimisation algorithm for cutting materials depending on the task type (Petunin, 2010)
H. Dyckhoff, G. Wascher, H. Haubner, H. Schumann	Classifications development of cutting and packing problems (Dyckhoff, 1990; Wascher et al., 2007)
Euro Special Interest Group on Cutting and Packing (ESICUP)	The organisation was founded in 1988 to bring together practitioners and researchers interested in cutting and packing problems. The goal of ESICUP is to improve the interactions between people working in this field.

The issues of rational cutting of industrial materials in combination with reasonable material costs for manufacturing were considered by Tolstobrov (2019) and Salkova (2019). The analysis of scientific publications and practical work on the problem of cutting and packing showed that national and international researchers have developed mathematical methods and approaches to organising rational cutting of industrial materials in terms of the optimal location of blanks on a given material resource and the optimal choice of a material resource for manufacturing blanks from it. This ensures an increase in the material utilisation rate, change in the indicators of the enterprise's operating activities (production volume in physical and value terms, unit technological costs, depreciation deductions from tangible and intangible assets, and operating profit).

However, in the reviewed works on the rational cutting of industrial materials, no attention has been paid to the issue of sorting the material resources obtained after cutting, with the goal of classifying them into groups of business or non-business materials. The relevance of reducing the amount of recycling of industrial waste from the point of view of environmental problems and increasing the economic efficiency of the enterprise was confirmed by Demidenko and Malevskoy-Malevich (2013, 2014).

3. Methods and materials

The research methodology is based on the concept of lean production, which is focused on the formation of a continuous value-creating flow for the consumer, continuous improvement of organisational processes through the involvement of personnel, and elimination of all types of losses. The study explores the issues of lean production related to reducing material costs through the use of business materials, the cost of storing and transporting business or non-business material resources, and reducing the time spent searching for and transporting business material resources in the manufacturing process.

The developed toolkit for managing the material resources obtained after cutting takes into account some components of supply chain management (demand forecasting, stock and replenishment management in relation to the allocated classes of material resources, and visualisation of information on material residues in the context of their nomenclature with allowance for business and non-business material resources). The proposed methods are based on the provisions of managerial accounting, since timely collecting, processing, analysing, and interpreting diverse information is required for making prompt and informed decisions, according to the enterprise specifics.

The authors used the following general research techniques:

Analysis (theoretical and practical aspects of rational cutting, lean production, and managerial accounting were analysed)

Synthesis (methodological provisions for sorting the material resources obtained after cutting were synthesised)

Formalising (graphic description of the studied processes using the activity diagram (UML language) was given; dependence of the analysed economic indicators was described using mathematical formulas).

The analysis of production processes at mechanical engineering enterprises manufacturing capacitive equipment in the city of Vologda and the analytical materials presented in the studied literature constitute the empirical aspects of the study.

4. Results

4.1. Identifying the problems of material resource management

The costs and process of cutting sheet metal analysis at mechanical engineering enterprises in the city of Vologda, with a single and small-scale type of capacitive equipment manufacturing, were considered to determine the problems of managing material resources in terms of the theoretical and practical foundations of rational materials cutting at mechanical engineering enterprises:

The cost of sheet metal is approximately 70% in the structure of material costs, and the sheet metal utilisation rate is approximately 0.8. The selling price of non-business material resources is significantly lower than the purchase price of the source material (by about 80–85%). Thus, the enterprise increases the cost of production with an increase in the number of non-business material resources.

Disparate design of sheet metal cutting maps prevails; therefore, there is less opportunity to place blanks more densely, and the material utilisation rate decreases.

Sheet metal cutting is carried out on the basis of the technologist's empirical perception; there are no regulations, reducing the possibility of increasing the sheet metal utilisation rate.

Classification of material resources after cutting into business and non-business ones is carried out empirically with no methodology, which is reflected in the growth of material costs (business materials can be classified as non-business materials), storage costs, and transport and procurement works (non-business materials can be classified as business materials).

There is no marking equipment or procedures for marking business material resources after cutting, which complicates their accounting.

There is no reasoned design of cutting maps with an allowance for business materials, which is reflected in increased material costs.

Sheet metal is accounted for in terms of the original nomenclature in kilograms, which is reflected in the inability to analyse data on the residues of solid sheets, variety of business material resources, and number of non-business ones. This complicates the operational design of cutting charts with allowance for business materials, and planning the correct purchase.

Information support has the possibility of more detailed accounting, but the necessary actions of the process participants are not defined.

There is no regulation of the accounting of materials after cutting.

There is no technique for defining the selling price of material resources after cutting. Non-business materials are sold for recycling at the price of scrap metal.

Based on a cause-and-effect analysis of the lack of data on business material resources in the accounting system, it can be concluded that the main reasons for shortcomings of management accounting for business materials are related to accounting techniques and accounting equipment. Consequently, it is necessary to adjust the existing rules for managing material and information flows within the accounting process and warehousing business and non-business material resources after cutting. The identified organisational and economic aspects, and problems of managing material resources in the field of cutting industrial materials are relevant, since managerial decisions affect enterprise performance and value stream for the consumer. It is necessary to improve the tools for managing material and information flows associated with material resources received after cutting. The set of managerial tools and regulated business processes aimed at managing material resources in an enterprise is understood in this study as the toolkit for managing material resources.

4.2. Developing a terminological apparatus in the field of cutting industrial materials

This study introduces the concept of 'multilevel cutting', that is, the cutting of material resources at the 0 level or *n* level (n are natural numbers from 1 to infinity) when considering the set of material resources obtained after cutting source materials as a system of material resources that have different indicator values characterising them.

The 0-level material resource is the material resource that was not used to produce blanks. The *n*-level material resource is the material resource that was the initial resource for the cutting chart design *n* times. The level of cutting is understood as cutting from the material resource of the 0 level or from the material resource of the *n* level of cutting. Material resources of the *n* levels are obtained as a result of *n*-1 level cutting and represent a set of material resources for further product manufacturing or selling to external consumers. From a technological point of view, interchangeable material resources at different levels can be used in the development of cutting charts. However, preference should be given to those that are more cost-effective for making blanks. Such a material resource has substitutive properties.

Integrated design of cutting charts is the design of blank cutting charts for the entire range of products manufactured at the enterprise, taking into account the available range of material resources. It is necessary to identify the resulting material resources of the *n*+1 level into groups of 'business' and 'non-business' material resources when cutting from material resources of the 0 or *n* level. Business material resources of the *n* level are resources that are technically possible and economically feasible to use for *n* level cutting. Non-business material resources are resources of the *n* level that are not economically feasible to use for *n*-level cutting. Assessment of the *n*-level material resource is determination of the indicator values and characterising the material resource of the *n* level, based on which identification of the material resource of the *n* level is carried out to justify the feasibility of manufacturing products from it.

Identification of the material resource of the *n* level is a comparison of the indicator values characterising the material resources of the *n* level with the reference indicator values of the corresponding classes of material resources. The expediency of allocating classes of material resources is substantiated in the framework of the developed sorting technique described in the next segment. Sorting of the *n*-level material resource is a categorisation of the material resource of the *n*-th level into the group of business or non-business material resources, taking into account changes in costs and net income, and the ratio of supply and demand for the corresponding class of material resources.

This study developed **a technique for sorting the material resources obtained after cutting into business or non-business material groups** (Smirnov et al., 2019). The technique is represented by a set of sequential actions for assessing the indicator values characterising consumer properties of material resources after cutting, identifying them with the corresponding classes, and classifying them as business and non-business ones with an allowance for changes in unit costs and net income from the enterprise's operating activities.

1. Designing cutting charts

When designing a cutting chart for a reasonable and prompt selection of the optimal option, it is advisable to use software tools (CAD/CAM-systems) developed on the rational cutting techniques proposed in the theory.

2. Classifying material resources

Since material resources can be interchangeable after cutting, it is advisable to determine their classes in accordance with their similarities in terms of assessed indicators in a certain range of values. If there are classes, the software tool can sufficiently analyse templates of the generated classes in the process of designing a cutting chart, taking into account business material resources. It is necessary to keep quantitative records of the material resources being cut in terms of classes, not only in kilograms but also in pieces, so that the cutting chart design programme can determine the choice of material resources, taking its availability into account. Thus, the indicator values characterising the material resources should be obtained after cutting and identified with the corresponding classes.

3. Pre-sorting

We propose assessing the estimated demand (Qsm, pcs./month) for classes of material resources, the value of which is compared with the quantity of material resources in the class (Nsm, pieces) at the time of sorting, since it is not advisable to store materials suitable for making blanks, but there is no need for manufacturing at the moment. The assessed demand should be carried out on the basis of a statistical assessment of the average consumption volume of the corresponding class. Depending on the managerial tasks, the values of the enterprise average monthly performance indicators can be assessed for different periods, for example, quarter, half a year, or a year. The seasonality factor has a significant impact on production activities for a number of mechanical engineering enterprises in single and serial production. Therefore, it is advisable to use the average monthly value for the past year (starting from the month preceding the month of assessment) when assessing the average consumption volume of the corresponding class of business material resources, in order to smooth the seasonality factor and use the most relevant data.

4. Final sorting

Sorting decisions must be based on the assessment of the storage and transportation of material resource cost changes when they are classified in the group of business materials in comparison with the uncovered costs of purchasing raw material when selling non-business material resources at a reduced price.

5. Reassessment of business material resources

A monthly reassessment of stored business material resources should be carried out, since the range of manufactured blanks may change due to possible changes in the production programme. The number of stored business material resources in the respective classes should be determined monthly, and the data should be compared with the average monthly consumption. It is expedient to implement this use of the appropriate software in the format of a monthly scheduled job. In addition, the demand for business materials should be monitored daily using the appropriate reports of the software package to promptly adjust inventory management parameters. The decision support system (DSS), CAD/CAM system, and accounting system (such as ERP) should be used to make operational decisions on sorting due to the complexity of assessing and identifying material resources when performed by a staff member.

Based on the developed proposals, Figure 1 presents a graphical interpretation of the process of organised material cutting in mechanical engineering enterprises, considering the business material resources. Changes are proposed at the stages of designing cutting charts, sorting, marking, and managerial accounting of material resources after cutting.

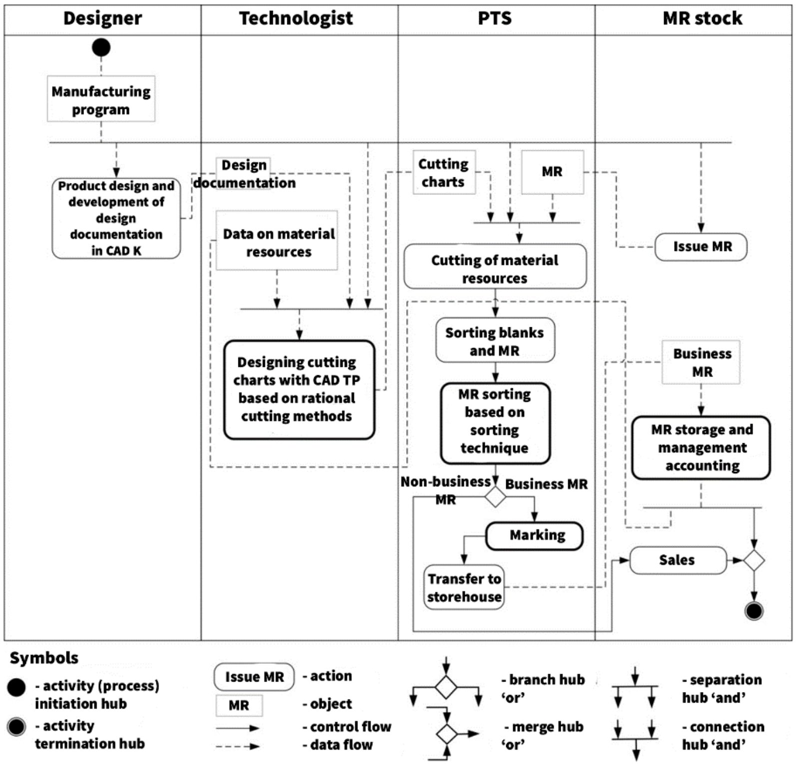

Figure 1. The process of organising material rational cutting taking with allowance for business material resources

Figure 2 shows a graphical interpretation of the process of sorting the material resources obtained after cutting.

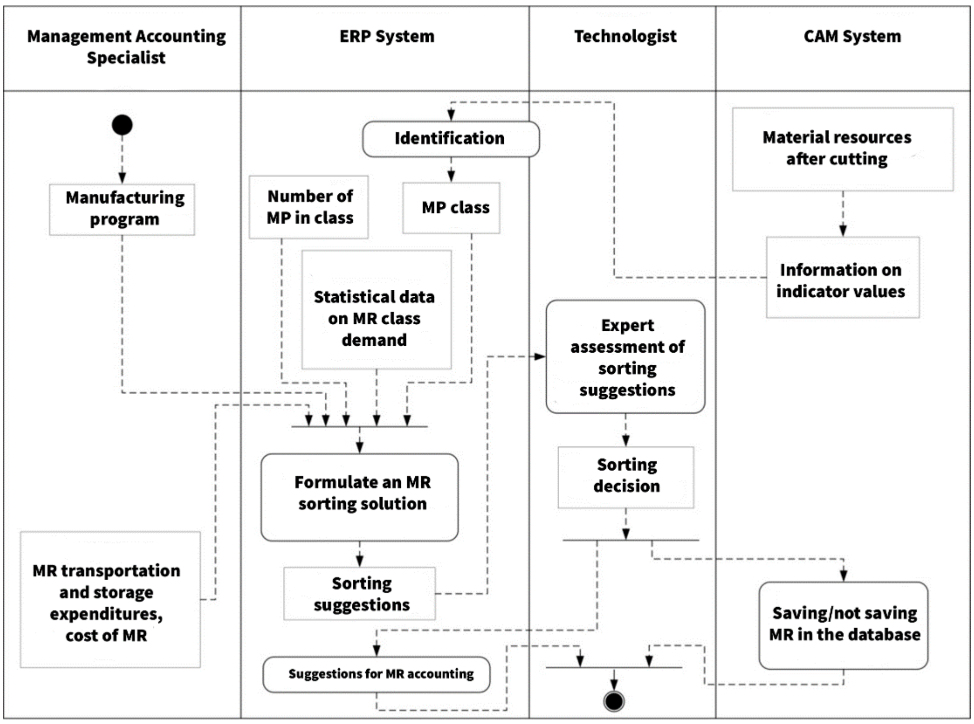

Figure 2. The process of sorting material resources after cutting when allocating them into groups of business or non-business materials

The technique of sorting material resources into business and non-business types and practical guidelines of its development are designed to reduce losses in the value-creating flow (operational and time costs), optimise the cost structure, improve consumer properties of products and increase net income at mechanical engineering enterprises.

4.3. Techniques for defining the possible selling price of material resources after cutting

As part of the cutting process, it is advisable to assess the transfer price of the material resources after cutting to organise a cost transfer or a possible selling price for external organisations. In this case, the price of the n-level material resource (Vscm, rub./kg) involved in the cutting process cannot be lower than the price of scrap metal (Vscm, rub./kg), since this is the minimum metal price formed by the market, and is generally lower than the market grade metal price (Vsm0, rub./kg) or actual metal costs (Wsmc, rub./kg). It should also be noted that the transfer price of material resources after cutting is equal to the possible selling price, as it is defined based on the actual purchase price of the source material. Therefore, it is proposed to define the material resource transfer price after cutting by its possible selling price.

The material resource selling price may differ depending on the changing indicator value characterising the consumer properties of material resources, and it decreases depending on the increase in the indicator level. This helps to form a customer-centric price in the consumer value-creating flow. Therefore, it is proposed to determine the possible selling price according to Formula (1):

$$\text{Vsm}_i = \text{Vsm}_0\left(1-\left(\sum\nolimits_{i=1}^{n} w_i k_i\right)\right) \quad (1)$$

where *wi* is the weight factor, *ki* is a coefficient that takes into account price decrease with the change of indicators characterising the consumer properties of the material, *i* is a coefficient index, serial number, and *n* is the total number of coefficients.

Depending on the production specifics, the use of coefficients can be considered in cutting sheet metal, taking into account: (1) the length deviation of the rectangle, formed by the material resource minimum addition, from the length of the 0 level material resource; (2) deviation of the rectangle width, formed by the material resource minimum addition, from the width of the 0 level material resource; (3) value of the fill factor (the ratio of the material resource area to the area of the rectangle formed by the material resource minimum addition); (4) deformation of the material resource plane; (5) change in the material resource edge roughness after cutting; (6) change in the deviation angle of the edge plane from the plane perpendicular to the sheet plane; and (7) mechanical damage to the surface; corrosion of the material resource.

The following conditions should be met when defining a possible selling price of the material resource after cutting according to formula (1): the sum of the weight coefficients *wi* is equal to one; Vsmi cannot be less than the selling price of the corresponding type of scrap metal Vscm. Methodological provisions for determining the material resource selling price after cutting, based on the assessment of changes in indicators characterising consumer properties, allow organising the cost transfer in value terms when manufacturing products from business material resources and increasing the net income when selling non-business material resources. From the point of view of lean manufacturing, allowance for changes in the consumer properties of the material resources obtained after cutting allows for forming a customer-oriented price in the value-creating flow for the consumer.

4.4. Methodological approach to assessing the economic efficiency of decision making in sorting material resources after cutting

The proposed technique of sorting material resources after cutting is considered in the example of sheet metal. The following geometric and technical indicators for identifying the material resources obtained after cutting are proposed: steel grade of sheet metal, thickness, area of the material resource, length of the rectangle formed by the material resource minimum addition, width of the rectangle formed by the material resource minimum addition, area of the rectangle formed by the material resource minimum addition, and fill coefficient. Further, sorting is influenced by such accounting indicators as the potential demand (Qsm, pcs/month) and amount (Nsm, pcs) of business material resources in a class stored at the time of new material resources identification.

The final sorting decision is made on the basis of an economic assessment of cost changes and net income from the operating activities of the enterprise, taking into account changes in transportation and storage costs of the material resources obtained after cutting the source material. To assess an increase in storage costs, storage time should be assessed through forecasted demand. We propose assessing the maximum allowable and expected storage times of material resources after cutting. The maximum acceptable storage time of business material resources (Tmax) is the storage time at which the change in net income from the sales of products by manufacturing them from business material resources (taking into account the increase in transportation and storage costs) is equal to the increase in net income when selling non-business material resources to external organisations without adding consumer properties. After cutting, material resources should be recognised as business resources if the expected storage time is lower than the permissible one. The estimated material resource storage time can be determined by the data on the values of Qsm and Nsm.

The assessment of the maximum material resource storage time should be carried out when comparing two manufacturing options, relying on possible solutions for sorting material resources (Smirnov, 2017):

Products are made from business material resources.

Products are made from 0-level material resources, and after cutting residues are recognised as non-business and are sold to external organisations. The cost of pre-sale storage is assumed to be insignificant, and the transportation of material resources is organised by the consumer.

During comparison, it is logical to assume that there is no restriction on the source material purchase in ideal market economy conditions in terms of the commodity market supply (which is confirmed in practice). Consequently, the enterprise will receive the same sales at different costs, regardless of the option of using material resources after cutting. The first option will require fewer costs of the source material, since part of the blanks will be made from business material resources. The second option will require more source material, since material resources at the *n* level will be sold to external organisations.

The net income change in blank production from business material resources (the first option) is assessed by Formula (2), taking into account additional transportation and storage costs (natural units of measurement on the example of sheet metal):

$$\Delta D_0 = D_i \cdot \mathrm{Gsm} - (1 - \mathrm{Np})(\mathrm{Wt} \cdot \mathrm{Gsm} + \mathrm{Ws} \cdot \mathrm{Gsm} \cdot T) \quad (2)$$

where ΔD0 is the increase in the net income from the product sales, rub./piece;

Di is the net income per 1 kg (e.g. sheet metal the product is made from), rub./kg;

Np is an income tax rate;

Gsm is the volume of the 0 or n level material resources, from which products are manufactured or which are sold to external organisations, kg/piece;

Wt is specific costs for transportation of material resources after cutting, rub./kg;

Ws is specific costs for storage of material resources after cutting, rub./kg·days;

T is the storage time of material resources, days.

When selling residues after cutting, external organisations are reimbursed for part of the source material costs (second option); therefore, the net income change is assessed by Formula (3):

$$\Delta \mathrm{D}_0 = D_i \cdot \mathrm{Gsm} - (1 - \mathrm{Np})(\mathrm{Wsmc} - \mathrm{Vsm}_i)\mathrm{Gsm} \quad (3)$$

where Vsmi is the selling price of the material resources obtained after cutting, rub./kg; and Wsmc is the specific costs of the source material (which are equal to the purchase price at the first cutting), rub./kg.

Then, under conditions of an unlimited amount of source material purchase, Tmax is assessed by Formula (4):

$$T\max = \frac{\text{W smc} - V\ \text{sm}_i - \text{Wt}}{\text{Ws}} \tag{4}$$

Thus, the time is defined in which the increase in transportation and storage costs is equal to the unreimbursed part of the costs (Wsmc′ rub./kg, the difference in the purchase price of the source material (Wsmc, rub./kg) and the selling price of non-business material resources (Vsmi, rub./kg)) when selling the material resources to external organisations at a reduced market price. Formula (5) presents requirements for the decision-making on attributing the material resources obtained after cutting to the group of business materials in economic terms:

$$\text{Wt} + \text{Ws} \cdot T < \text{Wsmc} - \text{Vsm}_i \tag{5}$$

Thus, the economic aspects of the sorting technique were determined with allowance for loss reduction, which arises in the bottlenecks of the cutting process.

4.5. Prototype of the software package with elements of the decision support system for sorting the material resources obtained after cutting

With the current development of information technologies and the need for prompt and justified managerial decision making, a software package should be developed for managing material resources. It was emphasised earlier that the corresponding programme relating to CAD/CAM systems is tasked with managing rational material cutting. The accounting of material resources is also maintained in a certain ERP system. With the developed proposals, it is essential to develop a software package with elements of the DSS to determine the manufactured material resources after cutting into groups of business and non-business materials according to the proposed sorting technique.

It is necessary to ensure cross-system data synchronisation since certain information on materials will be transferred from the CAD/CAM system to the ERP system (e.g. nomenclature of material resources and values of indicators characterising material resources after cutting), and from the ERP system to the CAD/CAM system (e.g. nomenclature of source material purchased from the supplier and sorting results). To implement the developed proposals, the model structure of the ERP system should be supplemented with a subsystem that implements the management of procurement production. This will expand the functionality of the software package in terms of implementing the DSS for sorting the material resources obtained after cutting and revaluing material resources stored in warehouses, as well as the CAD/CAM and ERP systems interaction.

It is proposed to develop the ‘Procurement production management’ subsystem based on interacting software modules, each performing its own function. The structure of this subsystem and its place in the ERP system are presented in Figure 3. This study considered DSS development based on fuzzy logic, the relevance of which is reflected in Kroshilin et al.’s (2010) and Skorodumova’s (2014) studies.

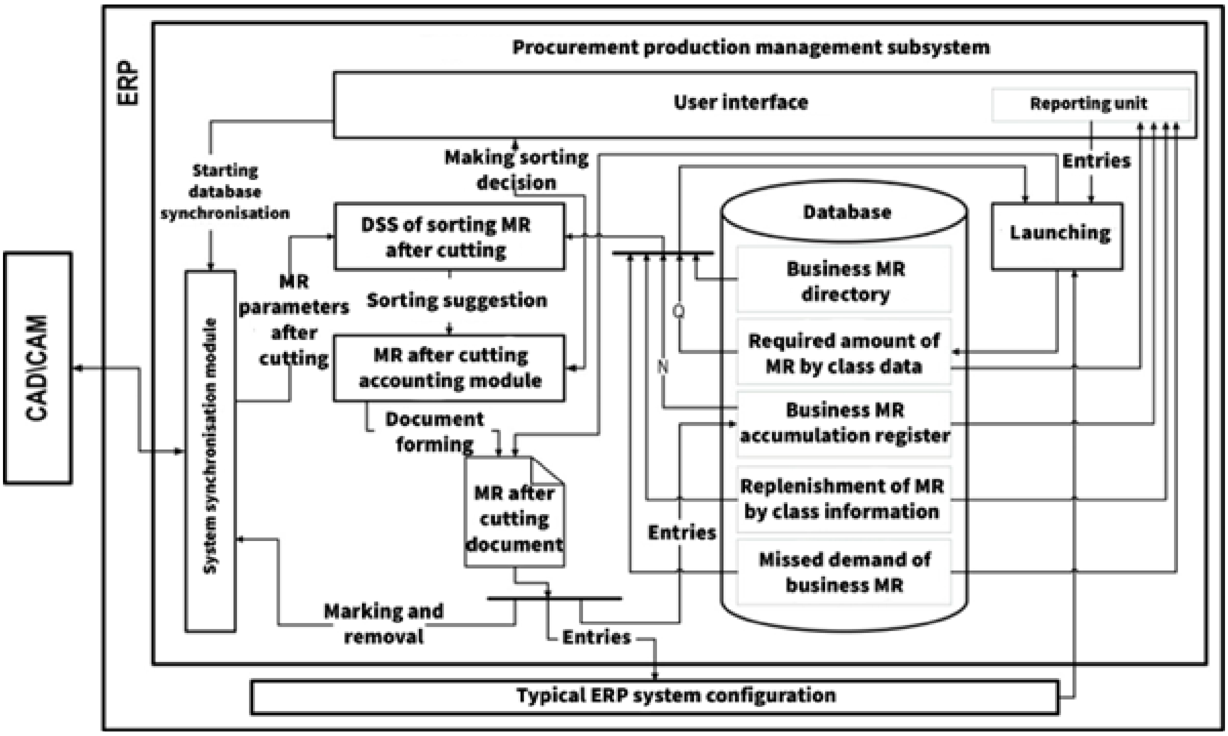

Figure 3. Structure of the 'Procurement production management' subsystem within the framework of the ERP system

Information is processed in the accounting system based on the decision made after the operational proposal for sorting material resources is formed by the DSS and approved by the user.

5. Discussion

The study focuses on the development of mechanical engineering enterprises with single or serial production types. Given that these production types have specific characteristics, the features of the obtained research outputs were not singled out in each of the selected production types. This is because the production types have similar features that equally affect the study results, for example, diverse product range, frequently changing customer requirements for technical characteristics of the existing product line of the enterprise, and inaccurate expected production programme for the expected period before business acquisition.

The study is based on the basic idea of lean manufacturing, namely improving business processes and eliminating various types of losses in the flow of value creation for the consumer. In connection with the identified applied features of the studied problems, the main emphasis was placed on the development of material resources management tools that are aimed at reducing material and time costs, as well as storage costs, when organising rational cutting of industrial materials at mechanical engineering enterprises. More in-depth studies are needed to apply and improve the existing lean manufacturing tools.

The study proposes a methodological approach to the value assessment of materials obtained after cutting, which can be used not only to define a possible selling price but also for transfer pricing. However, there are no specific ranges of the proposed coefficients that affect the price formation of material resources when the values of the assessed indicators change. This is because not all coefficients can be applied at each enterprise, and the range of their values can be different because of production specifics. That is, universal values are quite difficult to choose, but more detailed testing of examples will enhance the practical value of the results. In assessing the cost change in the option of assigning the material resources obtained after cutting to the group of business materials, transportation costs refer to the costs of internal micro-logistic movements from production to warehouse and back to production when necessary. However, the results obtained do not define the technique for assessing these costs, which is certainly necessary for the final sorting of the materials obtained after cutting, and thus requires further research.

When developing the methodological approach to assessing the economic efficiency of assigning material resources to an appropriate group, we assumed that transportation costs are imposed on the consumer when selling non-business material resources to third-party organisations. On the one hand, the introduced condition is a special case. On the other hand, the study proceeded from the fact that separate payment for the service or its inclusion in the price of the materials sold is mainly provided in the case of material resource sale to external organisations on the delivery by the supplier terms. In this regard, it is logical not to take into account delivery costs to the consumer when making a decision on sorting, since they are compensated by the corresponding income. Further, there are no supplier's delivery costs in the self-delivery by the buyer terms. However, delivery costs are mainly borne by the supplier if materials are sold as scrap metal. Therefore, the indicator of the scrap metal delivery cost should be taken into account. If material resources are recognised as scrap metal, they should be added to the formula for assessing the change in the net income, determining the maximum storage time of materials after cutting, and comparing costs in the corresponding sorting options (Formulas 3–5) to increase the versatility of the methodological approach to assessing the economic efficiency of the sorting decision. These shortcomings should be considered in future research.

6. Conclusion

The study made several contributions to material resource management in lean manufacturing at mechanical engineering enterprises. We revealed the problems of material resources management in organising sheet metal cutting and proposed a terminological apparatus that can allow the exploration of a combination of material resources after cutting as a multi-level system. We developed a technique for sorting material resources after cutting to reduce the cost of source material and offer practical recommendations for its development. Methodological provisions for assessing the possible selling price of the material resources obtained after cutting were developed, which allows for organising the managerial accounting of business and non-business material resources in value terms. We also proposed a methodological approach to assessing the economic efficiency of the decision made when sorting the material resources after cutting was proposed. Notably, the study developed a software package prototype with elements of DSS sorting, which allows for making prompt and reasonable managerial decisions when assigning the material resources to the group of business or non-business materials.

Thus, the goal of the study was achieved, i.e., methodological provisions were developed to improve the management tools of material resources in lean manufacturing when cutting materials at mechanical engineering enterprises with single or serial production types. The following managing tools of the material resources were developed: technique for sorting the material resources obtained after cutting into business and non-business resources, software package prototype with elements of the DSS sorting, and managerial accounting regulations for the business process of the material resources received after cutting.

The toolkit developed in this study can help improve the process of rational material cutting at mechanical engineering enterprises and reduce losses in unreasonable sorting of the material resources obtained after cutting from the point of view of lean production. By applying this toolkit, material costs are reduced due to the use of business material resources, which could be recognised as non-business under empirical sorting. Further, the costs of storage and transportation of non-business material resources that could be recognised as business ones are reduced, and less time is spent finding and transporting business material resources in case of the production need. This allows enterprise managers to increase the net income or optimise the cost structure in the customer value-creating flow, offer a customer-oriented price, increase competitiveness, and promote lean and responsible use of natural resources in manufacturing, which ensures sustainable development of the enterprise.

Future studies should focus on developing proposals for organising the storage process and marking the material resources received after cutting.

References

Demidenko, D.S., Malevskaia-Malevich, E.D., 2014. The industrial waste utilization as an economic challenge. St. Petersburg State Polytechnical University Journal. Economics 209 (6), 90–97.

Demidenko, D.S., Malevskaya-Malevich, E.D. 2013. Increasing production efficiency through increased use of secondary resources in enterprises of St. Petersburg. St. Petersburg State Polytechnical University Journal. Economics 175 (4), 84–89.

Dyckhoff, H., 1990. A typology of cutting and packing problems. European Journal of Operational Research 44 (2), 145–159.

Filippova, A.S., Valiakhmetova, Yu.I., 2013. L.V. Kantorovich's theory of optimal resource utilization in scientific papers of Ufa school. Omsk Scientific Bulletin 1, 39–42.

Kantorovich, L.V., Zalgaller, V.A., 1971. Rational cutting of industrial materials. Novosibirsk: Nauka.

Kartak, V.M., Mesyagutov M.A., Mukhacheva E.A., Filippova A.S., 2009. Local search of orthogonal packings using the lower bounds. Automation and Remote Control 70 (6), 1054–1066.

Kartak, V.M., Ripatti A.V., 2019. Large proper gaps in bin packing and dual bin packing problems. Journal of Global Optimization 74 (3), 467–476.

Kroshilin, A.V., Babkin, A.V., Kroshilina, S.V., 2010. Features of building decision support systems based on fuzzy logic. St. Petersburg State Polytechnical University Journal. Informatics. Telecommunications. Management 97 (2), 58–63.

Mukhacheva, E.A., 1984. Rational cutting of industrial materials. Application of ACS. M.: Mashinostroenie.

Petunin, A.A., 2010. Automatic technique selection of assessing the figured cutting using comparative algorithm analysis. Bulletin of the Tomsk Polytechnic University. Geo Asset Engineering 316 (5), 169–171.

Safronova, K.O., Tsvirkunov, D.I., 2020. Maturity level study of applying lean manufacturing at Russia's enterprises. Bulletin of Moscow University. Series 6: Economics, 2, 106–122.

Salkova, O.S., Sokolovskiy, M.V., Kononova, S.A., Kolotova, Ye.A., Organization of accounting the motion of metal at chemical engineering enterprises: Problems and opportunities. Fundamental Research 11, 163–168.

Shichkov, A., Gluhov V., 2019. Model and toolkit for the formation of the production enterprise digital platform. IOP Conference Series: Materials Science and Engineering 497, 012093. https://doi.org/10.1088/1757-899X/497/1/012093

Shichkov, A.N., 2016. Designing manufacturing technological systems. Scientific Israel-Technological Advantages 1, 89–106.

Shichkov, A.N., 2016. Innovative enhancement of an engineering business: Operation cycle method. Scientific Israel-Technological Advantages 4, 100–111.

Shichkov, A.N., Borisov, A.A., Kremleva, N.A., 2019. Digital platform of controlling applied tasks in engineering business. Digital Economy and Industry 4.0: Trends 2025. Proceedings of scientific and practical conference with international participation. Edited by A.V. Babkin, 652–664.

Skorodumov, P.V., 2014. Modelling of economic systems with Petri nets. Economic and Social Changes: Facts, Trends, Forecast 4, 253–259.

Smirnov, A., Kobzev, V., Skvortsov, S., 2019. Sheet metal material resources management in lean production. E3S Web of Conferences 110, 01029. https://doi.org/10.1051/e3sconf/201911001029

Smirnov, A.A., 2017. Economic aspects of making managerial decisions in the identification of material resources of sheet metal at an engineering enterprise. St. Petersburg State Polytechnical University Journal. Economics 6, 195–204.

Suloeva, S.B., Gultseva, O.B., 2017. Cost management system: Conceptual provisions. Organizer of Production (theoretical and scientific-practical journal) 25(3), 47–58.

Tolstobrov, D.A., 2019. Operational assessment of the probability of order fulfillment in the conditions of uncertainty of consumer demand. Applied Mathematics and Control Sciences 3, 133–157.

Turovets, O.G., Rodionova, V.N., 2016. On some problems of ensuring effective organization of high-tech production. Organizer of Production (theoretical and scientific-practical journal) 68 (1), 47–53.

Valiakhmetova, Yu.I, Filippova, A. S., 2014. Theory of optimum resource utilization by L. V. Kantorovich in cutting-packing problems: overview and history of development of solving methods. Vestnik UGATU (scientific journal of Ufa State Aviation Technical University) 18 (62), 186–197.

Valiakhmetova, Yu.I, Telitskiy, S.V., 2012. Application of computer-aided design of cutting charts in shipbuilding. Bulletin of Voronezh State Technical University 6, 38–43.

Wascher, G., Haubner, H., Schumann, H., 2007. Improved typology of cutting and packing problems. European Journal of Operational Research 183(3), 1109–1130.

Список источников

Dyckhoff, H., 1990. A typology of cutting and packing problems. European Journal of Operational Research 44(2), 145-159.

Kartak V.M., Mesyagutov M.A., Mukhacheva E.A., Filippova A.S., 2009. Local search of orthogonal packings using the lower bounds. Automation and Remote Control 70(6), 1054-1066.

Kartak V.M., Ripatti A.V., 2019. Large proper gaps in bin packing and dual bin packing problems. Journal of Global Optimization 74(3), 467-476.

Shichkov A. N., 2016. Designing manufacturing technological systems. Scientific Israel-Technological Advanteges 1, 89-106.

Shichkov A., Gluhov V., 2019. Model and toolkit for the formation of the production enterprise digital platform. IOP Conference Series: Materials Science and Engineering 497, 012093. https://doi.org/10.1088/1757-899X/497/1/012093

Shichkov A.N., 2016. Innovative Enhancement of an Engineering Business: Operation Cycle Method. Scientific Israel-Technological Advanteges 4, 100-111.

Skorodumov P.V., 2014. Modelling of economic systems with Petri nets. Economic and Social Changes: Facts, Trends, Forecast 4, 253-259.

Smirnov A., Kobzev V., Skvortsov S., 2019. Sheet metal material resources management in lean production. E3S Web of Conferences 110, 01029. https://doi.org/10.1051/e3sconf/201911001029

Wascher G., Haubner H., Schumann H., 2007. An improved typology of cutting and packing problems. European Journal of Operational Research 183(3), 1109-1130.

Валиахметова Ю.И., Телицкий С.В., 2012. Применение систем автоматизированного проектирования карт раскроя в судостроении. Вестник Воронежского государственного технического университета 6, 38-43.

Валиахметова Ю.И., Филиппова А.С., 2014. Теория оптимального использования ресурсов Л. В. Канторовича в задачах раскроя-упаковки: обзор и история развития методов решения. Вестник Уфимского государственного авиационного технического университета 1, 186-197.

Демиденко Д.С., Малевская-Малевич Е.Д., 2013. Повышение эффективности производства на основе расширения использования вторичных ресурсов на предприятиях Санкт-Петербурга. Научно-технические ведомости СПбГПУ. Экономические науки 175 (4), 84-89.

Демиденко Д.С., Малевская-Малевич Е.Д., 2014. Экономическая задача эффективного использования производственных отходов предприятием. Научно-технические ведомости СПбГПУ. Экономические науки 209(6), 90-97.

Канторович Л.В., Залгаллер В.А., 1971. Рациональный раскрой промышленных материалов. Новосибирск: Наука, 300 с.

Крошилин А.В., Бабкин А.В., Крошилина С.В., 2010. Особенности построения систем поддержки принятия решений на основе нечёткой логики. Научно-технические ведомости Санкт-Петербургского государственного политехнического университета. Информатика. Телекоммуникации. Управление 97(2), 58-63.

Мухачева Э. А., 1984. Рациональный раскрой промышленных материалов. Применение АСУ. М.: Машиностроение, 176 с.

Петунин А.А., 2010. Автоматический выбор метода расчета фигурного раскроя с использованием сравнительного анализа алгоритмов. Известия Томского политехнического университета. Инжиниринг георесурсов 316(5), 169-171.

Салькова О.С., Соколовский М.В., Кононова С.А., Колотова Е.А., 2019. Организация учета движения металла на предприятиях химического машиностроения: проблемы и возможности. Фундаментальные исследования 11, 163-168.

Сафронова К.О., Цвиркунов Д.И., 2020. Исследование уровня зрелости применения бережливого производства на российских предприятиях. Вестник Московского университета. Серия 6: Экономика 2, 106-122.

Смирнов А.А., 2017. Экономические аспекты принятия управленческих решений при идентификации материальных ресурсов листового металла на машиностроительном предприятии. Научно-технические ведомости СПбГПУ. Экономические науки 6, 195-204.

Сулоева С.Б., Гульцева О.Б., 2017. Система управления затратами: концептуальные положения. Организатор производства 25(3), 47-58.

Толстобров Д.А., 2019. Оперативная оценка вероятности выполнения заказа при условии неопределенности потребительского спроса. Прикладная математика и вопросы управления 3, 133-157.

Туровец О.Г., Родионова В.Н., 2016. О некоторых проблемах обеспечения эффективной организации высокотехнологичного производства. Организатор производства 68(1), 47-53.

Филиппова А.С., Валиахметова Ю.И., 2013. Теория оптимального использования ресурсов Л. В. Канторовича в работах Уфимской научной школы. Омский научный вестник 1, 39-42.

Шичков А.Н., Борисов А.А., Кремлёва Н.А., 2019. Цифровая платформа контроллинга прикладных задач инженерного бизнеса: Цифровая экономика и Индустрия 4.0: тенденции 2025. Сборник трудов научно-практической конференции с международным участием. Под редакцией А.В. Бабкина, 652-664.

The article was submitted 11.09.2022, approved after reviewing 14.12.2022, accepted for publication 23.12.2022.

Статья поступила в редакцию 11.09.2022, одобрена после рецензирования 14.12.2022, принята к публикации 23.12.2022.

About authors:
1. Artem Smirnov, postgraduate, Graduate School of Production Management, Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russia; senior lecturer, Vologda State University, Vologda, Russia. https://orcid.org/0000-0001-5431-4150, smirnov.artem.a@yandex.ru

2. Vladimir Kobzev, Doctor of Economics, Professor, Graduate School of Production Management, Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russia. https://orcid.org/0000-0002-4144-4287, kobzev_vv@mail.ru

3. Cholpon Nuralieva, Doctor of Economics, Deputy Head of the Department of Accounting, Analysis and Audit, Professor, Kyrgyz-Russian Slavic University named after B.N. Yeltsin, Bishkek, Kyrgyz Republic. https://orcid.org/0000-0001-8005-054X, nur-cholpon@mail.ru

Информация об авторах:
1. Артём Смирнов, соискатель, Высшая школа производственного менеджмента, Санкт-Петербургский политехнический университет Петра Великого, Санкт-Петербург, Россия; старший преподаватель, Вологодский государственный университет, Вологда, Россия. https://orcid.org/0000-0001-5431-4150, smirnov.artem.a@yandex.ru

2. Владимир Кобзев, доктор экономических наук, профессор Высшей школы производственного менеджмента, Санкт-Петербургский политехнический университет Петра Великого, Санкт-Петербург, Россия. https://orcid.org/0000-0002-4144-4287, kobzev_vv@mail.ru

3. Чолпон Нуралиева, доктор экономических наук, зам. зав. кафедрой бухгалтерского учета, анализа и аудита, профессор, Кыргызско-Российский Славянский университет им. Б.Н. Ельцина, Бишкек, Кыргызская Республика. https://orcid.org/0000-0001-8005-054X, nur-cholpon@mail.ru