OPTIMIZATION OF THE FULL PRODUCTION CYCLE OF NATURAL STONE PRODUCTS IN A SMALL ENTERPRISE: FROM SKETCH TO INSTALLATION

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Abstract. *The article is devoted to the problem of optimizing the full production cycle of natural stone products in a small enterprise. Modern development trends in the stone-processing industry are characterized, highlighting the high sensitivity of small-scale production to organizational losses. The typical stages of the full production cycle of natural stone products are disclosed and formalized, and their structural decomposition is presented with the identification of key sources of costs. The main problems faced by small enterprises are identified, including the lack of standardized operations, suboptimal sequencing of work, insufficient preparation of raw materials, and a high share of manual adjustments. Based on the analysis of contemporary research, the principal directions of optimization are identified. An optimization model is proposed – an integrated cyclical system consisting of process mapping, a matrix of losses and risk factors, an algorithm for self-assessment of technological maturity, and procedures for planning improvements. Groups of performance indicators applicable for evaluating the results of the model's implementation are specified.*

Keywords: *optimization of the full production cycle; stone-processing industry; technological operations in stone-processing production; optimization model for small-scale manufacturing; loss optimization in a stone-processing enterprise.*

The production of natural stone products belongs to resource- and labor-intensive activities characterized by a high share of material costs, energy-consuming processes, and a pronounced sensitivity to organizational errors and downtime. In the context of the continual increase in the cost of materials, the rising expenses of logistics, tools, and labor resources, the task of optimizing the production cycle becomes not merely a direction of development but a fundamental factor determining the economic feasibility and viability of small enterprises. In the stone-processing industry, the problem of optimization is particularly acute, as the quality of the final product directly depends on adherence to technology and on the efficiency of managing each stage of the production cycle. Production costs remain extremely high, and any losses arising during manufacturing processes adversely affect overall profitability.

It should be noted that the global natural stone industry is developing unevenly, yet overall it is characterized by rapid technological advancement and continuous modernization, accompanied by increasing demands for quality and environmental sustainability of processes. Global trends indicate a growing potential of production systems for manufacturing diverse product variations, along with an expansion of areas in which high-precision processing technologies are applied; at the same time, comprehensive systems for modernizing extraction and processing are being increasingly implemented in stone-processing and quarrying operations [1]. Conversely, enterprises operating primarily in the domestic market and effectively belonging to the segment of small-scale production continue to face the problem of insufficient technological levels of equipment and process organization in comparison with the requirements of modern competition [2], which further reinforces the importance of optimization-oriented solutions.

As a rule, the need to reduce costs is accompanied by a deterioration in quality; at the same time, the market for stone products operates on the principle of high trust in the manufacturer and minimization of defects (including qualitative losses). However, in the professional sense, optimization does not imply a mechanical reduction of expenses and personnel–an approach that often leads to the degradation of processes–but rather the well-grounded improvement of operations based on eliminating losses, unnecessary actions, movements, technological gaps, and suboptimal decisions. In essence, contemporary approaches to the technological enhancement of stone extraction, cutting, and mechanical processing confirm the effectiveness of optimization models grounded in a comprehensive analysis of the causes of losses and the algorithmization of solutions, as well as in the implementation of energy- and resource-efficient technologies, robotic processing methods, and intelligent information-modeling systems for cutting design. The application of these optimization solutions must follow a sequential and strictly formalized procedure; the management of optimization within the full production cycle of a small enterprise is tied to the numerous points at which potential losses may arise within its structure. At the same time, the issues of identifying such losses and modeling a system aimed at optimization remain largely undeveloped in the contemporary literature, which has determined the relevance of the topic under consideration.

The aim of the study is to substantiate an optimization toolkit for the full production cycle of natural stone products, oriented toward the specific features of a small enterprise.

In the context of a small enterprise, optimization of the production cycle is understood as a purposeful process of transforming operations aimed at reducing costs, eliminating losses, and increasing the accuracy and efficiency of work without diminishing the quality of the final product. It should be noted that in current conditions the problem of interpreting the concept of "optimization" remains one of the key issues, as in practical terms it is often perceived as a mechanical reduction of expenses through saving on materials, equipment, technologies, and personnel, which gradually leads to the degradation of business processes, the accumulation of errors, and an increase in hidden costs. For this reason, genuine optimization and rationalization must be based on the principles of functionality, justification, and systemic coherence

Thus, effective optimization does not aim to increase the workload on personnel, reduce staffing levels, or superficially cut equipment costs. On the contrary, it involves identifying organizational and technological solutions that make it possible to redistribute operations, eliminate unnecessary transitions between stages, reduce the share of manual labor in areas where errors most frequently occur, and increase the overall manageability of core processes. Drawing on research in the optimization of production systems within the stone-processing industry, it should be noted that the most effective way to improve efficiency is to enhance operational technologies, strengthen quality control of material preparation, and increase the precision of processing [3; 4]. Overall, the optimization framework for a small enterprise is structured in a specific way (Figure 1).

In practice, optimization often begins with identifying bottlenecks–those operations that slow down the process or generate losses. Small enterprises typically face several common groups of issues, including: (1) lack of coordination between stages, (2) suboptimal sequencing of operations, (3) absence of standardized quality requirements, (4) insufficient diagnostic assessment of materials prior to processing, (5) downtime caused by the absence of a systematic machine-loading schedule, and (6) excessive labor and time costs resulting from manual error corrections.

At the same time, the key indicator of high-quality optimization is the achievement of several effects associated with reducing operating costs, shortening the time required to perform operations while maintaining their outcomes and quality, decreasing the share of defects, lowering the workload on personnel, increasing the predictability of results, and enabling the enterprise to handle a larger volume of work without overextending equipment resources. Equally important is the improvement of technological precision, since in stone processing an error made at an early stage typically leads to the complete loss of the item or to costly rework.

It should be noted that the raw material (natural stone) is highly valuable and sensitive to processing quality; therefore, by eliminating inefficient operations, the enterprise gains the ability to stabilize production costs amid rising market prices, ensure competitive product quality, reduce technological risks, and overall accelerate the transition from design to installation.

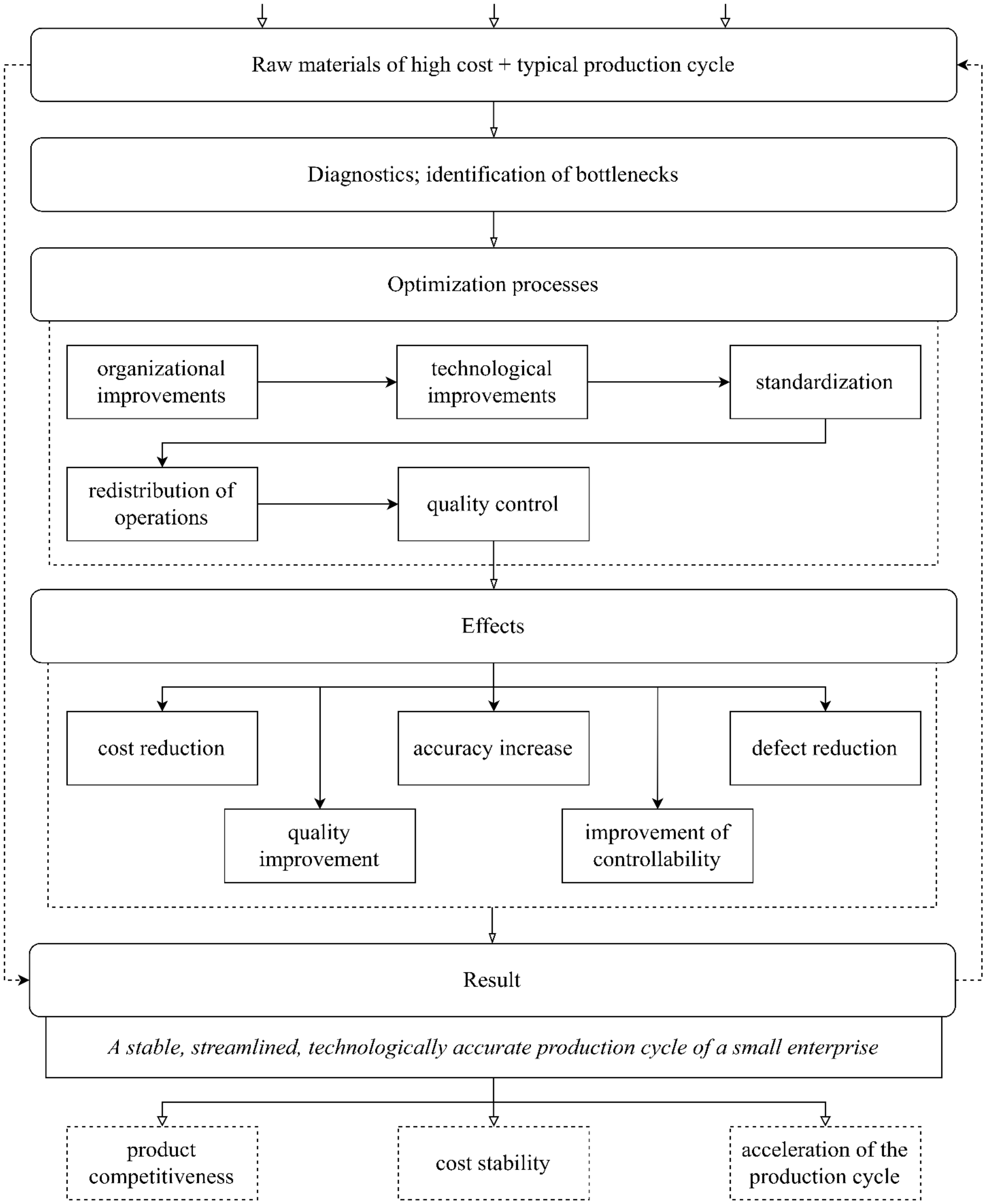

Figure 1. Optimization system in the context of a small enterprise

In the context of the production cycle for natural-stone products at a small enterprise, it should be noted that this cycle has a typical structure and can be formalized as a sequence of stages and their constituent operations (Figure 2): product design, material selection and procurement, primary cutting, mechanical processing, finishing operations, quality inspection, packaging, logistics, and on-site installation. Each stage has its own technological characteristics, set of operations, typical costs, and sources of losses, which together determine the economic efficiency of the enterprise, the quality of the products, and the consistency of order fulfillment.

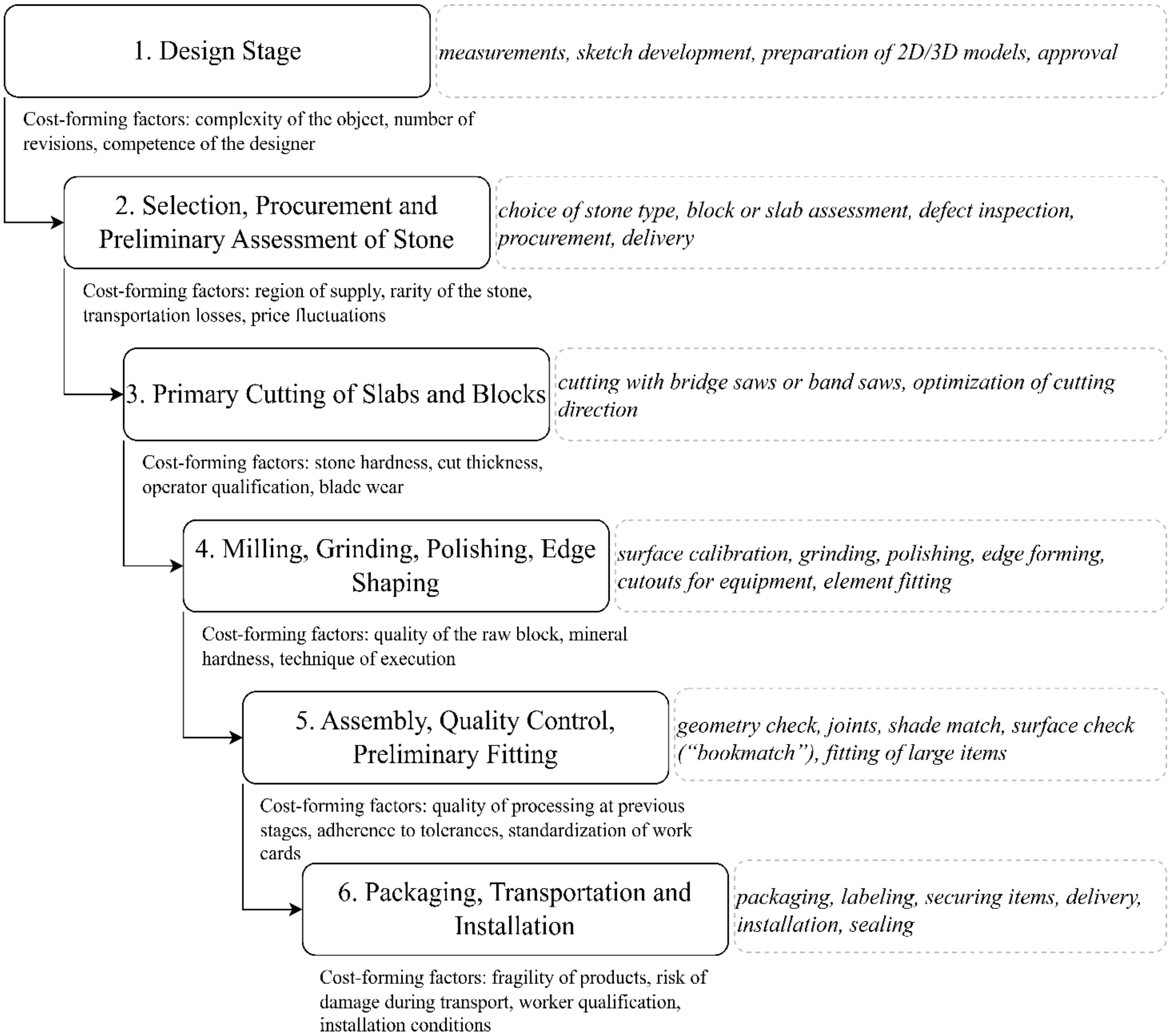

Figure 2. Full production cycle of natural-stone products at a small enterprise

At each stage, specific types of costs are generated; however, in most cases, the main losses are associated with:
- the absence of standardized tolerances;
- excessive adjustments;
- low quality of incoming raw materials;
- a non-optimal sequence of operations;
- equipment downtime;
- measurement errors;
- unnecessary movement of personnel and materials;
- insufficient surface preparation for subsequent operations.

According to recent research, the main approaches to overcoming these issues include:

1. Energy optimization and reduction of equipment energy consumption [5].
2. Environmental optimization and reduction of waste generation [6].
3. Technological optimization of stone cutting and processing [7].
4. Implementation of lean manufacturing in the supply chain and production workshop [8].
5. Optimization of the production process in terms of its readiness for change [9].
6. Optimization of processing parameters with consideration of raw material properties [10].

Moreover, within each of the directions presented in studies [5-10], specific methods and examples of optimization are identified; by grouping them and correlating them with the full production cycle of natural stone products, the following optimization matrix is formed (Table).

Moreover, given the variety of optimization procedures, measures, and implementation methods, it is important to develop a methodological toolkit for their application, aligned with the process-based structure of implementation (Figure 3).

Table. Optimization matrix for the full production cycle of natural stone products, compiled by the author.

Stage of production	Main problem / Source of losses	Optimization measures	Expected effect
1) Design and product modeling	Failure to account for stone properties; excessive design revisions; geometry errors leading to rework	Use of digital models that predict energy intensity and processing complexity, allowing advance optimization of product parameters	Fewer operations and errors; more accurate assessment of labor intensity; optimal processing trajectory
2) Raw material procurement and assessment	Material overuse due to structural defects; high share of waste and losses	Development of raw material selection standards and assessment criteria	Reduced unsuitable material; less waste; more stable raw material quality
3) Primary cutting of blocks and slabs	Suboptimal cutting direction; large amount of waste; unnecessary cut surfaces	Use of optimization software for cutting layouts and modern geometrical planning methods	Lower tool consumption; reduced energy use; higher yield of usable product per block
4) Mechanical processing, milling, polishing, grinding; quality control	Excessive labor intensity; too many passes; defects from poor sequencing; inconsistent quality; repeated fitting; increased waste (slurry, chips)	Implementation of lean strategies and flexible processing workflows; production chain modeling to eliminate unnecessary operations (Agile–Lean); assessment of processing impacts on particle-size distribution of waste	Shorter cycle time; fewer defects; reduced equipment load; lower abrasive use; improved quality stability; reduced waste; higher precision of fits
5) Assembly, test fitting, inspection of joints and dimensions	Frequent adjustments; element misalignment; dimensional deviation during assembly	Use of hybrid lean methods in the stone product supply chain (flow modeling, bottleneck prediction, variability reduction)	Higher accuracy; shorter assembly time; fewer reworks; predictable results
6) Packaging, transportation, installation	Damage during transportation; lengthy installation; high workload on installation team	Installation optimization through forecasting resource intensity, calculating forces, minimizing on-site operations	Lower risk of damage; shorter on-site time; improved installation safety

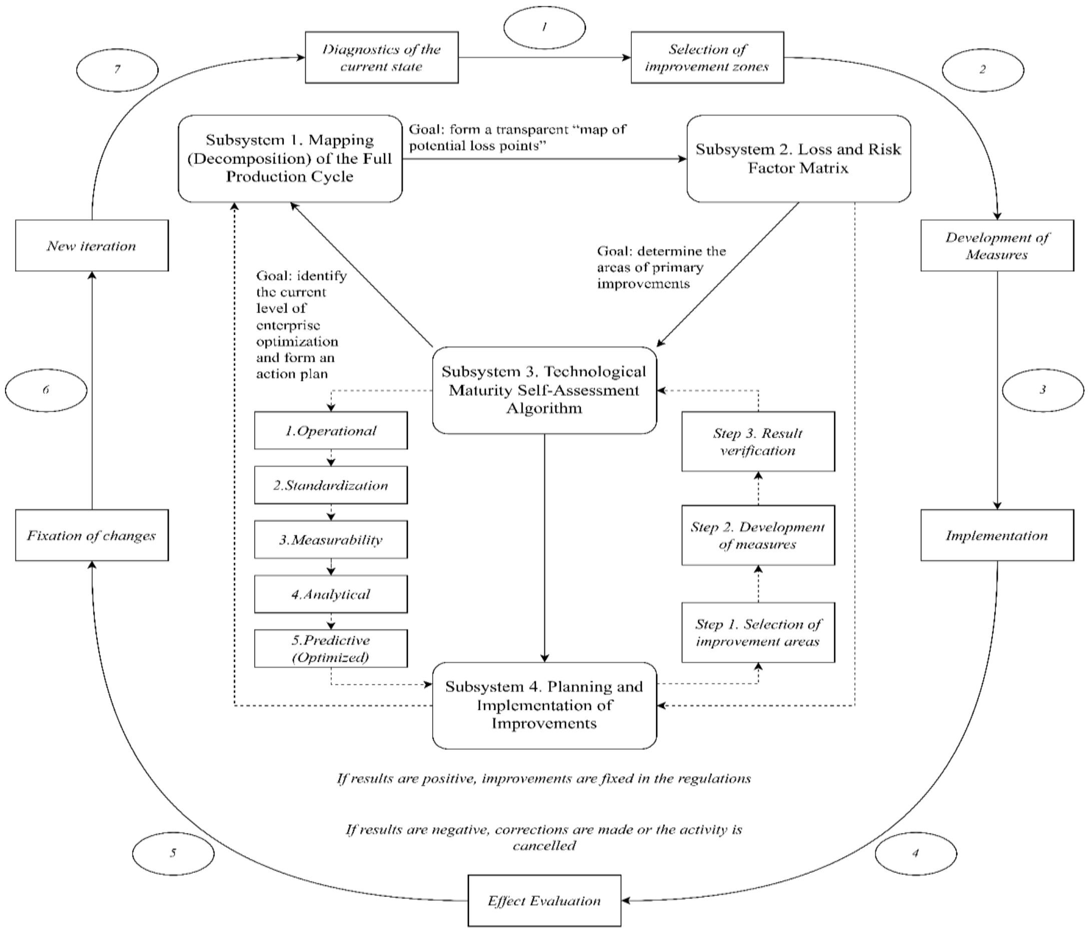

Figure 3. Model for optimizing the full production cycle of stone products

The developed model represents an integrated structure that includes a functional decomposition of the full production cycle, a system of evaluation criteria, an internal algorithm for self-assessment of technological maturity, and tools for planning improvements. The model consists of four interconnected subsystems.

Subsystem 1. Mapping (decomposition) of the full cycle. At the first stage, the enterprise creates a map of all processes (design and sketch development; procurement of blocks/slabs; cutting; mechanical processing; finishing operations; logistics; installation; quality control and final delivery). For each process, the inputs (data, raw materials, resources), outputs (results, semi-finished products, finished items), operations, executors, standard times, and typical deviations and errors are identified. The purpose of this subsystem is to form a map of loss generation points.

Subsystem 2. Loss and risk factor matrix. At the second stage, a loss matrix is created for each process, including the following categories of losses: technological (defects, chips, surface damage), material (waste, unused blanks), time-related (downtime, waiting, changeovers), informational (incomplete technical specifications, measurement errors), organizational (uneven workload, schedule conflicts), and financial (increased tool consumption, excessive use of chemicals). Each factor is assigned a probability of occurrence, its impact on cost, the probability of detection, and a priority level. The goal of this subsystem is to identify the areas that require improvement first.

Subsystem 3. The technological maturity self-assessment algorithm, which represents a sequence of diagnostic steps used to evaluate the enterprise's current level of optimization and to develop an action plan. For example, Level 1 (operational) is characterized by chaotic processes, the absence of standard times, dependence on individual craftsmen, and a lack of systematic quality control. In this case, the self-assessment records the presence of process descriptions, the stability of performance indicators, the share of defects, and the volume of waste. Gradually, the enterprise moves from describing individual operations to their standardization, measurement, analysis (detailed diagnostics), and ultimately to optimization.

Subsystem 4. Planning and implementation of improvements, which consist of selecting the improvement area, developing specific measures, and verifying the results based on whether losses have decreased, the yield rate has improved, operation time has been reduced, defects have decreased, and production costs have been lowered. A promising approach here is to focus on the performance indicators of optimizing the full production cycle, which can be grouped into technological, quality-related, resource-related, organizational, and financial-economic categories. These indicators are established by the company itself and are assessed as improvements (optimization measures) are implemented.

Thus, the study made it possible to develop a model for optimizing the full production cycle of a small enterprise specializing in natural stone products and to demonstrate that the enterprise's efficiency is determined by the coherence of all stages of the production cycle. Taken together, the proposed model, the optimization matrix, and the identified groups of indicators form a methodological tool that can be used by small enterprises to improve efficiency, reduce production costs, increase the precision and quality of products, and strengthen their competitive position in the local natural stone market.

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ОПТИМИЗАЦИЯ ПОЛНОГО ЦИКЛА ПРОИЗВОДСТВА ИЗДЕЛИЙ ИЗ НАТУРАЛЬНОГО КАМНЯ НА МАЛОМ ПРЕДПРИЯТИИ: ОТ ЭСКИЗА ДО МОНТАЖА

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Аннотация. *Статья посвящена проблеме оптимизации полного цикла производства изделий из натурального камня на малом предприятии. Охарактеризованы современные тенденции развития камнеобрабатывающей отрасли, определяющие чувствительность малых производств к организационным потерям. Раскрыты и формализованы типовые этапы полного цикла производства изделий из натурального камня, представлена их структурная декомпозиция с выделением основных источников издержек. Выявлены проблемы малых предприятий, связанные с отсутствием стандартизации операций, неоптимальной последовательностью работ, недостаточной подготовкой сырья и высокой долей ручных корректировок. На основе анализа современных исследований выявлены основные направления оптимизации. Предложена модель оптимизации – интегрированная цикличная система, состоящая из картирования процессов, матрицы потерь и факторов риска, алгоритма самооценки технологической зрелости и процедур планирования улучшений. Уточнены группы показателей эффективности, применимые для оценки результатов применения модели.*

Ключевые слова: *оптимизация полного производственного цикла; камнеобрабатывающая отрасль; технологические операции камнеобрабатывающего производства; модель оптимизации малого производства; оптимизация потерь на камнеобрабатывающем предприятии.*