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Technological solution for improving productivity and efficiency in manufacturing processes

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Abstract: The aim of this paper is to evaluate the impact of technological modernization on productivity, efficiency, and energy performance of manufacturing processes. In wood-processing production, the drying operation represents a critical technological stage due to its high time and energy demands. The applied methodology is based on a comparative case study approach. It includes technical, productivity, efficiency, and economic assessments of the existing drying technology and the proposed modern automated drying kiln. Productivity was evaluated as production output per unit of time, while efficiency was assessed using specific energy consumption per unit of dried lumber volume. The analysis was conducted using operational data obtained directly from the manufacturing environment. The results confirm that the modernization of drying technology leads to a significant reduction in drying cycle duration, enabling higher throughput and increased productivity without additional labour input. The modernization resulted in a productivity increase of up to 45% and a reduction in specific energy consumption of up to 25%. The economic evaluation demonstrates that productivity growth and energy savings create favourable conditions for reducing unit production costs and improving capacity utilisation. The findings indicate that targeted technological modernization of key production operations represents an effective tool for increasing productivity and efficiency in wood-processing manufacturing and provides a practical basis for investment decision-making and process optimisation.

1 Introduction

The wood-processing industry plays a strategically important role in economic development, as it transforms renewable raw materials into products with high added value [1,2]. However, despite the ecological benefits of wood, its limited availability and long regeneration period require companies to adopt a sustainable approach to resource utilisation and continuously improve operational efficiency in order to remain competitive [3,4].

Increasing global demand for wood-based products places continuous pressure on manufacturing companies to enhance productivity while reducing costs and environmental impacts [3]. Labour productivity represents a key indicator influencing production performance and business sustainability in the wood industry [5].

Recent research highlights that modernization of technological equipment is a fundamental prerequisite for eliminating production bottlenecks and ensuring stable output [6,7]. The implementation of automated control systems contributes not only to higher operational efficiency but also to reduced material waste and improved quality consistency [8,9]. Technological innovations therefore support sustainable economic growth by increasing process flexibility and reducing energy intensity in manufacturing.

Industrial enterprises operating in dynamic market environments must continuously optimise their production systems to remain competitive. Productivity represents the relationship between input resources and achieved outputs, while efficiency reflects the degree to which managerial and operational objectives are achieved in manufacturing enterprises.

In the wood-processing industry, productivity is significantly influenced by production planning, technological equipment, material flow organisation, workforce qualification, and the level of technological losses. Timber drying is recognised as one of the most time-intensive and energy-demanding operations in wood-processing manufacturing and significantly affects production lead time and overall throughput. Inefficient drying technology may result in low throughput, increased operating costs, quality deviations, and delays in order fulfilment.

To achieve higher performance indicators, modernization of key production technologies is essential. The implementation of advanced drying systems contributes not only to shortening the production cycle but also to improving mechanical stability, dimensional accuracy, and the commercial value of final products.

Based on the need to optimise productivity and efficiency in the production process, the aim of this paper is to evaluate the impact of drying technology modernization on productivity, energy efficiency, and economic performance under real industrial conditions. The study focuses on the replacement of outdated drying technology with an advanced automated system designed to support faster processing, more stable operating conditions, and reduced energy consumption.

2 Methodology

The research was conducted in a real wood-processing manufacturing enterprise focused on the production of coniferous timber products. The study applies a case study approach aimed at evaluating the impact of technological modernization on productivity, efficiency, and energy performance of the drying operation.

The methodological framework consisted of six consecutive steps. The first step involved an analysis of the current production system, with a focus on the drying operation as a critical bottleneck influencing production throughput, energy consumption, and product quality. The second step focused on the technical characterisation of the existing drying kiln, including capacity, drying cycle duration, operating temperature, installed power, and the level of process automation. Operational data were obtained from production records and direct observations. The third step consisted of proposing a modern drying technology represented by an automated Mühlböck drying kiln equipped with an intelligent K5 control system. The proposed technology was analysed based on manufacturer specifications and projected operational parameters. The fourth step involved a comparative evaluation of productivity, expressed as production output per unit of time. Productivity was assessed by comparing the number of drying cycles and processed lumber volume under identical time conditions before and after modernization. The evaluation focused on the reduction of drying cycle duration and the resulting increase in throughput. The fifth step focused on efficiency and energy evaluation based on the relationship between output volume and energy input. Energy efficiency was assessed using specific energy consumption per cubic metre of dried lumber ($kWh \cdot m^{-3}$), taking into account improvements in thermal insulation, air circulation, and automated process control. The final step involved an economic assessment of the modernization proposal, including a comparison of operating conditions and justification of the investment from a techno-economic perspective. The evaluation was based on real enterprise data and standard economic indicators commonly applied in industrial practice.

All quantitative data used in the analysis were derived from actual production conditions documented in the enterprise records and from calculations performed within the framework of the associated diploma thesis. Compared to the diploma thesis, this paper extends the analysis by introducing a structured quantitative evaluation framework combining productivity, energy efficiency, and economic indicators under consistent operational assumptions. The performance parameters of the proposed drying technology were derived from manufacturer-provided technical specifications and design documentation, enabling a direct comparison of the current and proposed technological solutions [10].

3 Results and discussion

3.1 Technical comparison of drying technologies

Drying represents one of the most time-consuming and energy-intensive technological operations in wood-processing manufacturing. Its performance significantly influences production throughput, operational costs, and product quality. The existing drying kiln used in the analysed enterprise is based on hydrothermal wood treatment and manual or semi-automatic process control. Although the kiln remains operational, its performance is limited by outdated control mechanisms, longer drying cycles, and higher thermal losses.

The proposed technological solution involves the replacement of the existing system with a modern Mühlböck drying kiln equipped with an intelligent K5 control system. The modernization introduces a higher level of automation, improved air circulation, enhanced thermal insulation, and optimised heat recovery. These technical improvements directly influence drying cycle duration, process stability, and energy utilisation. The K5 control system enables automated regulation of temperature, humidity, and airflow parameters throughout the drying process. The main functional architecture of the control and monitoring system is illustrated in Figure 1.

Figure 1 Mühlböck K5 automatic control and monitoring system [11]

To enable a quantitative comparison, Table 1 presents selected technical parameters of the current and proposed drying technologies.

Table 1 Technical comparison of current and proposed drying kilns (Source: own processing)

Parameter	Current	Proposed
Chamber capacity (m^3)	120	120 + 120
Drying time for spruce (h)	135 – 270	67 – 202
Drying time for fir (h)	192 – 384	96 – 288
Final moisture content (%)	80 → 10	80 → 10
Max. chamber temp. (°C)	70	95
Installed power (kW)	400	500 + 500

The comparison shows that the proposed solution enables the parallel operation of two drying chambers with a capacity of 120 m^3 each, resulting in an increase in the total installed drying capacity to 240 m^3. However, the increase in productivity is not achieved solely by expanding the drying capacity through parallel chamber operation, but also by shortening drying cycles and optimising process parameters due to a higher level of automation.

3.2 Productivity evaluation

Productivity in the drying process was evaluated as the ratio between production output and processing time. In accordance with the applied methodology, productivity was expressed as the volume of dried lumber processed per unit of time (1):

$$P = \frac{Q}{t} \tag{1}$$

where:
P is productivity ($m^3 \cdot h^{-1}$),
Q is the volume of dried lumber (m^3),
t is the total drying time (h).

For productivity evaluation, the production output Q was defined as the total volume of lumber processed by all drying chambers operating in parallel during one drying cycle.

Productivity growth results from the combined effect of parallel chamber operation and a significant reduction in drying cycle duration achieved through technological modernization and a higher level of process automation.

The modernization of the drying technology results in a substantial reduction in drying cycle duration. For spruce lumber, the drying time decreases from 135–270 h to 67–202 h, while for fir lumber the cycle duration is reduced from 192–384 h to 96–288 h. This reduction enables a higher number of drying cycles to be completed within the same operational time frame.

Productivity growth is primarily achieved through a reduction in technological waiting time and an increased number of processed batches per unit of time. Based on comparative calculations performed under identical operational conditions, the modernization of the drying technology resulted in a productivity increase of approximately 30–45 %, depending on the wood species and the applied drying regime. The reported percentage values represent interval values derived from a comparison of minimum and maximum drying regimes for individual wood species. These improvements are mainly associated with a reduction in drying cycle duration of approximately 35–50 %, which enables a higher number of drying cycles to be completed within the same operational time frame without additional labour input.

3.3 Efficiency and energy evaluation

The installed power of the drying equipment represents an indicative technical parameter and does not reflect the actual energy consumption, which depends on the drying process conditions, load level, and the degree of process control.

The efficiency of the drying process was evaluated with respect to energy consumption and the utilisation of input resources. In accordance with industrial practice, efficiency was assessed as the ratio between achieved output and energy input required for the drying operation. For comparative purposes, the evaluation focused on specific energy consumption per unit of dried lumber volume.

Energy efficiency was expressed using the following relationship (2):

$$E = \frac{\mathrm{Q}}{\mathrm{E_n}} \tag{2}$$

where:
E is energy efficiency ($m^3 \cdot kWh^{-1}$),
Q is the volume of dried lumber (m^3),
E_n is the total energy consumption during the drying cycle (kWh).

For improved clarity and comparability of results, specific energy consumption was also applied as an inverse indicator (3):

$$SEC = \frac{\mathrm{E_n}}{\mathrm{Q}} \tag{3}$$

where:
SEC is specific energy consumption ($kWh \cdot m^{-3}$),
E_n is the total energy consumption during the drying cycle (kWh),
Q is the volume of dried lumber (m^3).

The existing drying kiln exhibits relatively high specific energy consumption due to outdated thermal insulation, limited heat recovery, and less efficient air circulation. These factors lead to higher heat losses and increased energy demand per drying cycle. In addition, manual or semi-automatic control limits the ability to continuously optimise process parameters in response to actual wood moisture conditions.

The proposed Mühlböck drying kiln achieves higher energy efficiency through improved thermal insulation, optimised airflow distribution, and an intelligent K5 control system enabling continuous process regulation. These features reduce unnecessary energy losses and stabilise drying conditions throughout the cycle.

Comparative analysis indicates that the proposed drying technology leads to a reduction in specific energy consumption of approximately 15-25% per cubic metre of dried lumber. At the same time, the stabilisation of drying parameters contributes to lower technological waste, reduced risk of material defects, and improved consistency of final moisture content.

The reduction in specific energy consumption is not achieved solely by shortening the drying time, but primarily through optimisation of thermal management, improved process control, and stabilisation of drying conditions.

The achieved improvement in energy efficiency directly supports overall process efficiency by lowering operating costs and reducing the energy intensity of production. The results confirm that technological modernization of the drying operation has a positive impact not only on productivity but also on sustainable resource utilisation and operational efficiency.

3.4 Economic evaluation of the modernization proposal

In addition to technical and energy-related benefits, the proposed modernization of the drying technology was also evaluated from an economic perspective. The economic assessment focuses on the justification of the investment by considering operating conditions, productivity gains, and efficiency improvements achieved through the implementation of the modern drying kiln.

The replacement of the existing drying kiln with the proposed Mühlböck technology requires an initial capital investment associated with the acquisition of new equipment and its installation. However, this investment is accompanied by measurable operational benefits resulting from shorter drying cycles, increased throughput, and reduced energy consumption.

From an economic perspective, the modernization results in a reduction of energy-related operating costs by approximately 15-25%, corresponding to the decrease in specific energy consumption.

In addition, increased productivity contributes to a reduction in unit production costs by approximately 20–30 %, primarily due to improved capacity utilisation and shorter processing time per production batch. These combined effects significantly enhance the economic performance of the drying operation and justify the investment from a long-term operational perspective.

Improved automation and process control also contribute to more stable operation, reducing the likelihood of unplanned downtime and technological losses. As a result, the drying process operates closer to optimal conditions, improving cost efficiency throughout the entire production cycle.

Based on a comparison of the current and proposed technological solutions under identical operational assumptions, the economic evaluation confirms that the modernization of the drying technology represents a rational investment. The combined effects of productivity growth, energy savings, and improved process stability create favourable conditions for long-term cost reduction and increased competitiveness of the manufacturing enterprise. Under the assumption of maintaining comparable operating conditions and production volumes, the proposed modernization can be considered economically justified.

4 Conclusion

Improving productivity and efficiency is a fundamental prerequisite for maintaining competitiveness in contemporary manufacturing environments. In wood-processing production, the drying operation represents a critical technological stage that significantly influences production throughput, energy consumption, and final product quality.

This study evaluated the impact of drying technology modernization on productivity, energy efficiency, and economic performance under real industrial conditions. The results indicate that the modernization of the drying process leads to a productivity increase of up to 45% and a reduction in specific energy consumption of up to 25%.

The replacement of outdated drying technology with a modern automated Mühlböck drying kiln resulted in a substantial reduction in drying cycle duration, enabling a higher number of processed batches within the same operational time. As a result, the productivity of the drying process was significantly increased without additional labour input or an extension of working hours.

The analysis further confirmed that technological modernization contributes to improved energy efficiency through reduced specific energy consumption per unit of dried lumber. Enhanced thermal insulation, optimised air circulation, and intelligent process control enable more stable drying conditions. As a result, energy losses and technological waste are reduced, supporting sustainable resource utilisation and overall process efficiency.

From an economic perspective, the modernization of the drying technology represents a justified investment. Productivity growth, energy savings, and improved process stability contribute to lower unit production costs and better utilisation of installed production capacity. The combined technical and economic effects strengthen the competitiveness of the manufacturing enterprise and create favourable conditions for long-term operational optimisation.

The findings confirm that targeted technological modernization of key production operations represents an effective instrument for increasing productivity and efficiency in wood-processing manufacturing. The applied evaluation methodology and achieved results provide a practical basis for investment decision-making and process optimisation in similar industrial environments.

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