SILESIAN UNIVERSITY OF TECHNOLOGY PUBLISHING HOUSE

SCIENTIFIC PAPERS OF SILESIAN UNIVERSITY OF TECHNOLOGY 2024
ORGANIZATION AND MANAGEMENT SERIES NO. 205

THE ESSENCE OF PRODUCTION MANAGEMENT IN THE ERA OF INDUSTRY 4.0 – ASSESSMENT OF THE IMPACT OF CNC LASER IMPLEMENTATION ON THE EFFICIENCY AND QUALITY OF MANUFACTURING PARTS OF SELECTED PRODUCTS

Jaromir MYSŁOWSKI[1], Mariusz NIEKURZAK[2*], Wojciech LEWICKI[3*]

[1] Maritime University of Technology in Szczecin, Faculty of Mechanical Engineering, Energy Department; j.myslowski@am.szczecin.pl, ORCID: 0000-0002-5464-7622
[2] AGH University of Krakow, Faculty of Management; niekurz@agh.edu, ORCID: 0000-0003-4966-8389
[3] West Pomeranian University of Technology in Szczecin, Faculty of Economics; wojciech.lewicki@zut.edu.pl, ORCID: 0000-0002-8959-8410
* Correspondence author

Purpose: The work aims to assess the impact of the implementation of CNC laser technology on the efficiency and quality of machine parts production, using the example of a company in the metal industry. The introduction of the CNC laser is intended to increase the precision and automation of production processes, which will translate into increased efficiency and quality of manufactured products, in line with the idea of industry 4.0 promoted in the modern economy.
Design/methodology/approach: As part of the research, a detailed analysis of the impact of CNC laser implementation on production was carried out, taking into account aspects such as production efficiency, product quality and process optimization. The study used a methodology based on observations of the production process, analysis of technical documentation and interviews with employees involved in the implementation process.
Findings: The results of the analysis indicate significant benefits resulting from the implementation of CNC technology, such as shortening production time, increasing the machine utilization rate (OEE) and reducing production waste. At the same time, potential challenges related to the transformation in line with the idea of Industry 4.0 were identified, such as the need to constantly monitor and analyze the effectiveness of the implemented technological solutions.
Practical implications: The work is a valuable contribution to the literature on production management and technological innovation in industry. Providing empirical evidence of the benefits of automation and implementation of modern technologies in production processes.
Originality/value: The original contribution of this work is the implication of the data on real-world research models. These data allowed the authors to make calculations and indicate directions for design improvements in the machinery sector in line with the promotional idea of industry.4.0.
Keywords: production management, efficiency and quality measurement, CNC laser, industry 4.0.
Category of the paper: Research paper.

1. Introduction

The modern production industry is characterized by the dynamic development of technology and growing competition, which means that companies face the need to constantly optimize production processes. Key challenges they have to face include increasing efficiency, improving product quality and reducing production costs and time. In response to these needs, companies are increasingly turning to advanced technologies, such as computer numerical control (CNC), which enable the automation of complex material processing processes. In particular, CNC laser technology has gained importance in the machine parts manufacturing sector thanks to its precision flexibility and tools (Frank, 2018). Automation of processes through the use of CNC lasers not only contributes to improving the quality of production but also contributes to increasing efficiency and reducing the share of manual work in line with the promotional idea of industry 4.0.

This work aims to assess the impact of implementing laser technology CNC for efficiency and quality of production of machine parts. The goal was achieved by examining how the implementation of advanced manufacturing technologies, such as the CNC laser, affects key operational performance indicators. These indicators include cycle time, machine utilization rate (OEE), level of production waste and product quality. As part of our research, the benefits of automation were identified and precise control of production processes, and potential challenges were identified and limitations related to the implementation of CNC technology on the example of a manufacturing company from the metal industry. The long-term effects of CNC laser implementation on the company's operations were assessed and how this technology could be further optimized to maximize the benefits of its use was examined. The research results provide valuable conclusions for management staff and other companies considering implementing similar technological solutions to improve their production processes and gain a competitive advantage. The research conducted provides empirical evidence about the benefits of the implementation of CNC technology, especially in the context of operational efficiency and production quality. The results of the work can constitute a valuable contribution to the development of innovation strategies for manufacturing companies that seek to increase their competitiveness in the global market through automation and technological innovation.

Based on a review of domestic and foreign literature, a research gap was noticed regarding the limitations related to the implementation of innovative technologies, such as steel-cutting lasers, in production plants (Ammar et al., 2022; Haverkamp, Beuducel, 2019). This problem is particularly important in the context of increasing requirements of quality standards for finished products, which recommend the use of precise processing technologies, such as laser cutting. In response to this need, the authors undertook an analysis of the process of implementing this technology in production conditions, examining its impact on operational efficiency and product quality in the example of a specific manufacturing company. Pointing directly to the practical benefits of implementing solutions based on industry 4.0.

2. Materials and Methods

2.1. Coceptual framework

In this part of the work, the impact of the implementation of a CNC laser on the production of metal products at Leather Sensor was analyzed in detail. The research was divided into two parts, which described:

- analysis of production efficiency after the implementation of the CNC laser. A comparison of key performance indicators, such as cycle time, machine utilization rate (OEE) and operating cost reduction, was carried out before and after the implementation of CNC technology,
- analysis of production quality, assessing changes in the precision of workmanship, repeatability of processes and the level of production waste.

The research methodology used in this work included various data collection techniques, such as observations of production processes, analysis of technical documentation and interviews with key company employees who were directly involved in the implementation process and operation of the CNC laser (Wróblewski, Niekurzak, 2022). These data were subjected to detailed analysis, which allowed for verification of the research hypotheses regarding the impact of the implementation of modern technologies on the operational parameters of the enterprise. In addition, recommendations resulting from the analysis were presented (Bécue et al., 2021). Both benefits and potential challenges related to further optimization of production processes were indicated; (Niekurzak; Mikulik, 2021). These recommendations can serve as a basis for planning future activities in the company, as well as constitute a valuable source of knowledge for other enterprises that are considering implementing CNC technology in their production processes. The importance of continuous monitoring and analysis of the effectiveness of implemented technologies to ensure their maximum use was also emphasized and further developed.

The OEE (Overall Equipment Effectiveness) indicator is a key tool for assessing the efficiency of using machines in production processes. OEE measures how well resources perform when production facilities are used to their maximum potential. It consists of three main components: availability, performance and quality:

- availability: measures whether a machine is operational for the scheduled operating time, including downtime due to breakdowns, maintenance and adjustments.

$$Availability = \frac{Operational\ time - Availability\ losses}{Operational\ time} \quad (1)$$

- efficiency: evaluates how fast the machine is running compared to standard speed, taking into account minor stops and speed drops.

$$Efficiency = \frac{Number\ of\ executions * Normative\ cycle\ time}{operational\ time - Availability\ losses} \quad (2)$$

- quality: determines what percentage of produced pieces meet the quality requirements.

$$Quality = \frac{Number\ of\ executions - Number\ of\ non-compliant\ pieces}{number\ of\ executions} \quad (3)$$

- the final OEE indicator is calculated as the product of the above indicators:

$$OEE = Availability * Efficiency * Quality * 100\% \quad (4)$$

As part of the research, the OEE index was calculated for minute band heaters, which are currently the main product manufactured using a CNC laser in the company.

3. Results and discussion

3.1. Machine Utilization Efficiency Index

The implementation of CNC laser technology into the production process significantly influenced the efficiency of producing minute band heaters, which are one of the plant's key products. The CNC laser is particularly important in the production of these heaters because it allows for the precise firing of all stainless-steel elements, which was previously more difficult to achieve using traditional processing methods. Laser technology also enables the marking of micanite, an insulating material, which makes its subsequent cutting and installation in the final product much easier. Marking allows you to precisely determine where to cut, which reduces the number of errors and improves the quality of production (Zinn et al., 2021). Thanks to the CNC laser, it is possible not only to shorten the processing time but also to increase the accuracy and repeatability of operations, which translates into higher-quality heaters. The following calculations analyze the production efficiency of minute heaters before and after the implementation CNC laser.

Assumptions for the production of heaters before the introduction of the laser:

- average number of heaters per employee per day: 3 heaters,
- number of employees: 5,
- working time: 8 hours a day, 5 days a week,
- number of working days in a month: 22 days,
- total daily production:

Daily production = 5 × 3 = 15 heaters

- monthly production:

Monthly production = 15 × 22 = 330 heaters

Calculations for OEE before the introduction of the laser:

Availability before:

- operating time (month): 22 days × 8 hours / day = 176 hours,
- availability losses: based on data collected over three months, it was calculated that the time needed to repair failures and maintain devices is on average 26.4 hours.

$$Availability_{before} = \frac{176-26.4}{176} = \frac{149.6}{176} \approx 0.85(85\%) \tag{5}$$

Performance before:

- standard cycle time: operating time of machines that are later replaced by the laser 20 min/heater (0.33 hours),
- number of heaters produced (day): 15 heaters,
- operating time (day): 8 hours,
- availability losses (day): 1.2 hours.

$$Efficiency_{before} = \frac{15 \cdot 0.33}{8-1.2} = \frac{4.95}{6.8} \approx 0.70(70\%) \tag{6}$$

Quality before:

- number of pieces produced: 330 heaters per month,
- several defective pieces: based on data collected over three months, it was calculated that the number of defective pieces is on average 16.5 pieces per month.

$$Quality_{before} = \frac{330-16,5}{330} = \frac{313,5}{330} \approx 0.95(95\%) \tag{7}$$

$$OEE_{before} = 0.85 \cdot 0.70 \cdot 0.95 = 0.565(56.5\%) \tag{8}$$

Assumptions for the production of heaters after the introduction of the laser:

- average number of heaters per employee per day: 5 heaters,
- number of employees: 4,
- working time: 8 hours a day, 5 days a week,
- number of working days in a month: 22 days,

Total daily production:

- Daily production: 4 × 5 = 20 heaters,
- Monthly production:

Monthly production: 20 × 22 = 440 heaters

- Calculations for OEE after laser introduction:

Availability after:

- operational time (month): 22 days × 8 hours/day = 176 hours,
- availability losses: based on data collected over two months, it was calculated that the time needed to repair failures and maintain devices is on average 16.2 hours.

$$Availability_{after} = \frac{176-16.2}{176} = \frac{159.8}{176} \approx 0.91(91\%) \tag{9}$$

Performance after:

- standard cycle time: laser operation time, 12 min/heater (0.2 hours),
- number of heaters produced (day): 20 heaters,
- operating time (day): 8 hours,
- availability losses (day): 1 hour.

$$Efficiency_{after} = \frac{20 \cdot 0.2}{8-1} = \frac{4}{7} \approx 0.85(85\%) \qquad (10)$$

Quality after:

- number of pieces produced: 440 heaters per month,
- several defective pieces: based on data collected over two months, it was calculated that the number of defective pieces is on average 8.2 pieces per month.

$$Quality_{after} = \frac{440-8.2}{440} = \frac{43.,8}{440} \approx 0.98(98\%) \qquad (11)$$

$$OEE_{after} = 0.91 \cdot 0.85 \cdot 0.98 = 0.7580(75.80\%) \qquad (12)$$

Analysis of the availability of machines before and after the implementation of the CNC laser indicates significant differences that have a direct impact on the overall efficiency of the production process of micanite band heaters. Before the introduction of the laser, machine availability was 85%, which means that approximately 15% of the planned operating time was lost to various types of downtime. Availability increased to 90%, indicating an improvement of 5 percentage points. This increase was primarily due to higher machine reliability, fewer unplanned downtimes and reduced time needed for adjustments and settings. Production efficiency was approximately 70%. This means that the machines were operating at speeds lower than their maximum potential, which was caused by minor downtime, drops in operating speed and suboptimal use of cycle time. The efficiency increased to 85%, which is a significant improvement. Production quality was around 95%, which meant that 5% of the heaters produced were defective. Mistakes resulted from manual cutting and machining processes, which were more susceptible to inaccuracies, operator errors and difficulties in maintaining constant precision. Quality increased to 98%, showing a significant reduction in the number of defective products. The OEE rate increased from 56.5% before the CNC laser was implemented to 74.97% after its introduction, an improvement of 18.47 percentage points. This change reflects a significant improvement in the overall efficiency of the production of micanite band heaters, which are the main products manufactured using the new technology.

3.2. Cost change analysis

In this part of the research, an analysis of the costs of producing frequently used elements in heating units, i.e. the housing flange, was carried out (fig. 1) and the retaining disc (fig. 2).

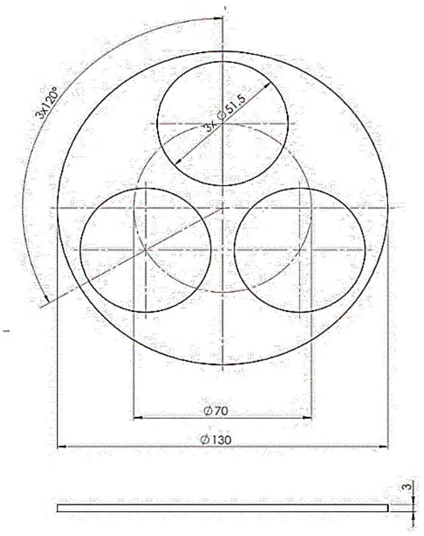

Figure 1. Locating disc.

Source: own study.

The housing flange shown in Figure 2 is one of the most frequently used elements, but special sizes for larger heating units are also used. This forces you to order these elements only when there is an order for a given heating unit. The effect of this approach is extended production times caused by waiting for a given part.

Costs for firing the retaining disc (fig. 1):

- material: stainless steel sheet, 3 mm thick,
- cost of machine operation: the average cost of CNC laser operation is approximately PLN 150/hour,
- cutting time: estimated 1 m/min at a thickness of 3 mm,
- operator's labour cost: PLN 50/hour,
- material cost: PLN 6.42,
- cutting length:

$$Length\_total = 408 + 220 + 486 = 1114mm \approx 1.114m \tag{13}$$

- cutting time:

$$time\_cut = 1m/min \cdot 1.114m/min = 1.114min \approx 1.11min \tag{14}$$

- cost of machine operation:

$$Cost_{machine} = \frac{150}{60} \cdot 1.11 \approx 2.78PLN \tag{15}$$

- operator's labour cost:

$$Cost\_operator's = \frac{50}{60} \cdot 1.11 \approx 0.93\ PLN \tag{16}$$

$$Cost\_total = 2.78 + 0.93 + 6.4 = 10.11\ PLN \tag{17}$$

The average unit price of the analyzed element purchased from an external company for the last five orders was PLN 31.88. Currently, after implementing the CNC laser, the cost of producing the same element internally is PLN 10.11 per piece. The difference in price per piece is PLN 21.77, which is a saving of approximately 68% compared to purchasing from an external supplier.

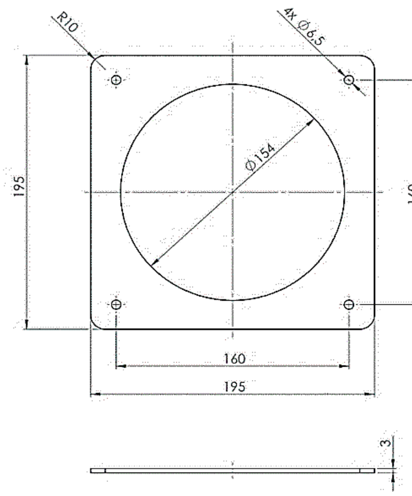

Figure 2. Housing flange.

Source: own study.

The average monthly consumption of these elements in the plant is 122 pieces. By analyzing the costs and taking into account this number, the savings were calculated:

- cost of purchasing elements from an external supplier:

$$122\cdot 31.88 \text{ PLN}=3889.36 \text{ PLN} \tag{18}$$

- cost of producing the elements yourself using a CNC laser:

$$122 \cdot 10.11 \text{ PLN} = 1233.42 \text{ PLN} \tag{19}$$

- total monthly savings:

$$\text{PLN } 3\,889.36 - \text{PLN } 1\,233.42 = \text{PLN } 2\,655.91 \tag{30}$$

Savings of PLN 2 655.91 per month show how profitable it is to implement laser technology in production. While these calculations do not take into account the costs associated with purchasing and maintaining a CNC machine, even assuming the machine is depreciated over a few years, the difference in manufacturing costs suggests a significant reduction in operating expenses. Thanks to such a large difference in costs, the investment in a CNC laser quickly pays off, and the plant gains greater control over the quality and timeliness of production. In the long run, this solution contributes to improving the company's competitiveness in the market by reducing production costs and increasing flexibility in order fulfilment.

Costs for firing the casing flange (fig. 2):

- material: stainless steel sheet, 3 mm thick,
- cost of machine operation: the average cost of CNC laser operation is approximately PLN 150/hour,

- cutting time: estimated 1 m/min at a thickness of 3 mm,
- operator's labour cost: PLN 50/hour,
- material cost: PLN 9.52,
- cutting length:

$$Length_{total} = 780 + 484 + 81.6 = 1345.6mm \approx 1.346\ m \tag{31}$$

- cutting time:

$$time_{cut} = \frac{1m}{min} \cdot \frac{1.346m}{min} = 1.346min \approx 1.346\ min \tag{32}$$

- cost of machine operation:

$$Cost_{machine} = \frac{150}{60} \cdot 1.346 \approx 3.37\ PLN \tag{33}$$

- operator's labour cost:

$$Cost\_operator's = \frac{50}{60} \cdot 1.346 \approx 1.12\ PLN \tag{34}$$

$$Cost_{total} = 3.37 + 1.12 + 9.52 = 14.01\ PLN \tag{35}$$

The unit price of the analyzed element purchased from an external company for the last order was PLN 30. Currently, after implementing the CNC laser, the cost of producing the same element internally is PLN 14.01 per piece. The difference in price per piece is PLN 15.99. The average monthly consumption of these elements in the plant is 31 pieces. Analyzing the costs with this number in mind, we can see how significant the savings are:

- cost of purchasing elements from an external supplier:

$$31 \cdot 30\ PLN = 930\ PLN \tag{36}$$

- cost of producing the elements yourself using a CNC laser:

$$31 \cdot 15.99\ PLN = 495.69\ PLN \tag{37}$$

- total monthly savings:

$$930\ PLN - 495.69\ PLN = 435.31\ PLN \tag{38}$$

Annual savings for both analyzed details:

$$2655.91\ PLN \cdot 12 + 435.31\ PLN \cdot 12 = 37094.64\ PLN \tag{39}$$

For the two analyzed elements, after the introduction of CNC laser technology, it was calculated that in total these activities allowed savings of PLN 37 094.64 per year compared to the costs of purchasing these elements from external suppliers. These savings result from reduced production costs through precise and efficient laser cutting, which minimizes material waste, reduces operator time and eliminates common quality issues. The implementation of a CNC laser for the production of heating unit elements brings measurable financial and operational benefits, which translate into an overall improvement in the company's efficiency. This shows that investments in modern technologies are not only profitable but also strategically crucial for the further development of the company.

3.3 Production quality analysis

Assessment of the quality of production in the plant is based on several key criteria that determine the compliance of products with technical requirements and industry standards. The main criteria are:

- dimensional accuracy: requirements for precise dimensions and tolerances that must be met for the element to work properly with other parts of the heating unit,
- compliance with technical documentation: elements must be made by technical drawings and specifications, without discrepancies in the arrangement of holes or shapes,
- aesthetics and surface finish: no sharp edges, irregularities or traces of processing that could affect functionality or safety of use,
- low number of defects and waste: production should generate as few defective elements as possible, which directly translates into cost reduction and less waste.

Before the implementation of laser technology, the production of e.g. minute heaters (Fig. 3) was carried out mainly using traditional mechanical processing methods. This process required great precision and skill of the operator. In manual operations such as drilling and cutting, the risk of human error was much higher. For example, the frame heater shown in Figure 3 was made before the implementation of the CNC laser. Due to the errors of the operator who made the heater manually, there were discrepancies in the arrangement of the holes. The holes were imprecisely placed, which affected the quality of assembly and cooperation with other elements of the heating unit. The consequences of such an error include not only the need for corrections but also the risk of product non-compliance with standards and customer requirements. After re-making the heating element, it turned out that due to another inaccuracy that could not be verified at the quality control stage, it was impossible to install the heater. This was due to incorrect drilling of the holes. In this case, the operator was only wrong by 2 mm, it did not help Unfortunately, it is not possible to install the described heater.

Figure 3. Micanite frame heater.

Source: own study.

The complaint about this heater coincided with the implementation of the CNC laser into production. After implementing the CNC laser, the same element was made again. Thanks to the precision of laser cutting, which offers an accuracy of hundredths of a millimetre, all holes were placed by the technical documentation, eliminating previous problems. Laser technology guarantees repeatability of operations, which minimizes the risk of errors and improves the overall quality of the product. This guarantees that once an element has been made using a laser, there will be no errors in the future. One of the key advantages of introducing laser technology is a significant reduction in defects and production waste. Before the introduction of the CNC laser, hole pattern discrepancies were a common problem, leading to defective products that had to be reworked or rejected altogether. Such discrepancies not only increased production costs but also delayed order fulfilment. After implementing the CNC laser, thanks to its high precision and process automation, the number of defects and waste has been significantly reduced. The ability to precisely cut and drill holes according to precise guidelines significantly reduced the risk of making a mistake. This means fewer reworks, less material consumption and more efficient use of machine and operator time. The introduction of a CNC laser into the production process significantly improved quality control. Before the laser was implemented, each batch of products had to be carefully inspected to detect errors such as discrepancies in the arrangement of holes. It was often related to the need to make corrections, which increased production costs and time. After implementing the CNC laser, the quality control process was simplified and shortened because the laser's precision virtually eliminates production errors resulting from inaccurate hole arrangement and other inaccuracies. The laser ensures compliance of elements with standards and documentation technical, which allows for faster detection of possible problems and their immediate solution. After implementing the CNC laser in the plant, a new procedure was introduced to ensure the highest quality of manufactured elements. This procedure assumes making one trial batch for each new project or order. After this batch is made, the elements are carefully checked for compliance with technical documentation and quality standards. If all parameters match, the design is approved for series production. Thanks to the precision and repeatability offered by laser technology, subsequent production runs are carried out without the need for additional verification. This procedure guarantees that all subsequent productions will meet quality requirements, which minimizes the risk of shortages and waste and increases the efficiency of the entire production process. The introduction of the CNC laser into production significantly improved the quality of manufactured elements, eliminating problems related to manual errors and inaccuracies. Reducing scrap and waste, improving quality control and ensuring compliance with standards are the main resulting benefits from automation of the cutting and drilling process. Thanks to this, the company can provide products of higher quality, with greater repeatability and lower production costs.

4. Conclusions and recommendations

Modern researchers have no doubt that Industry 4.0 is a collective concept meaning the integration of intelligent machines, systems and introducing changes in production processes aimed at, among others, increasing production efficiency and introducing the possibility of flexible changes in the assortment (Radanliev et al., 2021). The authors would like to emphasize that Industry 4.0 is not an abstract concept, but real technologies and implementations, as exemplified by the following conclusions and recommendations in this area (Lewicki et al., 2024).

Based on the analysis of the impact of the implementation of CNC laser technology on production in the analyzed company, the following conclusions can be drawn:

- increasing production efficiency: the implementation of CNC laser technology significantly contributed to the increase in production efficiency. Noticeable improvements in operational efficiency metrics such as production cycle time and machine utilization rate (OEE) indicate more optimized production processes that require less human intervention and are less error-prone;
- improvement of product quality: CNC technology enabled the production of machine parts with higher precision and repeatability, which directly translated into the quality of final products. Data analysis showed a reduction in the number of defective products and a reduction in production waste, which is a direct result of better control of machining processes;
- reducing production costs: although the implementation of CNC technology was initially associated with high expenditure investment, long-term benefits in the form of reduced operating costs, reduced material consumption and reduced machine downtime offset these costs. Process optimization also allowed for more effective use of human resources;
- increase in production flexibility: the introduction of CNC technology increased the company's production flexibility, enabling quick and precise adaptation of production processes to changing customer and market requirements. The ability to quickly change the production program allows for easy introduction of new products to the offer without the need for long-term downtime;
- implementation challenges: despite numerous benefits, the implementation process of CNC laser technology has encountered some challenges. These included: the need to train staff, adapt the production infrastructure and initial difficulties related to the optimization of machining parameters. This required both time and resources to fully develop and integrate new technology with existing processes;

- the need for continuous monitoring and optimization: the analysis results show that the implementation of CNC technology alone is not sufficient; continuous monitoring and optimization of production processes is crucial. Only through systematic analysis of production data and quality indicators can the benefits of this technology be maximized.

Based on the conclusions, recommendations for further development and optimization of production processes are as follows:

- continue monitoring key performance indicators: it is recommended to continue monitoring indicators such as OEE, cycle time, waste level and product quality to be able to quickly respond to possible problems and adjust machining parameters to optimize processes;
- regular training and skill development of staff: As CNC technology continues to evolve, operational and technical staff must be continually trained in the new functions and capabilities of CNC machines. Regular training and workshops can help increase work efficiency and better use of technology;
- implementation of systems supporting quality management: integrating CNC technology with quality management systems, such as CAQA (Computer-Aided Quality Assurance), will allow for more automatic and precise monitoring of production quality, which can contribute to further waste reduction and improvement of product quality;
- optimization of production parameters: it is recommended to conduct regular technological and process audits to identify areas where further optimizations can be introduced. This can be achieved by using Lean Management techniques, Six Sigma or other modern production management methods;
- development of research and development activities (R&D): further investment in research and development, especially in the area of new processing technologies and automation, will allow the company to maintain a competitive advantage and quickly respond to market changes. It is worth considering cooperation with technical universities and research centres to develop innovative solutions;
- cost-benefit analysis in the context of further technological investments: before deciding on further investments in CNC or other machining technologies, it is recommended to conduct a cost-benefit analysis, to ensure that future investments are strategically justified and contribute to further optimization of production processes;
- purchase of a modern sheet metal bending machine with greater power and capabilities: to fully use the potential of CNC laser technology and optimize production processes, it is recommended to purchase a modern sheet metal bending machine that will enable the processing of sheets of greater thickness than the currently used machine, which is limited for bending sheet metal with a maximum thickness of 1.5 mm. The current technological limitation is a significant barrier to the development of the company's

production capabilities and limits its ability to implement more complex and demanding projects. Investing in a more powerful machine and bending capabilities will allow you to expand your product offer, improve production flexibility and increase the company's competitiveness in the market, enabling the implementation of more complex orders for customers from various industries. Thanks to the combination of modern CNC laser cutting technology with a more efficient sheet metal bending machine, a company can significantly increase its operational efficiency and gain an advantage in the market.

To sum up, the implementation of CNC laser technology has brought measurable benefits to the company, but further development requires continuous process optimization and investment in innovation. These recommendations can serve as guidelines for further actions that will help the company maintain and strengthen its position in the market through the use of modern production technologies.

References

1. Agrawal, P., Aggarwal, S., Banthia, N. et al. (2022). A comprehensive review of incremental deformation in rolling processes. *J. Eng. Appl.* Sci., *69, 20,* https://doi.org/10.1186/s44147-022-00072-w.
2. Alexandrov, S., Lyamina, E., Hwang, Y-M. (2021). Plastic Bending at Large Strain: a Review. *Processes, 9(3),* 406, https://doi.org/10.3390/pr9030406.
3. Alrikabi, H.T.S., Ali Jasim, N. (2021). Design and implementation of Smart city applications based on the Internet of Things. *International Journal of Interactive Mobile Technologies (iJIM), vol. 15, no. 13,* 4-15, https://doi.org/10.3991/ijim.v15i13.22331.
4. Ammar, M., Haleem, A., Javaid, M., Bahl, S., Verma, A.S. (2022). Implementing Industry 4.0 technologies in self-healing materials and digitally managing the quality of manufacturing. *Materials Today Proceedings, 52,* 2285-2294, https://doi.org/10.1016/j.matpr.2021.09.248.
5. Bécue, A., Praça, I., Gama, J. (2021). Artificial intelligence, cyber-threats and Industry 4.0: challenges and opportunities. *Artificial Intelligence Review, vol. 54, no. 5,* 3849-3886, https://doi.org/10.1007/s10462-020-09942-2.
6. Bosley, T. (2019). *Comparative power of the Friedman, Neave and Worthington match, Skillings-Mack, trimmed means repeated measures ANOVA and bootstrap trimmed means repeated measures ANOVA tests.* Doctoral dissertation. Wayne State University.
7. Frank, S.A. (2018). Control theory Tutorial. *Springer Briefs in Applied Sciences and Technology*. Cham: Springer, https://doi.org/10.1007/978-3-319-91707-8_4.
8. Hamrol, A., Zerbst, S., Bozek, M., Grabowska, M., Weber, M., Hamrol, A., Ciszak, O., Legutko, S., Jurczyk, M. (2018). Analysis of the conditions for Effective Use of

Numerically Controlled Machine Tools, Advances in Manufacturing. *Lecture Notes in Mechanical Engineering.* Cham: Springer, https://doi.org/10.1007/978-3-319-68619-6_1, 2-s2.0-85032661085.

9. Haverkamp, N., Beauducel, A. (2017). Violation of the sphericity assumption and its effect on Type-I error rates in repeated measures ANOVA and multi-level linear models (MLM). *Frontiers in Psychology, 8*, *Article 1841*. https://doi.org/10.3389/fpsyg.2017.01841.
10. Haverkamp, N., Beauducel, A. (2019). Differences of Type I error rates for ANOVA and Multilevel-Linear-Models using SAS and SPSS for repeated measures designs. *Meta-Psychology, 3*, Article MP.2018.898.
11. Javaid, M., Haleem, A., Singh, R. P., Suman, R. (2021). Significant applications of Big Data in industry 4.0, *Journal of Industrial Integration and Management*, 6, no. 04, 429–447, https://doi.org/10.1142/s2424862221500135.
12. Kumar, A., Sharma, D.K., Gupta, D., Khanna, A., Bhattacharyya, S., Hassanien, A.E., Anand, S., Jaiswal, A. (2021). An optimized Multilayer Outlier Detection for Internet of Things (IoT) Network as industry 4.0 automation and data Exchange. International Conference on Innovative Computing and Communications. *Advances in Intelligent Systems and Computing, Vol. 1166.* Singapore: Springer, https://doi.org/10.1007/978-981-15-5148-2_5.
13. Lewicki, W., Niekurzak, M., Wróbel, J. (2024). Development of a Simulation Model to Improve the Functioning of Production Processes Using the Flex Sim Tool. *Applied Sciences, 14(16),* 6957. https://doi.org/10.3390/app14166957.
14. Niekurzak, M., Mikulik, J. (2021). Modelling of Energy Consumption and Reduction of Pollutant Emissions in a Walking Beam Furnace Using the Expert Method—Case Study. *Energies*, *14*, 8099.
15. Radanliev, P., De Roure, D., Nicolescu, R., Huth, M., Santos, O. (2021). Artificial intelligence and the Internet of Things in Industry 4.0. *CCF Trans. Pervasive Comp. Interact, 3,* 329-338, https://doi.org/10.1007/s42486-021-00057-3
16. Rezaee, K., Jeon, G., Khosravi, M.R., Attar, H.H., Sabzevari, A. (2022). Deep learning-based microarray cancer classification and ensemble gene selection approach. *IET Systems Biology*, *vol. 16, no. 3-4,* 120-131, https://doi.org/10.1049/syb2.12044.
17. Wróblewski, P., Niekurzak, M. (2022). Assessment of the possibility of using various types of renewable energy sources installations in single-family buildings as part of saving final energy consumption in Polish conditions. *Energies*, *15*, 1329.
18. Yang, F., Gu, S., (2021). Industry 4.0, a revolution that requires technology and national strategies. *Complex Intell. Syst., vol. 7, no. 3,* 1311-1325, https://doi.org/10.1007/s40747-020-00267-9.
19. Zinn, J., Vogel-Heuser, B., Gruber, M. (2021). Fault-tolerant control of programmable logic controller-based production systems with deep Reinforcement learning. *Journal of Mechanical Design, vol. 143, no. 7*, 072004, https://doi.org/10.1115/1.4050624.