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Optimization of the laser cutting process by integrating an automatic storage and loading system with enterprise resource management integration

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ABSTRACT

Automation of tasks performed by people is one of the natural activities influencing the optimization of production time in Industry 4.0. It helps to eliminate errors and reduce work in conditions dangerous for people. In addition, the implementation of automation allows to shorten production time, save resources, protect the environment and provides a competitive advantage. This publication describes the implementation of the system implemented by us for the integration of two cutting laser stations with one automatic sheet metal storage system and an automatic loading and unloading system to the cutting laser workstations. These activities were previously performed manually by employees. Thanks to the automation of these activities, the preparation and production time was shortened and errors resulting from the need to manually manage the number of sheet metal sheets were eliminated. The system includes a control panel with information on real-time stocks and the production process. The system includes a database informing about the current states of sheet metal sheets available in the automatic warehouse and the number of sheet metal sheets used in the production process. Integration with the ERP system allows the staff to be informed in real time about the production progress, laser cutting time, downtime and the current stock levels of sheet metal in the automatic sheet metal warehouse.

Keywords: production, system integrations, laser cutting, optimization, automatic sheet metal warehouse.

INTRODUCTION

Modern industrial production is constantly striving to improve efficiency, reduce costs and optimise manufacturing processes. In the context of the laser cutting area, automated sheet metal storage and loading and unloading systems play a key role in improving productivity and reducing material losses. The implementation of advanced automation technologies not only saves time and resources, but also increases the precision and repeatability of manufactured parts [1].

In the case of the company described, the production station was equipped with a single cutting laser controlled from the operator panel. The increase in orders resulted in longer lead times. The single production process contained too many inefficient steps, such as the manual loading of sheets onto the laser and the unloading of cut material by two operators who did not contribute to value-adding production steps. In addition, the workflow was slowed down by the need to manually review documentation, retrieve appropriate sheets of sheet metal with the set parameters, load them onto the laser platform and run the cutting programme. The process was further slowed down by the need for workers to complete stock documentation and account for production materials used.

In laser cutting, automated material processing enables faster switching between production batches, reducing downtime and increasing flexibility [2, 3]. The automation of sheet loading and unloading in laser cutting brings numerous benefits, including reduced production cycle times, reduced material waste [4, 5] and increased operator safety. The implementation of fully automatic systems allows for reduced downtime and more efficient management of production processes, resulting in optimal use of raw materials and human resources [6]. These types of production systems [7, 8] allow machines to be easily reconfigured to accommodate different production volumes, from high-volume runs to small custom batches, while maintaining high productivity. Advanced software and simulation tools support these systems, positioning them as the future of mass production [9, 10].

The integration of laser cutting with enterprise resource management (ERP) systems enables effective planning, cost monitoring and tracking of material consumption. These systems allow production planning to be optimised by automatically generating orders for raw materials and updating stock levels on an ongoing basis. As indicated in the literature, the effective automation of logistics, warehousing and production processes significantly improves the efficiency of the entire plant, while reducing the need for operator intervention [11].

The development of flexible manufacturing systems (FMS) and group technology (GT) provides the foundation for modern manufacturing plants that seek to minimise changeover times, optimise production layouts and rationally deploy resources [12]. Automatic storage and transport systems, integrated with production management systems, allow for dynamic adaptation to changing market conditions and increased productivity while maintaining the high quality of the final product [13].

To solve these problems, the company expanded its machine park with an additional cutting laser and equipped the workstations with an automated sheet metal storage system and an automatic system for loading and unloading sheet metal onto the laser stations. Our task was to program the system to integrate the two lasers, the automated sheet storage, the loading and unloading system, optimise the operation of all components and integrate the system into the company's existing ERP system. The automated sheet storage and loading and unloading systems eliminated manual operations, often identified as bottlenecks in production processes.

MATERIALS AND METHODS

The company utilized one cutting laser. The machine is designed for cutting elements from various types of sheets: mild steel, stainless steel, aluminum, brass, or copper. It is equipped with an IPG YLR resonator with a power of 2000 W. The machine operates at speeds of up to 210 m/min along the X and Y axes, with strokes of 1550 mm (X axis) and 3050 mm (Y axis). The sheet being cut can weigh up to 1200 kg and have a thickness of up to 3 mm (copper), 4 mm (stainless steel, aluminum, brass), or 10 mm (mild steel). The laser is controlled by a Bosch Rexroth CNC controller, which offers trajectory cutting visualization and speed regulation. The cutting machine's equipment includes a Fiber laser head with automatic focus for up to 3300 W, a pallet exchange system, and a 4 kW filter-fan system. Laser operation is controlled via a touch HMI operator panel.

Initially, a single laser cutting station was used for cutting structural elements from various types of sheets. Based on process mapping and value-added analysis derived from observations and spaghetti diagrams [14] of the operator's and materials' movements, a movement scheme for the operator was developed, as illustrated in Figure 1.

In the initial phase of the analysis, the company had a sheet metal warehouse, which was located at a distance from the production line and was supplied by the supply section. Sheets of metal from the warehouse were transported to the production station by a forklift, according to production needs.

The progression and description of the stages are presented in Table 1, which outlines the initial state of the production process before any improvements were implemented. This data includes detailed durations of individual tasks, broken down into stages. Time measurements were taken for a selected cycle, from the shipment of sheets from the warehouse in the adjacent building to the moment the operator completed the documentation for the cut semi-finished products and used materials.

The total time for a single technological process is approximately 69.33 minutes. According to the audit, the target was to achieve 5–6 cuts per 8-hour shift from a single type of sheet, with 5–6 forklift trips. The C/T (cycle time) is 4160 seconds, with O/T (operator time) at 3720 seconds and M/T (machine time) at 2240 seconds. NVA (non-value-added) is 2840 seconds, while VA (value-added) is 1320 seconds.

The analysis highlighted that the key issue was the transport time and the associated setup time for the production cell. The challenge was compounded by the production of small batches

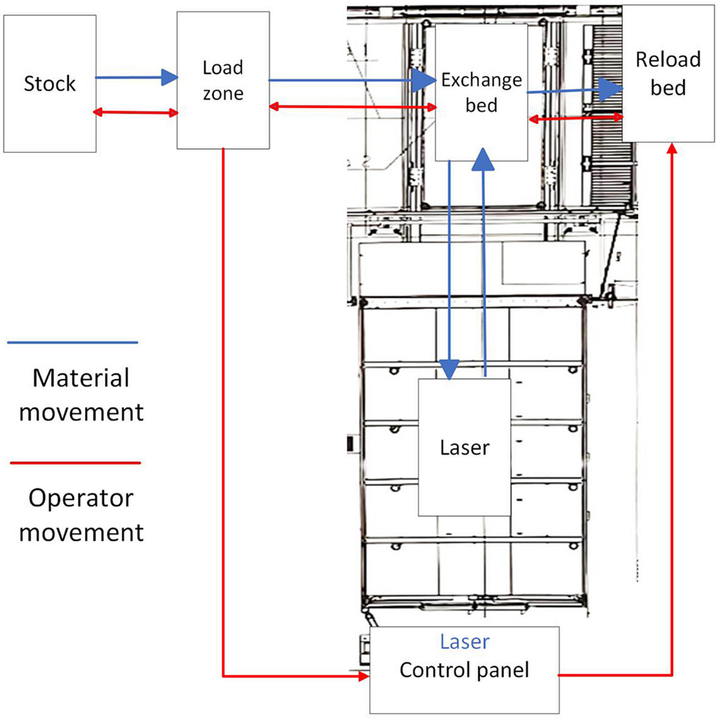

Figure 1. Process parts on scheme with marked material and operator movement

Table 1. Data collected from the production line for analysis

No.	Time [s]	Activity description
1	1800	Shipment of sheet metal from stock, operator decision, paper work, transportation to laser
2	300	Sheet loaded to laser zone
3	300	2 operators transport sheet to exchange bed
4	120	Operator movement to control panel and decision on cutting program choice
5	20	Laser table exchange
6	420	Laser cutting
7	600	Collecting pcs
8	300	Removing scrap
9	300	Quality control documentation of pcs

and the use of various types of sheets (thickness, size, type), leading to production errors, equipment failures, downtimes, and the inability to apply an agile strategy in the company [15, 16].

To increase production flexibility, the company invested in an additional laser cutting station and a sheet metal warehouse integrated into the production cell, creating a streamlined production line.

The automated sheet metal warehouse is designed to store various types of sheet metal on nine available shelves. Each shelf can hold several dozen sheets depending on their thickness. The warehouse is equipped with an automatic elevator that, through an operator panel or built-in remote communication, can retrieve any shelf containing the required sheets. These sheets are then transferred to the laser cutting table. Two of the shelves in the automated warehouse are designated for storing used sheets processed by the laser.

The automated sheet metal warehouse works in conjunction with an automatic loading system that transfers sheets to the laser cutting station and an unloading system for removing used sheets from the laser cutting station. The device is equipped with a suction system that transports sheets from the automated warehouse to any laser cutting station and a conveyor system that transports cut sheets to the automated warehouse or to a discharge cart. This setup ensures that both loading and unloading processes are automated.

Figure 2 illustrates the material flow and operator movements after these changes have been implemented. A diagram was also created to illustrate scenarios related to the reuse of sheets when they return to the tower or when Laser 2 is used if Laser 1 is already in operation (see Figure 3).

Table 2 provide a detailed description of various scenarios for a single process, from the moment the operator selects a shelf with a sheet to the removal of cut elements and cutouts. These scenarios correspond to those previously illustrated in Figure 3. The analysis includes the time needed

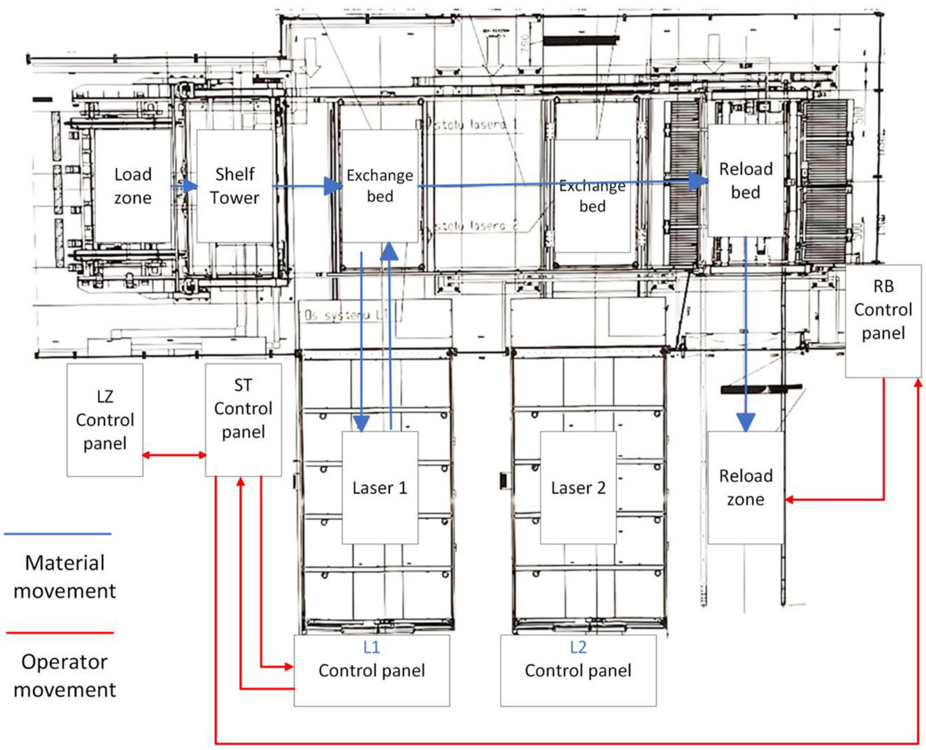

Figure 2. Process parts in time with analyze values

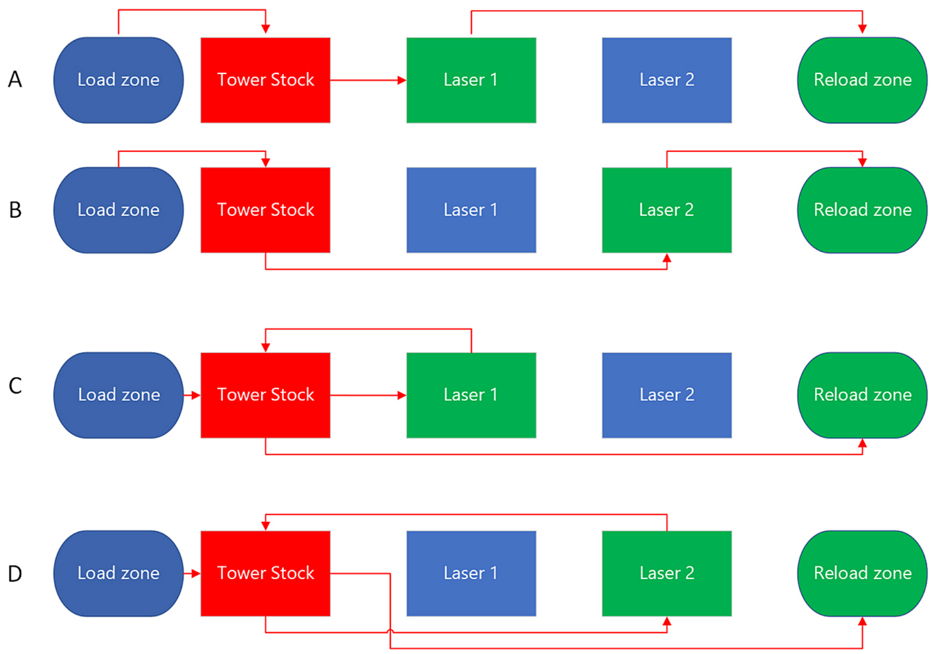

Figure 3. Variants of production cycle scenarios

for the operator to make decisions, such as selecting a shelf, choosing a laser based on its readiness (whether it is ready to operate or when it will finish the cutting process), observing the unloading table, and managing the tower if the sheet returns to the warehouse. The results of the averaged time measurements are presented in Figure 4.

In scenarios A and B (Table 2) it is observed that the time values are identical in both cases. NVA (non-value added) is 530 seconds, VA (value added) is 1020 seconds, C/T (cycle time) is 1550 seconds, O/T (operator time) is 900 seconds, and M/T (machine time) is 650 seconds.

In scenario C (Table 2), NVA increases to 590 seconds, C/T to 1610 seconds, and M/T to 710 seconds, while VA and O/T remain unchanged. Scenario D (Table 2) shows that NVA further increases to 630 seconds, C/T to 1650 seconds, and M/T to 750 seconds, with VA and O/T remaining constant.

These results suggest that the introduction of the tower and the second laser has led to significant changes in the process. Scenarios A and B

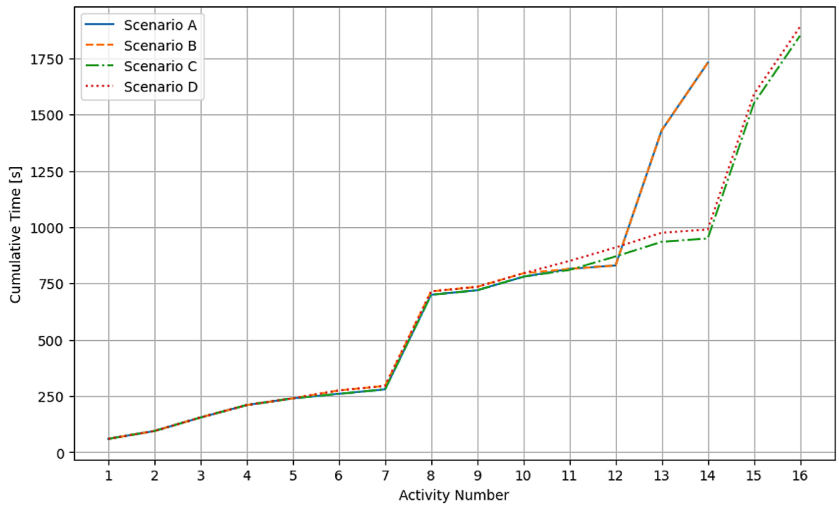

Figure 4. Variants of production cycle scenarios

Table 2. Scenario A to D

No.	Time [s] A	Time [s] B	Activity description A&B	Time [s] C	Time [s] D	Activity description C & D
1	60	60	Operator decision shelf choice	60	60	Operator decision shelf choice
2	35	35	Sheet loaded to shelf 1,2,3,5,6,7,8,9,10	35	35	Sheet loaded to shelf 1,2,3,5,6,7,8,9,10
3	60	60	Operator decision after monitoring lasers state	60	60	Operator decision after monitoring lasers state
4	55	55	Sheet transported to AP2 from shelf 3 (changeover)	55	55	Sheet transported to AP2 from shelf 3 (changeover)
5	30	30	Separating and thickness check	30	30	Separating and thickness check
6	20	35	Transport to laser 1 (scenario A)/2 (scenario B)	20	35	transport to laser 1(scenario C)/2 (scenario D)
7	20	20	Table exchange	20	20	Table exchange
8	420	420	Laser cutting	420	420	Laser cutting
9	20	20	Table exchange	20	20	Table exchange
10	60	60	Operator decision after monitoring reload zone	60	60	Operator decision
11	35	20	Transport to reload zone	30	55	Transport to tower AP3
12	15	15	Reload table move from cage	60	60	Operator decision after monitoring reload zone
13	600	600	Collecting pcs.	65	65	Transport to reload zone
14	300	300	Removing scrap	15	15	Reload table move from cage
15				600	600	Collecting pcs.
16				300	300	Removing scrap

are the most effective in minimizing NVA time, while scenarios C and D, although less effective in terms of NVA, might better optimize other aspects of the process.

The implemented changes theoretically doubled production capacity and increased efficiency. However, in practice, operators had to wait for the automatic warehouse and loader to become available, which slowed down the production process. Each laser cutting machine, automated sheet metal warehouse, and loading system had separate HMI (Human-Machine Interface) panels, requiring operators to simultaneously manage various aspects of sheet metal loading and unloading. The integration system designed and manufactured by us consists of many modules that work together. The system diagram is in the Figure 5.

Loading was controlled by entering the shelf number into the warehouse HMI panel and issuing commands to retrieve or return the shelf. Unloading cut sheets from the lasers required stopping the lasers, entering the safety zone, manually unloading the cut sheets from the laser tables, and then reloading new sheets.

A significant issue in both cycles was the need for operators to monitor the available sheet metal in the warehouse and the status of other lasers. After completing the production cycles, operators accounted for the used material and updated the status to the ordering department. This allowed the department to make updates in the ERP system and ensure continuity of supply. Lack of synchronization between the production system and the ERP system led to the need to maintain higher inventory levels, resulting in additional storage costs [17].

The primary task of the team was to optimize the production process to reduce machine downtimes and minimize human errors through automation and system integration using various communication standards. This is a trend not only in large manufacturing corporations but also in small enterprises, as evidenced by numerous publications on the topic [18–20].

A material flow diagram for the production line was created, highlighting the points where the operator makes key decisions (see Figure 6).

This analysis was based on possible scenarios and process rules [18], leading to the proposal of a solution based on software that integrates the automated sheet metal warehouse with the laser cutting stations. The software also manages the automatic loading and unloading of sheets onto the laser tables.

The operator initiates one of the sheet metal cutting programs with specified parameters and quantities, and the system automatically updates the inventory status in the database with each

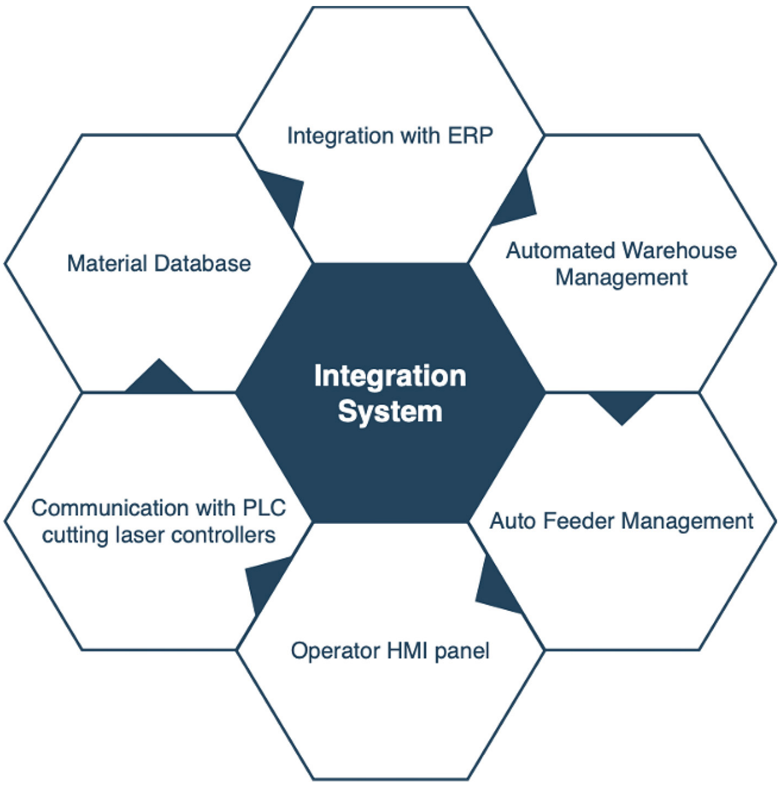

Figure 5. Components of the programmed integration system

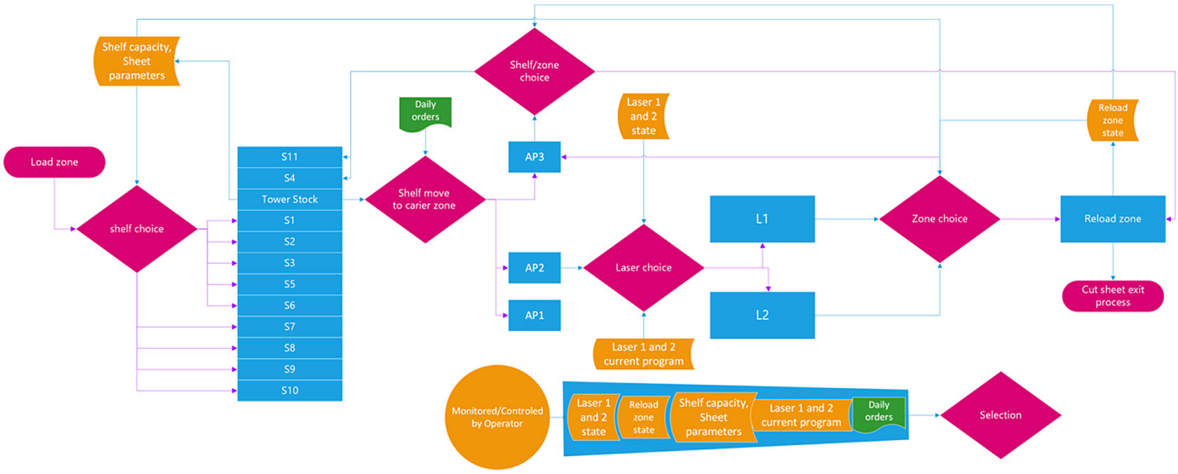

Figure 6. The operator's decision-making process has been replaced by an integrated system

material withdrawal. Additionally, this solution integrates with the ERP system, which monitors the availability of sheets both in the automatic warehouse and in a separate material warehouse. Each sheet withdrawal by the feeder results in an automatic update of the statuses in the ERP, providing the operator with a real-time view of material availability and the current state of machines via the HMI interface. In case of low stock levels, the ERP system generates a notification for the procurement department, enabling timely replenishment of materials. The procurement department, analyzing the availability of raw materials in the ERP system, determines the delivery lead time. This integration allows for the optimization of the production process, minimization of downtime, and increased operational efficiency of the enterprise. The integrating system consists of three main components:

System Integration: The integration system for laser cutting machines with the automated sheet metal warehouse, automatic loading system, inventory database, and ERP system (see Fig. 5) consists of three components:

- Business LOGIC SYSTEM – written in Python3, this system handles communication with laser PLCs via the OPC UA protocol, manages interactions with the automated sheet metal warehouse, controls the loading and unloading of sheets to and from the laser stations, and manages inventory states. It also includes interfaces for connecting to the ERP system and overseeing inventory management.
- REST API system – developed in TypeScript using the NestJS framework, this versatile and open interface serves as the backend for the HMI (human-machine interface) frontend system. It can also function as a platform for warehouse management and communication with the ERP system.
- UI (HMI) system – built using the React library, this operator panel is located at the operator's workstation. It allows for the editing of sheet metal types, adjustment of quantities, provides information on current operations, displays the current status of the automated warehouse, and highlights potential system issues or errors (Fig. 7).

Figure 7 shows the user interface of an automated system for storing, loading, and unloading sheet metal in a laser cutting process. The system supports two laser stations, an integrated automatic magazine, and a dual sheet metal loader. The left section of the interface shows the current status of the shelves in the automated sheet metal magazine. Each shelf has a unique number (from 1 to 11), with shelves 4 and 11 containing burnt sheet metal, indicating their consumption by the laser stations. The remaining shelves store sheets of different material specifications. Each shelf in the sheet metal magazine has information on the current number of sheets and their maximum capacity. The right side of the panel shows the status of the key components of the system: the laser stations (Laser 1 and Laser 2), the sheet metal magazine, and the automatic loading system. The panel allows for efficient production management.

The use of a REST API solution combined with a user authorization system enables the network connection of multiple panels of this type. One

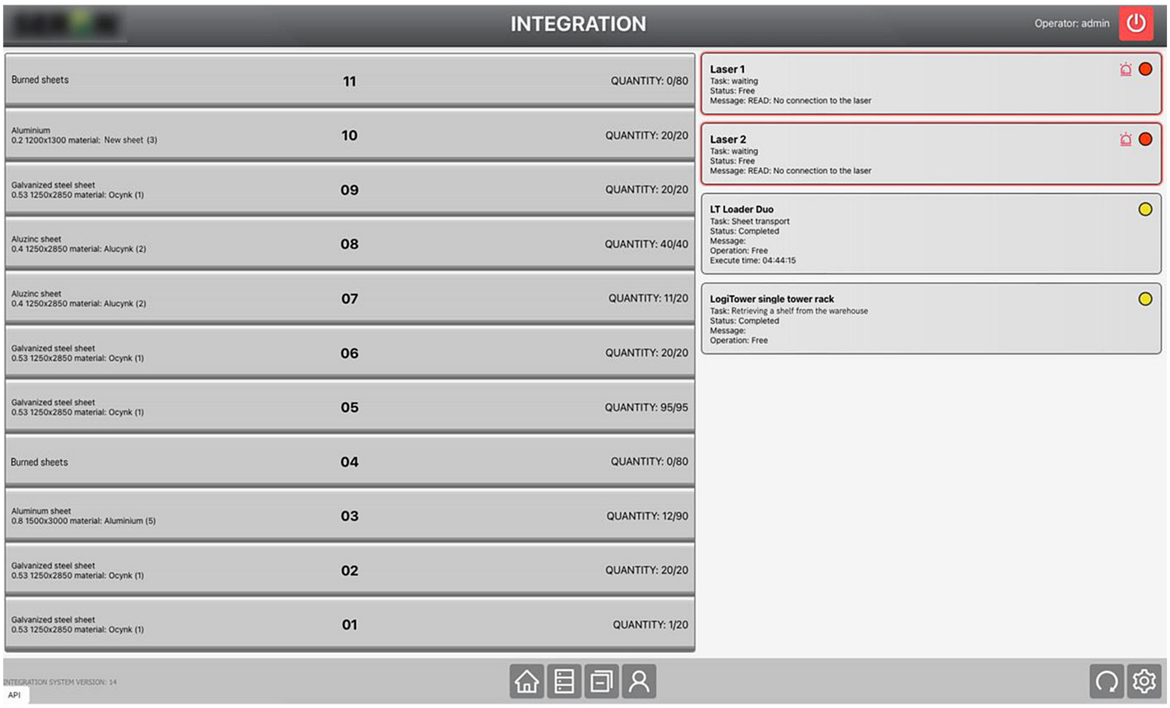

Figure 7. Integration system operator panel

such panel has been deployed in a different location within the production manager's office to provide real-time monitoring of the production line's status.

The communication standard between the PLC controllers and the integration system is based on the OPC UA protocol. This choice was made because the Bosch PLC controllers have built-in support for OPC UA. OPC UA is a universal standard developed and maintained by the OPC Foundation [19]. Although OPC UA is commonly used for communication with HMI panels, in this case, the PLCs' communication with the machines was programmed to utilize this protocol. Thus, the integration team had to employ OPC UA for system integration.

The OPC UA information model allows for the description of objects and processes within a specific system and the relationships between them. Each object is characterized by certain properties.

The factory houses two lasers of the same type, which communicate using a defined format. Each laser includes specific properties, such as a serial number. The data format structure for each laser is divided into objects to separate properties specific to laser actions from those related to system integration. Each property assigned to an object has a specified data type, and the format structure is consistent between the integration system and the PLC controller of each laser.

With support for authentication, OPC UA is a flexible and secure standard, allowing it to be adapted to changing market needs. A significant advantage of OPC UA is the availability of free libraries for many programming languages. In this case, the OPC UA IEC 62541 Client and Server library for Python was used [20]. The system's flexibility allows for future expansion with additional laser stations.

The PLC laser controller and the integration system contain an identical variable structure and their types. OPCUA variables are converted to Python language variables. In the Laser variable structure 0:Root, 0:Objects, 2:Logic, 2:Laser, 2:stLaser the value is issued by the Laser controller, and the integration system does not have access to change these values. These variables inform about the status of the tasks performed by the lasers. The integration system starts analyzing the command when any of the lasers issues Status=1 (is free and waiting for a command). In the event of a link failure or an unexpected restart of the laser controller, the system is resistant to such problems. Additionally, both the laser and the integration system have a watchdog that monitors the program progress and, in the event of a lack of communication, reacts appropriately and stops the system.

The introduction of new IT systems in industrial processes is associated with the potential risk of disruption of production continuity, damage to equipment or software malfunction. For this reason, testing was carried out in a simulation environment before implementation on a real production line. The programmed simulator reflects the automatic sheet metal warehouse and automatic loading system systems, which allowed for the reproduction of the full system work cycle without the risk of interfering with the real process [21]. Thanks to the use of the simulator, we also eliminated threats to the safety of operators and technical staff.

Verification of the integration system operation logic on the simulator allowed for a thorough check of the correctness of the implementation of control algorithms, data flow logic and communication between system components. The virtual environment allowed for conducting limit tests and exception analysis in a controlled manner, which was difficult to achieve in real conditions. Simulator tests also allowed for the preparation of emergency scenarios and the development of procedures in the event of technical problems. After successful tests on the simulator, the system was implemented in industrial conditions.

RESULTS AND DISCUSSION

Figure 8 displays the final times for the selected scenarios described in Table 3, divided into the same four scenarios (A, B, C, D) presented in Figure 6. The results are as follows:

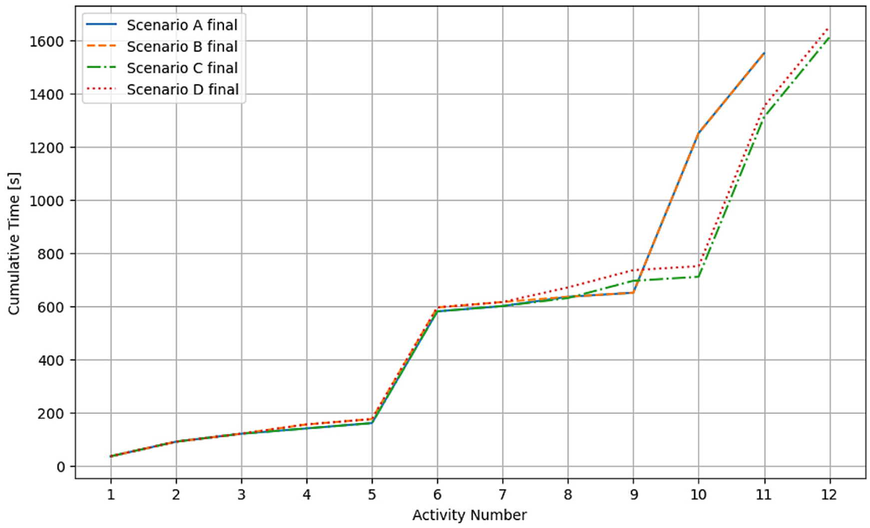

Figure 8. Depending on the material flow variant, the individual stages of the process and their time consumption

Table 3. The final times for the selected scenarios after implementing the IT integration

No.	Time A [s]	Time B [s]	Activity description A&B	Time C [s]	Time D [s]	Activity description C & D
1	35	35	Sheet loaded to shelf 1,2,3,5,6,7,8,9,10	35	35	Sheet loaded to shelf 1,2,3,5,6,7,8,9,10
2	55	55	Sheet transported to AP2 from shelf 3 (changeover)	55	55	Sheet transported to AP2 from shelf 3 (changeover)
3	30	30	Separating and thickness check	30	30	Separating and thickness check
4	20	35	Transport to laser 1(scenario A) 2 (B)	20	35	Transport to laser 1(scenario C) 2 (D)
5	20	20	Table exange	20	20	Table exange
6	420	420	Laser cuting	420	420	Laser cuting
7	20	20	Table exange	20	20	Table exange
8	35	20	Transport to reload zone	30	55	Transport to tower AP3
9	15	15	Reload table move from cage	65	65	Transport to reload zone
10	600	600	Collecting pcs.	15	15	Reload table move from cage
11	300	300	Removing scrap	600	600	Collecting pcs.
12				300	300	Removing scrap

- Scenarios A and B: both scenarios show identical time values: NVA is 560 seconds, VA is 1020 seconds, C/T is 1580 seconds, O/T is 930 seconds, and M/T is 650 seconds.
- Scenario C: NVA increases to 630 seconds, C/T to 1650 seconds, O/T to 940 seconds, and M/T to 720 seconds.
- Scenario D: NVA further increases to 670 seconds, C/T to 1690 seconds, O/T remains at 940 seconds, and M/T rises to 750 seconds.

These changes indicate a further reduction in NVA time compared to previous stages, especially in Scenarios A and B, where significant reductions in operational and cycle times were achieved.

Notably, the results differ from previous measurements in tab. Figure 3 primarily due to the elimination of operator-related decision-making times. These tasks have been taken over by the system and are considered automatic, thus not impacting the process cycle time. This difference can be observed in Table 4 in the O/T column, which shows 900 seconds for the scenario where the operator's role is limited to system oversight and unloading. The machine time remains unchanged across the scenarios.

The implementation of the integration software required training the staff and adapting to new work procedures. Before optimization, the system was operated by two operators, but after the implementation of the automatic system, the processes were optimized to such an extent that one person is sufficient to manage the automatic warehouse system and operate the sheet feeder. This change required the staff to acquire new skills related to operating the HMI interface, monitoring inventory levels, and interacting with the ERP system. The initial transition period involved additional workload for the employees, who had to adapt to new procedures and increased responsibilities. However, after the full implementation of the system and staff training, work efficiency significantly improved, and warehouse processes became smoother and more precise.

CONCLUSIONS

The optimisation of the production process of components using laser cutting and the use of full integration of automatic systems into a single unit allowed efficient management of resources, optimisation of production paths and reduction of operating costs. The combination of an automatic sheet metal warehouse with a system for automatic loading and unloading of metal sheets at the two laser stations and the integration with the ERP platform allowed greater transparency of production processes and more effective control of costs and material consumption.

The analysis of all three stages demonstrates that the introduction of new technologies and automation has had a significant impact on improving production process efficiency. The key findings are as follows:

Table 4. The comparison of value-added results for the baseline state, adding to the line with a tower and laser and after implementing the IT integration system (Scenarios A-D)

Scenario	NVA (before/after IT integration)	VA (before/after IT integration)	C/T (before/after IT integration)	O/T (before/after IT integration)	M/T (before/after IT integration)
Base	2840	1320	4160	3720	2240
A	710/530	1020/1020	1730/1550	1080/900	650/650
B	710/530	1020/1020	1730/1550	1080/900	650/650
C	830/590	1020/1020	1850/1610	1140/900	710/710
D	870/630	1020/1020	1890/1650	1140/900	750/750

Table 5. Return on investment (ROI) analysis

Position	Before implementation	After implementation	Change
Number of operators	2	1	-50%
Production cycle time (C/T)	4160 s	1730 s	-58%
Operator operational time (O/T)	3720 s	1080 s	-71%
Machine efficiency (M/T)	2240 s	650 s	+40%
Material losses	100%	80%	-20%
Operator labor cost (annual)	100,000 PLN	50,000 PLN	-50,000 PLN/year

- Reduction in NVA: the implementation of the tower and the second laser, followed by subsequent process automation, significantly reduced non-value-added (NVA) time. Scenarios A and B in the “system change” phase achieved the lowest NVA values.
- Increase in C/T and M/T: the increase in cycle time (C/T) and machine time (M/T) in later stages, particularly in scenarios C and D, suggests that the introduction of additional technologies involved more complex operations but also enabled the handling of more sophisticated production processes.
- Stability in VA: value-added (VA) time remained relatively stable across all scenarios, indicating that the value added in production was preserved despite changes in the process.
- Reduction in cycle time (C/T) – the operational time was reduced by an average of 58%, minimizing downtime caused by waiting for loading and unloading.
- Reduction in non-value-added time (NVA) – the time spent on operations not directly contributing to added value decreased by 65%.
- Increase in machine efficiency (M/T) – better synchronization between the sheet metal storage and laser workstations enabled a 40% increase in laser processing capacity.
- Optimization of raw material utilization – automated inventory management allowed for a reduction in excess material storage and a 20% decrease in material waste.
- Minimization of non-value-added (NVA) times – the time spent on non-value-added operations has been reduced by 65%.

Thanks to the optimizations, the savings resulting from the reduction of one operator and increased process efficiency allow for a quick return on investment, as shown in Table 5. The cost of the integration system and its implementation amounted to 100,000 PLN, and the return on investment was achieved within 0.5 years.

In summary, the modernization of the process through the introduction of new tools and automation has contributed to improved operational efficiency, particularly by reducing non-value-added activities and better utilizing operator and machine time. Consequently, the result of the automation has been an increase in the company’s market competitiveness through enhanced production capabilities, minimized human safety risks, and reduced costs. Many human-operated tasks, such as manual material feeding to the laser and unloading of finished products, have been eliminated, leading to increased safety and reduced downtime for loading and unloading compared to the pre-optimization state.

Further development directions of the system include the use of artificial intelligence for predictive production planning and the implementation of data analysis algorithms in the cloud to optimize raw material logistics. This system can be the foundation for modern factories in line with the assumptions of Industry 4.0.

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