



Article

Simulation-Based Optimization of Assembly Line Efficiency Through Intelligent Operator Rotation and Resource Utilization Balancing

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Abstract

This paper addresses the use of discrete-event simulation as a tool for optimizing the production process of an assembly line and identifying the potential for improving production efficiency. A digital model of the manufacturing system was developed in the FlexSim simulation environment based on real production data, technological operation sequences, and statistically defined cycle times. The model was designed to accurately represent real production conditions, including control logic, resource interactions, and material flow. The simulation results were analyzed using graphical and quantitative reports, which enabled the identification of production bottlenecks and inefficient resource utilization. Based on the obtained data, a process optimization strategy was proposed in the form of intelligent operator rotation between workstations to increase operator utilization and improve overall system efficiency. The proposed modifications were subsequently verified through simulation experiments, confirming the preservation of the required production capacity while improving the efficiency of human resource utilization. The findings confirm that simulation modeling represents an effective tool for the analysis, design, and verification of optimization measures, enabling the reduction in operational costs and risks associated with implementing changes in real manufacturing environments.

Keywords: discrete-event simulation; production process optimization; assembly line; simulation model; FlexSim

1. Introduction

Simulation of manufacturing processes currently represents an important tool for planning, analysis, and verification of changes in industrial systems. It enables experimentation with different solution variants in a virtual environment without the need to intervene in real production operations, thereby contributing to the reduction in costs and risks associated with the implementation of changes in manufacturing systems [1]. In the field of industrial engineering, simulation modeling has become an important component of the design and optimization of manufacturing processes, as digital models enable the analysis of system behavior and the experimental verification of proposed optimization measures before their implementation in practice [2].

Balancing production processes from the point of view of optimal efficiency is a frequent phenomenon that can be observed in manufacturing companies. This problem



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concerns both manual workplaces and fully automated workplaces where the process owner wants to achieve maximum efficiency. It is necessary to state that in manual workplaces the phenomenon of the importance of correct balancing is even more pronounced. Especially when it comes to several interconnected manual workplaces, this topic is often discussed in manufacturing companies. The specifics of manual workplaces are largely influenced by the subjectivity of the work object—the production operator. This brings with it a significant number of variables and deviations that have an impact on the efficiency of the individual as well as on the efficiency of the entire system. When a combination with automatic workplaces is added to this area, a complex problem and the need for a comprehensive overview and assessment of this research area are taken care of [3]. If we separate the issue of automatic workplaces from manual ones, then in the case of automatic ones it can be stated that these are characterized by a certain degree of constancy and adaptability according to requirements, and therefore the automatic processes themselves are not the main cause of the complexity of the system in terms of achieving the necessary efficiency of systems formed by a combination of automatic machines and manual workplaces. It is precisely the aforementioned manual processes that cause the need for in-depth analyses and these problems, while these efficiency problems are typical for processes with a fixed—rigid division of work tasks. The intention of every process engineer is for the process to be tuned and optimal, which in practice means that there are no large differences between the percentage of operator utilization, but rather that the operators have approximately the same percentage of utilization and efficiency. In practice, the same percentage of utilization for everyone is almost unattainable because it is necessary to take into account that each manual work is in its own way specific and requires a certain time to perform, but the aim is to minimize the emergence of bottlenecks and in the event of such a bottleneck, the aim is to effectively utilize adjacent operations and people at adjacent workplaces and therefore not wait to exit the bottleneck. It is in these areas that space opens up for optimization, which will be discussed later, and as mentioned, this phenomenon is typical for rigid lines [3–5].

It is necessary to say that every single production system must have a bottleneck somewhere, the intention is to minimize its adverse impact on the entire system so that the production flow is not negatively affected by the slowest process. Bottleneck in some automatic workplaces can be associated with the nature of the operation being performed and its time consumption, such as the heating, cooling process, etc. Rigid systems ignore these factors and also ignore the variability of manual workplaces, which is increased by factors such as operator subjectivity, skills, experience or fatigue, etc. The aforementioned factors lead to uneven utilization of labor force, since by human nature, each person is unique [5]. Optimization and rotation in such systems is aimed at eliminating the accumulation of adverse effects, mainly downtime of manual but also automatic workplaces, while simultaneously maintaining the production potential and maintaining the necessary quality of production. Such an optimizer can simultaneously lead to the fact that the introduced automation made sense because the automated workplace is maximally utilized and is not idle due to the non-optimized process in front of it. Another important factor that must be mentioned in favor of optimization is that the rigid model, unlike rotation, also causes uneven loads from the point of view of ergonomics, weight load, monotony of work, which can have an impact on the quality of work, while these factors must also be addressed from the point of view of laws. In summary, it can be stated that in such processes it is very important, even necessary, to introduce optimization and introduce a model of some kind of adaptive dynamic control of the production process and a system of training multi-skilling operators [4–6].

In the context of production digitalization and the Industry 4.0 concept, simulation is gaining even greater importance. It enables the analysis of the utilization of production resources, the identification of potential problems, and the evaluation of manufacturing system performance under various operational scenarios [7,8]. Simulation modeling also provides tools for identifying production bottlenecks and analyzing interactions between individual elements of the manufacturing system, which is essential for effective production management [9]. A fundamental prerequisite for the successful use of simulation is the creation of a representative model that accurately reflects the real conditions of the manufacturing system, including the technological sequence of operations, material flow, and process control logic [10]. The quality of input data and their proper processing significantly influence the accuracy of simulation results and the subsequent interpretation of the obtained data [11].

Based on the above facts and advantages of simulation, it is possible to deduce the basic thought processes and intentions why the use of simulation as such is so necessary in the case of this study. In connection with the previous paragraph, the simulation in this study will identify the potential of a specific manufacturing process, the characteristics of which will be discussed later. Therefore, the potential of simulation in the area of potential identification and line performance assessment will be used, the bottleneck will be defined and then the comparison with the achievable reality will be approached. After verifying the correctness of the model, the authors thought about a possible functional model of smart rotation that would significantly increase the performance and effective parameters of the previously inefficient process [11,12].

It is good to mention that in the available literature, simulation is widely used in the design and optimization of manufacturing systems, production planning, and the analysis of manufacturing and logistics processes [12,13]. Simulation tools enable the creation of digital models of manufacturing systems, the analysis of resource utilization, and the experimental verification of various optimization measures [14,15]. In practice, simulation is used, for example, in the optimization of manufacturing processes, logistics systems, or the design of manufacturing workplace layouts, but the authors see a gap in research precisely in the aforementioned study of resource utilization in specific processes where a significant part of the process is manual in nature and when the production line is largely represented by manual processes and operators. This area or the case where the production line is a combination of machines and manual workplaces which are more represented is a specific case because from this fact in the specific process also stemmed the phenomenon of uneven utilization and loss of efficiency caused by a rigid way of dividing work and these specific cases are little represented in research studies today [16].

Despite the extensive use of simulation methods in the optimization of manufacturing systems, most published studies focus primarily on the optimization of technological production parameters, the design of manufacturing workplace layouts, or the optimization of material logistics flows within the production system. Less attention has been devoted to optimization approaches based on the rotation and organization of operators' work and their dynamic reassignment between workplaces depending on the current system workload. This aspect is particularly important in practice, especially in assembly systems with a high proportion of manual operations, where an appropriate organization of operators' work can significantly influence the overall efficiency of the manufacturing process. The last sentences clearly point to the fact or rather to the purposes and subjects of interest of the most frequently implemented and proposed optimizations today. Based on the real situation and demand of real operations and the identified unrepresented area in scientific publications, it is important to pay due attention to the optimization of processes and lines of the aforementioned nature. Lines characterized by a combination of automatic

workplaces and prevailing manual workplaces are often associated with the need for a study of process efficiency and the subsequent optimization proposal. Optimization in the form of smart rotation represents an innovative approach to optimizing a very specific combined process. A survey of available publications in this area indicates the absence of a solution to this specific issue and type of optimization in connection with the specifics of the production process [17–19].

In summary, this work focuses in the initial phase on the design and analysis of a specific process of a real production line with a focus on the efficient use of resources and in the second step, based on the performed and verified analysis, the work focuses on the design of an optimization approach based on intelligent rotation of operators between workstations on the assembly line. The proposed approach is analyzed through a simulation model developed in the FlexSim environment, which enables a detailed analysis of manufacturing system behavior and the evaluation of the impact of the proposed changes on resource utilization and overall process efficiency. The main contribution of the study lies in the parameterization of the process, the study of the current efficiency of the process and the use of its resources and, last but not least, in the demonstration of the potential of discrete event simulation as a tool for experimental verification of organizational and optimization options or measures in the assembly production environment without the need to intervene in the real production system and the design of possible operating schemes in the digital environment, thus eliminating the risk of losses associated with an inappropriately designed optimization method. In connection with and based on the defined research gap and literature review which provides a theoretical overview of the area under study, in the initial phase the correctness of the model is verified by comparing and analyzing the simulation output and the achievable reality of the production line and the secondary, but key contribution is the design of an optimization scheme or possible operation of the process by introducing the concept of intelligent rotation optimization with an assessment of the impact on the system, i.e., on its production capacity, the impact on overall and partial efficiency, compliance with legal restrictions, etc.

2. Methodology

The methodological approach used in this work is based on the use of discrete simulation as a tool for the analysis and optimization of the assembly line manufacturing process. The aim of the methodology is to create a representative simulation model of the manufacturing system that allows the analysis of process behavior, identification of potential inefficiencies, and experimental verification of proposed optimization measures without the need to intervene in real production operations.

The methodological scenario of this particular application is not based on the investigation of a new methodology of the simulation-optimization approach, but uses the approaches known today, in which the standard scheme consists of the initial quantification and analysis of the current state of the process, identification of room for improvement and subsequent experimental verification of the feasibility of the proposed optimization model. Thus, to a certain extent, it is a relatively open optimization algorithm based on experimental verification and subsequent adaptation to the specific nature of the process with a fundamental impact on the system while maintaining or increasing the quantitative and qualitative indicators of the line. It is precisely the quasi-open approach or algorithm and the specificity of the specific simulated process under study that are its most fundamental difference in comparison with other structured approaches of simulation-based optimization and other use cases represented in the literature, which makes this publication contribution unique. It is possible to confirm with certainty that the specific process has not yet been studied in the literature and it follows that the proposed optimization also

exhibits features of uniqueness and originality that are characteristic only of the given process. The reviewed literature and cases in it make extensive use of systematic and purely mathematical approaches and optimization proposals, whereas in this case, the optimal rotation scenario is discovered by open optimization using an experimental method and subsequent verification in a virtual environment.

The key to the design of a suitable optimization and subsequent operating scheme is the correct identification of the bottleneck, which is based on the analysis of the current state. From this, it is necessary to identify the bottleneck and therefore the slowest process, which must not be slowed down even more by the proposed optimization, but on the contrary, the optimization should, in an ideal scenario, increase its throughput. A simultaneous bottleneck identifier in the case of a manual workplace is also the highest percentage of operator utilization working at a given station. The greatest specificity and at the same time innovative advantage of this open approach, based on experience from this application, lies mainly in its flexibility, the possibility of flexible and rapid design and introduction of changes with subsequent rapid verification of the impact of the proposed changes. One of the biggest benefits of this approach is also suitability of optimization approach especially for cases where very complex nonlinear production systems are analyzed. The speed of change and, consequently, the speed of obtaining the results of the introduced changes, as well as the possibility of relatively simple testing of the introduced changes, especially in complex systems, is one of the most evaluated in comparison with historical models used by mathematical models and approaches where almost all changes in conditions are connected with the necessity of relatively demanding modification of complex mathematical optimizations. A distinctive feature of this approach to optimization design is the division of the overall system into smaller groups within which rotation occurs with the aim of increasing the efficiency of work in these particular groups. The following paragraph of this chapter describes in more detail the individual steps necessary to achieve the work output.

The first step of the methodological procedure was the analysis of the existing assembly line production process. The most important characteristic in this introductory part of the description is the clarification of the product produced by the line under study. In the case of this particular line, it is a line that produces compressors for commercially used refrigerators. In this phase, individual technological operations, the material flow between workstations, time characteristics of operations, and the organization of operators' work were identified. This phase also included the collection of input data necessary for the creation of the simulation model.

The data in this section were obtained and recorded thanks to the interconnected digital twin system. Thanks to this system, it was possible to obtain important inputs for creating a model and analyzing the current state of the line and, based on this, to propose improvements. The system of interconnecting the line with the digital twin on the basis of which the data was obtained and therefore a detailed description of the method of obtaining data can be a separate specific area and is not the content of this research and it is assumed that these necessary data are already available at the beginning of the research and analysis as necessary documents. In addition to the aforementioned independence of the issue, there is also the factor of the possibility of access in terms of policy and protection of know-how. In addition to this method of data collection, data was also obtained by direct methods directly at the workplace, namely by measuring, observing and evaluating the effects. The collection of these documents was a process lasting several weeks in order to capture the widest possible range of possible scenarios, so that random unexpected phenomena were absent in the subsequent analysis and optimization process to the greatest extent possible. In principle, this data included in particular the cycle times of operations of automatic and manual workplaces, the number of operators, the number of workstations,

the logic of material flow in the production system, the impact of bottlenecks on the system, the capacity of buffers, the definition of errors and malfunctions and the definition of the repair workplace, the definition of indicators such as ergonomics and weight loads of individual manual stations, the definition of critical stations, logistical support, processes of support or following lines, given that the investigated line is a pre-assembly intended for further assembly, distances of workplaces, duration of retyping in case of type change, quantification of circumstances associated with the production plan, definition of achievable optimization goals, definition of the ratio of manual and automatic workplaces. The true ratio of manual and automatic workplaces is very important when considering balancing and improving the process. From the analysis, it is clear that approximately 35% of workplaces are automatic; therefore, the vast majority are manual. The specificity lies in the combination of prevailing manual workplaces with automatic ones.

A separate and very key point was the definition of the statistical distribution of cycle times of manual workplaces, where the evaluation of the obtained data was performed using the company's statistical software.

Based on the obtained data, a digital model of the assembly line was subsequently created in the FlexSim 2025 simulation environment. The model was designed to represent the real conditions of the manufacturing process as faithfully as possible. During the modeling process, individual simulation objects representing workstations, operators, and material flows between them were defined. The model also included the implementation of the system control logic, which reflects the technological sequence of operations and the interactions between individual elements of the manufacturing process. After the model was created, its verification and validation were performed. Model verification focused on checking the correctness of the implemented model logic and the functionality of individual simulation objects. Model validation consisted of comparing simulation results with real data from the manufacturing process in order to verify whether the model sufficiently accurately represents the behavior of the real system. Directly related to the aforementioned correctness check was and is also the factor of consideration of simplified simulation assumptions. Based on these simplified assumptions, deviations from achievable reality may occur and the simulation results may be distorted, and it is necessary to keep in mind that if we create optimization scenarios based on model analysis with simplified assumptions, the proposed optimization model may also show certain distortions from achievable reality. In general, such a simplified assumption may be, for example, unlimited material supply, absence of failures, constant times of automatic workplaces but also times of manual workplaces within the defined distribution range, process quality, set ups, reworks and scrap, operator availability, logistics delays, and others. After creating the current state model and simulating it, the simulation result was almost identical to the defined achievable and achieved production standard. It follows that the model is relatively well developed and the included factors correctly influence the simulation model. Despite the above, there are simplifications that were considered in this model.

The model works with cycle times within the limits of the selected distribution, conversions according to the production plan, a rework station for a timely monitored percentage of production, a fixed production process, the need to retype to another product variant but with the assumption of continuous demand and trouble-free retyping, operator availability, constant supply of material from a logistics perspective without delays, no prioritization of product model lines, limitation of inter-operation buffers, the time the product spends on the line does not affect its quality, inclusion of warm-up for filling the line, absence of consideration of risks and uncertainties in the context of variable possible scenarios such as conveyor slowdown, loss of performance and other unexpected scenarios. These mentioned

factors are the most frequently occurring and the correctness of their inclusion is confirmed by the correspondence between the simulation output and the achievable standard.

In the next phase, simulation experiments were carried out to analyze resource utilization and identify potential bottlenecks in the manufacturing process. Based on the results of the analysis, an optimization approach based on the intelligent rotation of operators between selected workstations was proposed. The aim of this optimization was to increase the efficiency of human resource utilization while maintaining the required production capacity of the system. The proposed optimization measure was subsequently implemented in the simulation model and verified through additional simulation experiments. The simulation results were analyzed using quantitative indicators, including operator utilization, manufacturing system throughput, and time characteristics of the production process. Based on the obtained results, it was possible to evaluate the impact of the proposed changes on the overall efficiency of the manufacturing system.

The applied methodological approach therefore enables a systematic analysis of the manufacturing process and provides a basis for the design of optimization measures that can be safely verified in a virtual environment before their implementation in real manufacturing operations. The following Figure 1 shows a flow chart that clearly illustrates the research methodology.

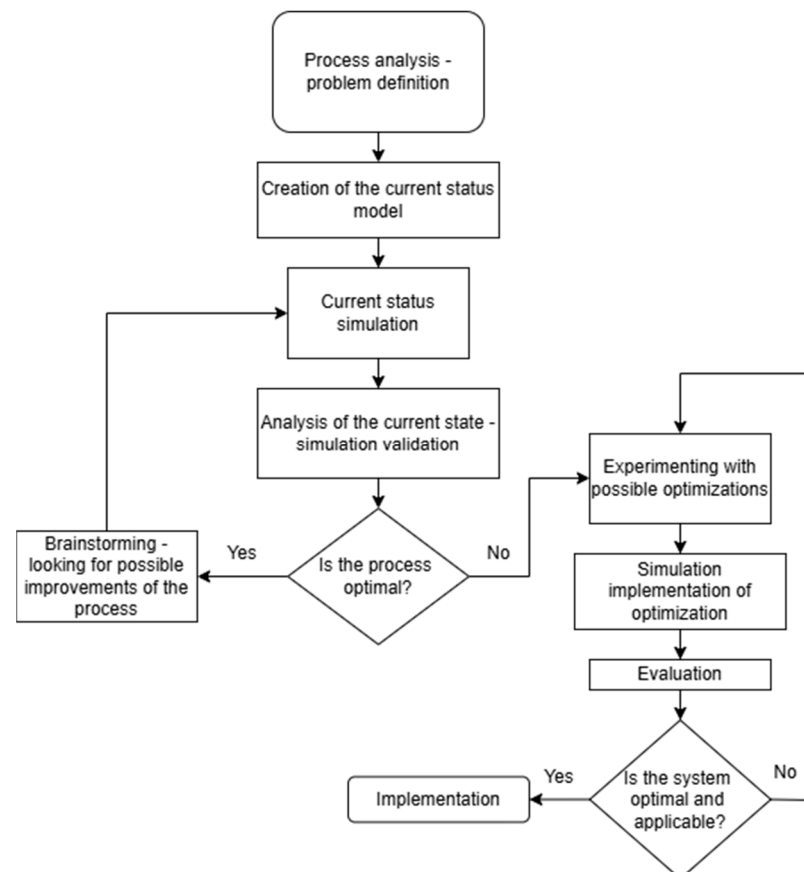


Figure 1. Methodology model flowchart.

3. Development of the Simulation Model of the Manufacturing Process

For the analysis of the assembly line manufacturing process, a simulation model was created in the FlexSim environment. This software enables the modeling, simulation, visualization, and optimization of manufacturing and logistics systems. With the help of the ExpertFit tool, it is possible to identify an appropriate statistical distribution of input data and thus account for the variability that naturally occurs in real manufacturing processes.

FlexSim also allows the import of 3D models or CAD drawings, enabling the creation of a realistic digital model of the manufacturing system with real dimensions [20,21].

When modeling more complex processes, the ProcessFlow tool was used, which is designed for creating the control logic of the simulation using block diagrams. This tool allows the definition of relationships between individual simulation objects and, if necessary, the implementation of custom functions using the FlexScript programming language [22].

3.1. Basic Simulation Objects of the Manufacturing System

From the perspective of simulation modeling, the manufacturing process can be represented using basic simulation objects. In the analyzed manufacturing system, four basic objects were used:

- Source—an object generating products entering the manufacturing process. In this simulation, the source generates objects representing the product after importing its 3D model. In a real manufacturing process, this object represents the beginning of the production line.
- Buffer—an object representing an intermediate storage area between individual workstations. In the simulation, it serves to accumulate products between individual operations. In real production, this element represents the space of the conveyor system between manufacturing stations.
- Processor—an object representing a technological operation performed on the product. This object can represent various manufacturing operations such as assembly, welding, machining, or product inspection.
- Sink—an object representing the end of the manufacturing process. After the completion of the production cycle, the product is recorded in the simulation counters and subsequently leaves the model [23,24].

In the case of more complex manufacturing systems, it is necessary to use additional simulation objects. In the analyzed model, objects of the combiner type were also used, which enable the merging of multiple components into a single product, as well as separator objects that allow the division of material flow. An important part of creating a simulation model is the definition of the manufacturing system layout [25].

The layout represents a graphical representation of the arrangement of the assembly line and the transport routes between individual workstations. In the analyzed system, the stations are arranged along the production line and interconnected by a conveyor belt. The layout was created in a CAD environment using the real dimensions of the production line and subsequently imported into the FlexSim simulation environment. The imported model serves as a basis for the placement of simulation objects and ensures that the distances between individual workstations correspond to the real manufacturing system. An example of a part of the assembly line imported into the simulation environment is shown in Figure 2.

For the development of the simulation model, it was also necessary to define the technological sequence of operations of the manufacturing process. Based on the analysis of the real manufacturing system, a chronological sequence of assembly line operations was established, including both manual and automated workstations. This sequence represents the basic logic of the material flow of the product through individual manufacturing stations and simultaneously constitutes one of the key inputs for the development of the simulation model.

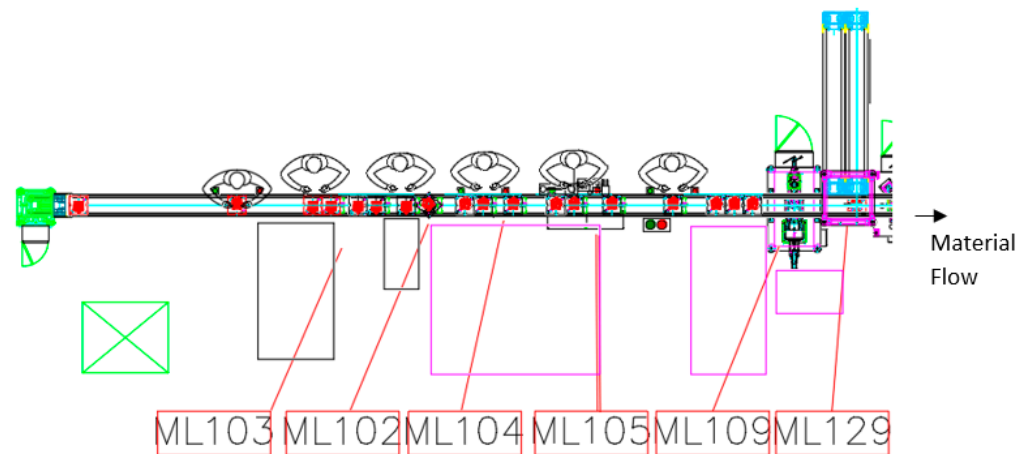


Figure 2. Sequence of operations in the assembly line manufacturing process.

The manufacturing process begins with the entry of basic components into the assembly line and continues with the gradual assembly of individual product parts, performed through a combination of manual operations and automated workstations. During the manufacturing process, inspection operations and technological tests are also carried out to verify the functionality and quality of the final product. The chronological sequence of operations of the analyzed manufacturing process is presented below.

Chronological sequence of assembly line operations:

- Assembly line—entry of the product into the assembly process;
- Piston—cylinder pairing;
- Shaft—body pairing;
- Assembly of rod with piston and piston pin + selection and unscrewing of connecting rod;
- Assembly of rod with piston and piston pin, oiling of piston and shaft;
- Rod assembly with shaft;
- Assembly of the outer bearing;
- AUTOMAT—Screwing of the outer bearing;
- AUTOMAT—Friction test;
- Preparation of valve plate—grinding and jamming;
- Assembly of valve plate NT—loading of valve plate on the pallet;
- Assembly of valve plate NT—completion of components;
- Assembly of valve plate NT—screwing valve plate to the required torque;
- AUTOMAT—Volumetric test NT;
- Assembly of valve plate and NT cylinder head;
- AUTOMAT—Piston overhang measurement—seal selection;
- Seal selection;
- AUTOMAT—Tightening the cylinder head;
- Translation of mechanics;
- AUTOMAT—Pressing three pins into the T body and one pin with an adapter into the NT body;
- Stator assembly;
- AUTOMAT—Centering and tightening the stator screws;
- Rotor assembly;
- AUTOMAT—Cooling tunnel;
- AUTOMAT—Oil pipe pressing;
- Installation of NT plastic muffler;
- Checking the air gap and axial gap;

- Loading the shell on the line—inserting a PVC pin with a spring into the shell;
- AUTOMAT—Pressing plastic pins and springs into the NT shell;
- Connecting the electrical terminal and storing the mechanics in the shell;
- AUTOMAT—Mechanics oiling;
- Assembly of the discharge pipe—pre-assembly of the discharge pipe;
- Assembly of the discharge pipe—screwing of the serpentine;
- Serpentine soldering;
- AUTOMAT—Dielectric test;
- Checking the serpentine position—centering;
- Setting up the top cover;
- AUTOMAT—Leak and pressure test;
- AUTOMAT—Product labeling.

The chronological sequence of operations represents the basic structure of the manufacturing process, which was subsequently implemented in the simulation model. Individual operations in the model are represented by separate workstations or technological stations, while the material flow between them is ensured by a conveyor system. Such a defined sequence of operations enables the accurate reproduction of the real organization of the manufacturing process and allows the analysis of interactions between individual workstations. From the perspective of simulation modeling, it is also important to consider not only the technological sequence of operations but also the organization of operators' work, the logistical support of the manufacturing process, and other operational parameters that influence the performance of the manufacturing system.

Operators are and will be grouped with respect to the sequence of operations, the nature of the processes they perform, and the physical distance between the stations at which they work. Such a division of operators allows more realistic modeling of work activities and at the same time creates the conditions for the subsequent implementation of optimization measures based on the flexible utilization of the workforce. This aspect will later be used in the design of the optimization of the manufacturing system. Another important configuration that must be included in the simulation model is the definition of the final number of pallets on which products move along the conveyor system of the production line. The source in the simulation generates the same number of pallets as in the real system. In the analyzed case, 70 pallets were defined circulating on the line due to the real line state and capacity limitation. After their generation, the source becomes inactive and the pallets subsequently circulate within the system. This configuration ensures that the simulated system operates within its real capacity and prevents overloading caused by excessive product generation. When generating products, it is also necessary to consider the production schedule and the process of retooling manufacturing equipment, since stations do not produce during the retooling process. This factor directly affects the resulting performance of the manufacturing system and must therefore also be included in the simulation model. Another important input parameter of the simulation is the definition of its time duration. The simulated line operates in work shifts lasting 8 h. In order to obtain values corresponding to the real capabilities of the line, the total simulation time was set to 8 h and 20 min. During a real shift, production takes place for 7 h and 20 min. The reason for extending the simulation by one hour is that the simulation starts with an empty line, whereas in practice the manufacturing system is already filled with products at the beginning of the shift. The first hour of the simulation therefore represents the so-called warm-up phase, during which the line is filled.

The most important configuration of the simulation model is the definition of the process time of individual operations. The process time can be defined either as a constant value or as a value defined in a source table. In the case of manual workstations, however,

the process time is most often defined using a statistical probability distribution, which allows the variability caused by the human factor to be taken into account.

Automated workstations generally exhibit minimal deviations from the nominal cycle time, whereas manual workstations show greater differences between the nominal and the actual cycle time. These differences are caused by the individual working speed of operators and other factors of the working environment. Based on statistical data collection, probability distributions that best represent the real cycle times of operations were therefore identified for individual workstations. An example of defining the cycle time distribution is shown in Figure 3.

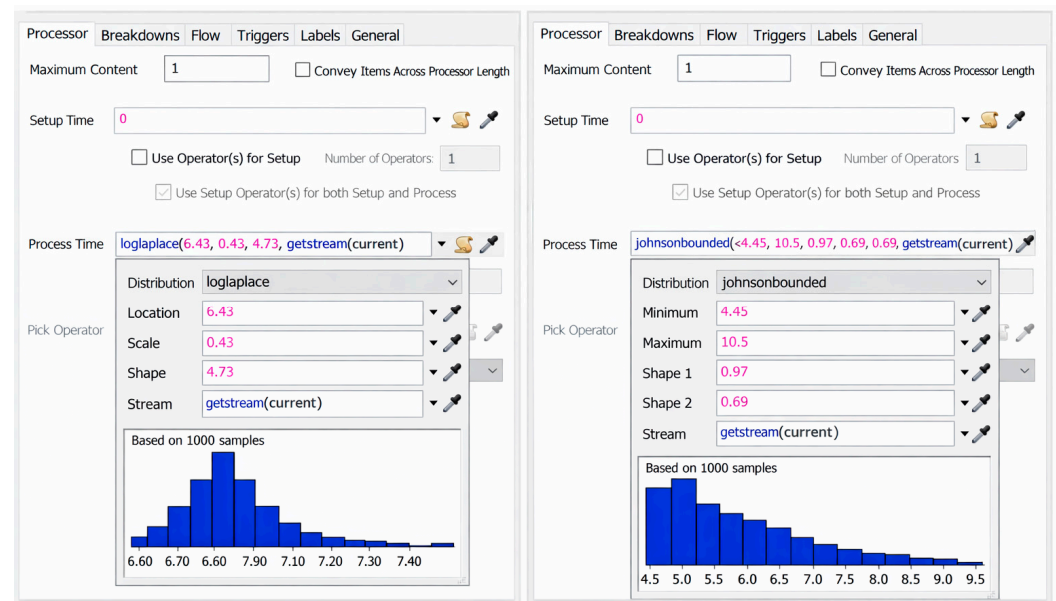


Figure 3. Definition of the operation cycle time distribution.

For a representative simulation, it is also necessary to consider the logistical support of the manufacturing system. In addition to the main assembly line, a supporting production process was therefore included in the model, which ensures the supply of components for the main line. This supporting line consists of six manual workstations whose output is delivered to the main assembly line by a logistics system. The implementation of this part of the model is shown in Figure 4.

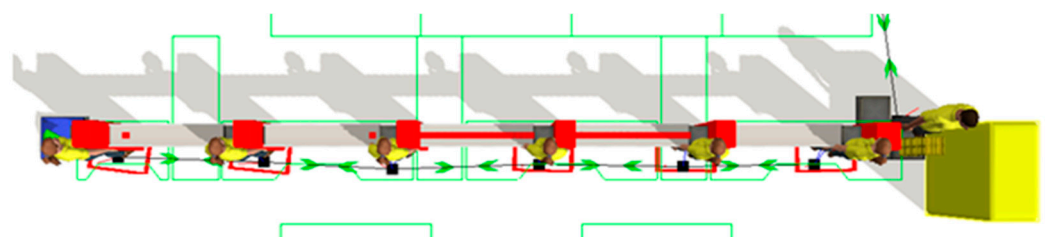


Figure 4. Simulation model of the supporting manufacturing process.

Another important element of the simulation is the implementation of a repair workstation. Based on long-term statistical monitoring, it was determined that approximately 1% of products must be repaired during the manufacturing process. Therefore, the testing station in the simulation is configured so that approximately 1% of products are redirected to the repair workstation, while the remaining 99% continue in the process. The implementation of this mechanism is shown in Figure 5.

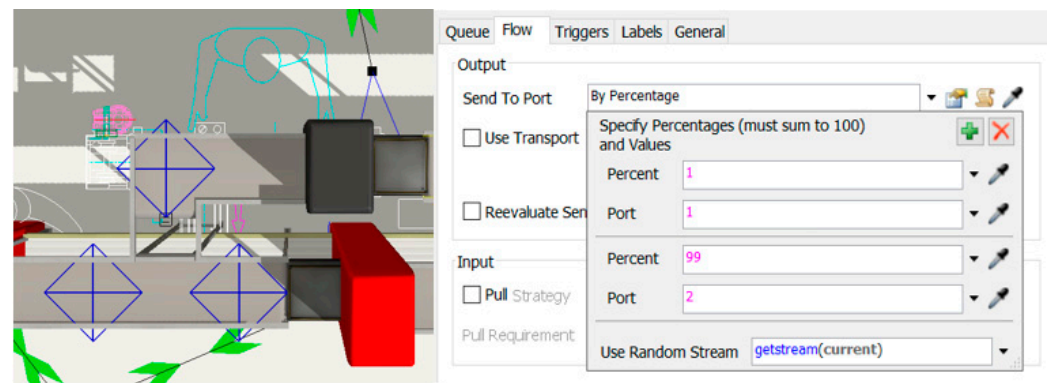


Figure 5. Implementation of the repair workstation in the simulation model.

3.2. Implementation of the Model Control Logic in the ProcessFlow Environment

The ProcessFlow tool is used for creating the control logic of more complex manufacturing processes, where the basic functionalities of simulation objects are no longer sufficient. In such cases, it is necessary to define relationships between objects, system variables, or specific conditions for process control. ProcessFlow can therefore be considered a higher-level approach to programming the control logic of a simulation model. This tool enables the creation of control algorithms through block diagrams that represent individual steps of the process logic. In addition to the standard blocks available in the library, custom functionalities can also be defined using source code written in the FlexScript language, whose syntax is based on the structure of the C programming language. The control logic of manual workstations implemented in the simulation model is illustrated in Figure 6, which presents an example of a ProcessFlow diagram controlling the activity of an operator at a manual workstation. A separate control block adapted to the specific nature of the operation was created for each manual workstation of the production line.

The basic element of the control logic is the Source block, which represents the triggering mechanism of the entire logic. In this block, a so-called token is generated, i.e., a virtual signal that sequentially passes through individual blocks of the diagram and triggers defined operations based on specified conditions. Another important block is the Buffer, in which an intermediate storage area for the given process is defined. In the simulation, this buffer is directly located on the conveyor, and its capacity is defined so that it does not affect the capacity of the conveyor system between individual workstations. If a product is present in the buffer, the activity of the corresponding operator is automatically triggered. At the same time, the parameter `batch_count` is defined in this block, which determines the minimum number of units that the operator should process upon arriving at the station. The maximum waiting time of the operator is set to 5 s. If the interval between incoming products is longer, the operator is released to perform another work activity. This ensures reasonable operator utilization and smooth smart rotation, even with respect to the distance traveled. It also prevents unnecessary system blocking of the operator if he is not needed in the station. The configuration of the control logic parameters for individual operations is shown in Figure 7, where examples of defining token attributes and operational parameters of the process block are presented.

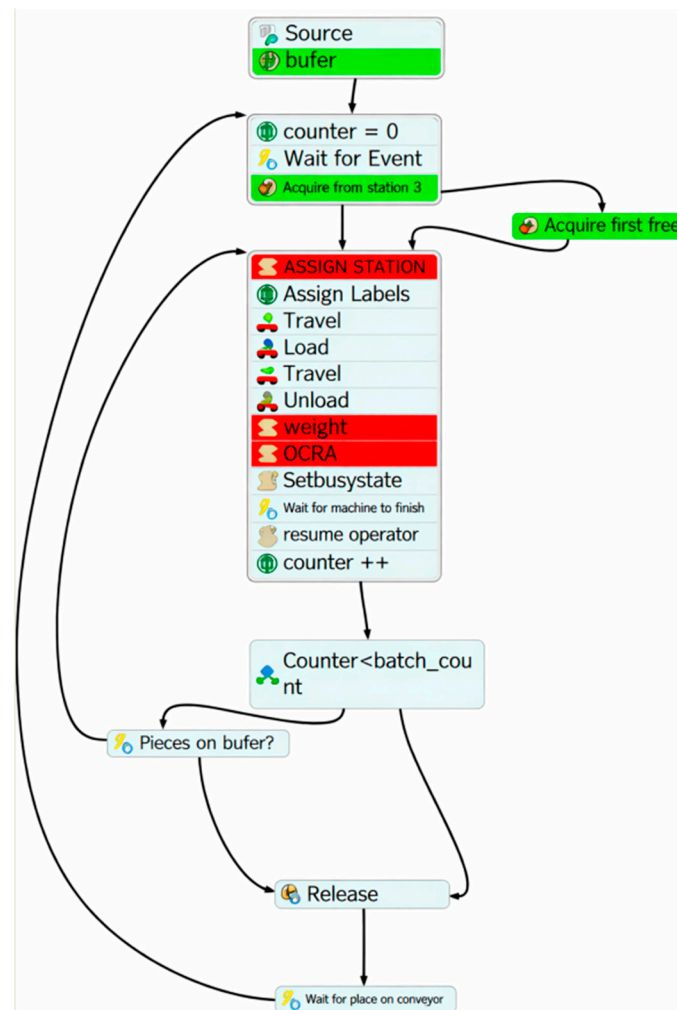


Figure 6. Control logic diagram of a manual workstation.

Assign Labels To	
token	
Labels	
Name	bufer
Value	B_ML103
Name	counter
Value	0.00
Name	batch_count
Value	5.00
Name	max_wait
Value	2.00

Figure 7. Definition of token attributes in ProcessFlow.

An important role in the control logic is played by the AcquireFromStation block, whose function is to ensure the correct assignment of an operator to a workstation. In real manufacturing, not every operator has the qualifications required to operate all workstations. For this reason, it is necessary to define which operator is allowed to perform a specific operation. This functionality is implemented through operator attributes defined in the Labels section, where it is possible to specify the workstations at which the operator

is authorized to work. An example of defining operator work competencies is shown in Figure 8.

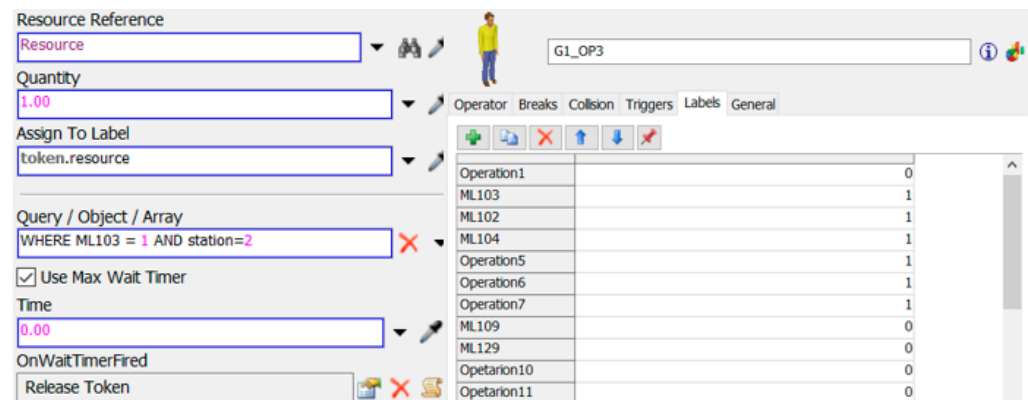


Figure 8. Definition of operator capabilities.

To ensure the representativeness of the simulation results, it was necessary to implement a mechanism for recording and resetting the monitored indicators, such as the number of produced units, handled weights, OCRA coefficients, or the distances traveled by operators. The logic for resetting these indicators is implemented in the ProcessFlow environment and is illustrated in Figure 9.

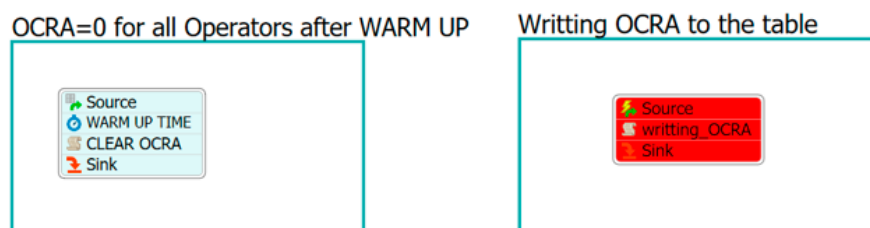


Figure 9. ProcessFlow blocks for resetting counters.

At the beginning of the simulation, a token is generated that triggers the timer of the so-called warm-up phase lasting one hour. After this period, the production line is filled with products and all monitored indicators are reset. Subsequently, the actual simulation of the work shift begins. To implement the resetting of ergonomic indicators, such as lifted weights or OCRA coefficient values, it was necessary to implement a custom function using FlexScript source code. An example of the implemented code is shown in Figure 10.

```

1 /**Custom Code*/
2 Object current = param(1);
3 treenode activity = param(2);
4 Token token = param(3);
5 treenode processFlow = ownerobject(activity);
6
7 Group op=Model.find("Tools/Groups/G1_OP 29");
8 Object operator;
9
10 for(int i=1;i<=op.length;i++){
11     operator=op[i];
12     operator.weight=0;
13 }

```

Figure 10. FlexScript source code for resetting lifted weight, OCRA values, and traveled distances.

The implemented code ensures the regular recording of operator workload values into the model's database table. This makes it possible to analyze the ergonomic workload of workers and at the same time obtain an overview of workload parameters that must be complied with from a legislative perspective. In a similar way, other control logic blocks of

the simulation were defined and adapted to the specific requirements of individual manual workstations [26,27].

4. Results Analysis and Process Optimization

After creating the simulation model of the production line and defining the logic of individual processes, it was possible to proceed with the execution of simulation experiments. This phase represents a key step of the analysis, as it enables the identification of weaknesses in the manufacturing system and subsequently the proposal of appropriate optimization measures. The Dashboard tool was used for the visualization and interpretation of simulation results, as it enables the graphical representation of selected operational indicators of the manufacturing process. The simulation of the original state of the line showed that the model sufficiently corresponds to the real system. During one simulated work shift, approximately 1900 units were produced, which corresponds to the actual production norm achieved in practice. For this reason, the model can be considered representative and suitable for further optimization analyses. In the original state, 28 operators worked on the production line, including a worker responsible for repairs, two line technicians, and one shift supervisor. During the entire work shift, operators were assigned to individual workstations without rotation. In the simulation, operational states of workstations were primarily monitored, such as Idle, Processing, Blocked, Breakdown, or Setup. In addition, indicators related to operator movement were analyzed, for example the distances traveled by operators, which are important from the perspective of legislative requirements for working conditions. An overview of the basic simulation results of the original system state is shown in Figure 11, where the percentage utilization of machines and operators, as well as the total distance traveled by individual workers during the shift, is presented.

A detailed analysis of the graph and the corresponding table indicates that the utilization of operators in the analyzed manufacturing system is significantly uneven. While some workers perform operations almost continuously and their utilization approaches near-maximum levels, other operators exhibit a relatively high proportion of time spent in the Idle state. This situation suggests that the distribution of work tasks among individual workstations is not optimal and that there is potential within the system for more efficient utilization of available human resources. The average operator utilization before the implementation of optimization measures reached approximately 76.6%, which means that nearly one quarter of the operators' working time is not used for productive activities. This fact indicates the existence of organizational reserves within the work process that can be eliminated through appropriate rearrangement of work operations or by introducing a more flexible system of task allocation. Uneven distribution of workload is typical especially for production lines with a high proportion of manual operations, where operators are permanently assigned to individual workstations and do not rotate between neighboring stations. In such cases, situations occur in which the operator must wait for the arrival of the next product or for the completion of an operation at the preceding workstation, thereby increasing the proportion of time spent in the Idle state. A more detailed assignment of operators to individual workstations and their percentage utilization is presented in Figure 12. Based on these data, it is possible to identify workstations with above-average or below-average operator workload, which provides an important basis for the design of subsequent optimization measures aimed at balancing workload and increasing the overall efficiency of the production line.

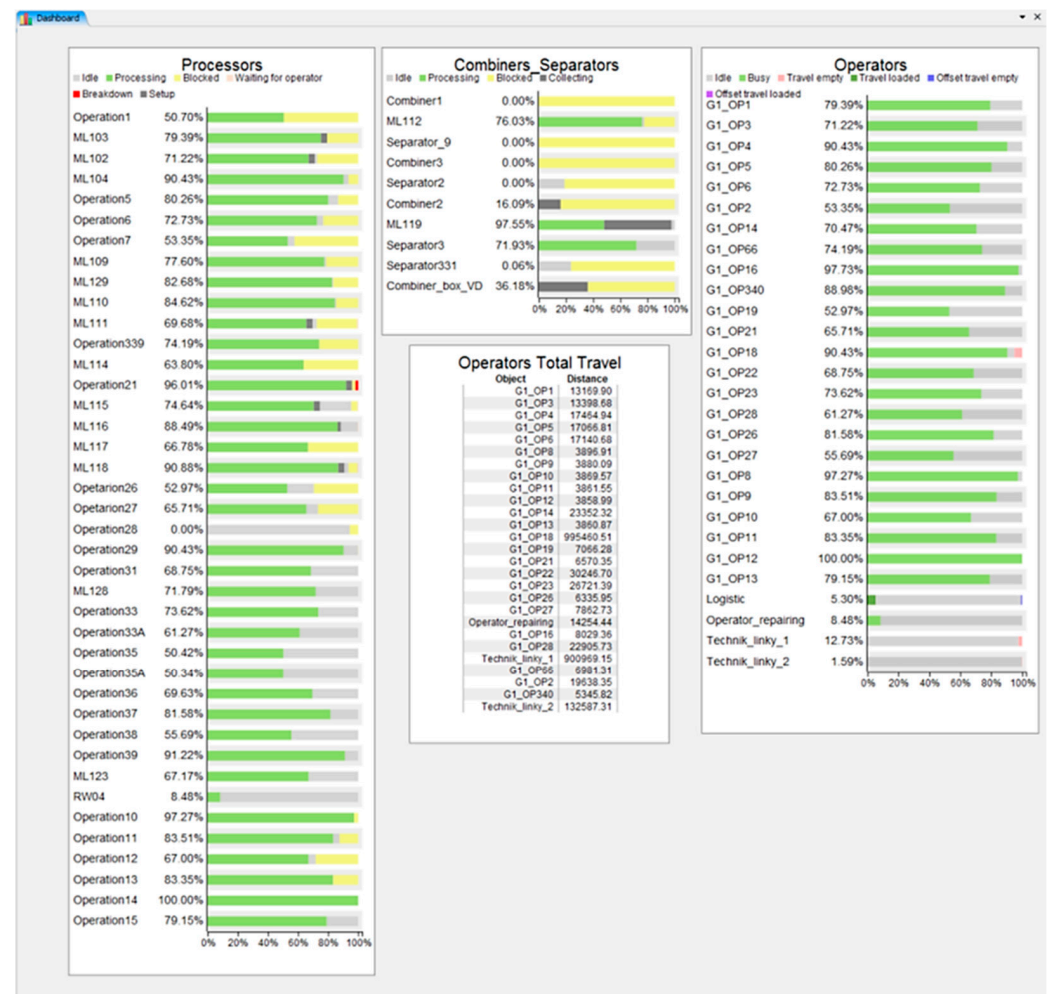


Figure 11. Bar chart of machine utilization, operator utilization, and traveled distances before the implementation of the proposed optimization.

The analysis of the data also made it possible to identify a potential bottleneck in the manufacturing process. In this case, it is the manual workstation Operation21, where operator G1_OP16 is assigned. If this workstation were blocked or the operator were unavailable, it could lead to a slowdown of the entire manufacturing process. Based on these findings, it was possible to proceed with the design of optimization measures primarily aimed at more efficient utilization of human resources. The objective of the optimization was to increase the percentage utilization of operators while maintaining the production capacity of the line. The proposed solution consisted of introducing the concept of intelligent operator rotation (smart rotation), in which one worker can operate multiple workstations. When designing the rotation, several criteria had to be considered:

- Distance between workstations;
- Ergonomic demands of operations;
- The nature of the performed work;
- Legislative requirements regarding maximum handled weight and workload.

Processors	Automat/Manual	Operators before optimalization	Busy in % before optimalization
Operation1	Manual	Logistics	
ML103	Manual	G1_OP1	79.39
ML102	Manual	G1_OP3	71.22
ML104	Manual	G1_OP4	90.43
Operation5	Manual	G1_OP5	80.26
Operation6	Manual	G1_OP6	72.73
Operation7	Manual	G1_OP2	53.35
ML109	Automat		
ML129	Automat		
ML110	Automat		
ML111	Manual	G1_OP14	70.47
ML112	Automat		
Opetarion339	Manual	G1_OP66	74.19
ML114	Automat		
Opetarion21	Manual	G1_OP16	97.73
ML115	Automat		
ML116	Manual	G1_OP340	88.98
ML117	Automat		
ML118	Automat		
Opetarion26	Manual	G1_OP19	52.97
Operation27	Manual	G1_OP21	65.71
Operation28	Manual	G1_OP18	90.43
Operation29	Manual	G1_OP18	
ML119	Automat		
Operation31	Manual	G1_OP22	68.75
ML128	Automat		
Operation33	Manual	G1_OP23	73.62
Operation33A	Manual	G1_OP28	61.27
Operation35	Automat		
Operation35A	Automat		
Operation36	Automat		
Operation37	Manual	G1_OP26	81.58
Operation38	Manual	G1_OP27	55.69
Operation39	Automat		
ML123	Automat		
Opetarion10	Manual	G1_OP8	97.27
Opetarion11	Manual	G1_OP9	83.51
Opetarion12	Manual	G1_OP10	67
Opetarion13	Manual	G1_OP11	83.35
Opetarion14	Manual	G1_OP12	100
Opetarion15	Manual	G1_OP13	79.15
RW04_1,3,4	Manual	Operator_repairing	8.48
Line Technic	Manual	Technik_linky_1	7.39
Line Technic	Manual	Technik_linky_2	6.7
		Supervisor	
		Σ operators	28
		Average busy %	76.62708333

Figure 12. Percentage utilization of operators and their assignment to individual stations.

Based on the analysis of workstations, operators were divided into 3 independent groups according to the spatial proximity of stations and the similarity of performed operations. Such a classification makes it possible to assess the potential for implementing operator rotation between neighboring workstations. The first group includes workstations that are the closest in terms of technological sequence and physical distance and therefore represent a suitable basis for the design of workload optimization. From the point of view of numerical quantification of the current state, it can be stated that in the first created group, the average utilization of the operator of this group is at the level of 74.5% and the numerically total percentage of inactivity of the operators of this group is 152.4%, which clearly indicates the need for optimization and room for potential elimination of the operator. However, it is necessary to ensure that the elimination does not affect the output and the nature of the bottleneck of the line. The utilization of operators in this group is shown in Figure 13.

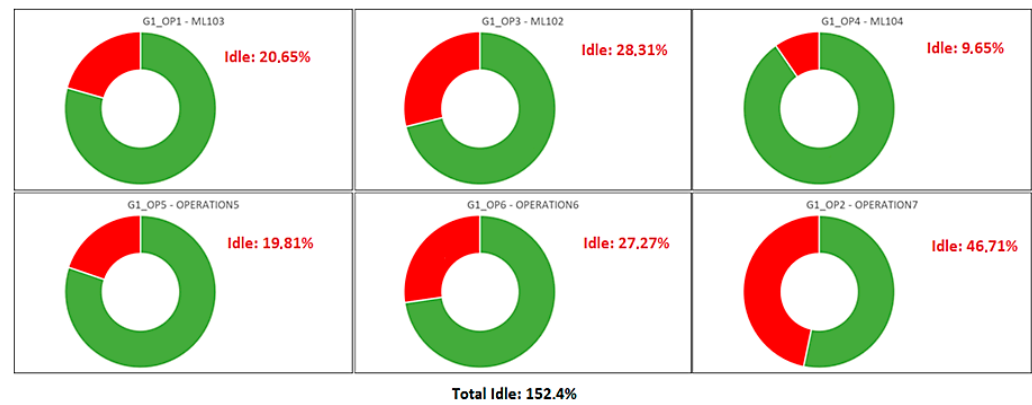


Figure 13. Group 1—operator utilization at neighboring workstations.

From the results of the first group, differences in the level of utilization among individual operators can be observed. Some workers achieve a high percentage of working activity, while others show a more significant proportion of idle time. This situation indicates that there is potential for a more efficient distribution of work tasks among operators within the group. An analogous analysis was also carried out for the second group of workstations, the results of which are presented in Figure 14. As with the first group, from the point of view of numerical quantification of the current state, it can be stated that in the created second group, the average operator utilization of this group is at the level of 68.75% and the numerically total percentage of inactivity of operators of this group is up to 244.6%, which, in comparison with the first group, even more clearly indicates the need for optimization and the space for potential operator elimination. However, it is also necessary to ensure that excessive elimination does not affect the output and bottleneck.



Figure 14. Group 2—operator utilization at neighboring workstations.

Similarly to the previous group, differences in operator utilization can also be identified in this part of the production line. Some workstations exhibit a relatively high level of working activity, while others show a higher proportion of time spent in the idle state. These differences confirm the need to optimize work organization and balance the workload among individual operators. The utilization of operators in the third group of workstations is shown in Figure 15.

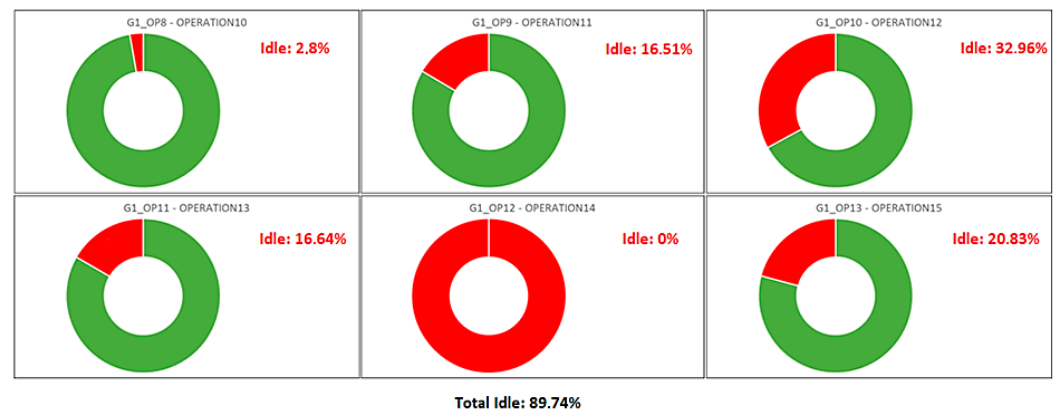


Figure 15. Group 3—operator utilization at neighboring workstations.

The analysis of the third group of workstations confirms a similar trend as in the previous cases. In this part of the production line as well, differences in the level of utilization among individual operators can be observed. Some workers achieve a high percentage of working activity, while others show a significant proportion of time spent in the idle state.

In this case, the numerical quantification says that in the created third group, the average utilization of the operator of this group is 85.01% and the numerically total percentage of inactivity of the operators of this group is 89.7%. When evaluating the initial state, this group is the best because the average utilization of targeted 85% is a relatively good indicator, but considering that these stations are suitable located in relation to the slowest element of the line—the bottleneck, it is also appropriate to consider an optimization proposal in this case. Analogously to the previous groups, it is necessary to ensure that the output and bottleneck are not affected by excessive elimination and that the slowest process of the line is not blocked due to elimination.

Based on the analysis of individual operator groups, it can be concluded that the workload on the production line is not distributed evenly. Significant differences appear among operators within the individual groups, where some workers reach a high percentage of active working time, while others exhibit a substantial proportion of idle time. Such a situation indicates that there is potential for more efficient work organization and better utilization of available human resources. In the analyzed manufacturing system, operators are, in the basic configuration, permanently assigned to individual workstations. Although this method of work organization ensures the stability of the production process, it simultaneously leads to situations where an operator must wait for the arrival of the next product or for the completion of an operation at the preceding workstation. In such cases, the operator remains in an idle state, which reduces the overall efficiency of workforce utilization. With a larger number of manual workstations, this phenomenon becomes more pronounced, as individual operations have different cycle times and technological dependencies. The simulation results also indicate that uneven operator workload may negatively affect not only production efficiency but also the ergonomic aspects of the working process. Operators with a high level of utilization are exposed to greater physical workload, which may lead to an increased risk of work fatigue or health-related problems. Conversely, operators with a high proportion of idle time represent unused capacity within the manufacturing system. For this reason, it is appropriate to analyze the possibilities of reorganizing work tasks among operators. One possible approach is the introduction of an operator rotation system between neighboring workstations, which allows for a more flexible redistribution of work activities. Such an approach may lead to a more balanced workload among workers and a reduction in the proportion of idle time in the system. However, when designing the

optimization solution, several factors must be considered. The most important include the distance between workstations, the technological sequence of individual operations, the ergonomic demands of work tasks, and legislative requirements for working conditions. In addition, it is necessary to ensure that the proposed reorganization of the work process does not negatively affect the production capacity of the line or the stability of the manufacturing process. Based on these considerations, in the next phase of the simulation an optimization of the manufacturing system was proposed through the implementation of the intelligent operator rotation concept. The objective of this approach is to increase the efficiency of workforce utilization, reduce the proportion of operator idle time, and at the same time maintain the required production capacity of the line. Therefore, within the simulation model, new work organization scenarios were created in which operators operate multiple neighboring workstations according to predefined rotation rules.

The biggest difference compared to the original model lies in the rotation of operators. This is based on the operator competence matrix, which defines how operators are assigned and rotated across individual workplaces. The following graphs, tables, and results presented in this paper reflect this rotation and the newly implemented operator routines.

The simulation results after implementing the proposed optimization solution are presented in Figure 16, where changes in the percentage utilization of machines and operators, as well as the distances traveled by workers within the production line, can be observed.

A comparison of the results before and after the optimization shows that the introduction of the operator rotation system led to a more balanced distribution of workload among individual workers. Operators who, in the original state, exhibited a high proportion of idle time were involved in operating multiple workstations, thereby increasing their overall workload utilization. Conversely, workstations with a high level of workload were partially relieved by redistributing tasks among multiple operators. Such a distribution of work enabled more efficient utilization of the available workforce without negatively affecting the stability of the manufacturing process.

The suitability of this operating model is already indicated by macro performance indicators and thus the preserved production potential, the increased overall efficiency of manual operators from 76.6% to 86.3% after optimization, which represents an absolute 9.7% significant positive increase, and it is also important to mention that the optimization eliminated 4 operators from one shift, which means savings, efficiency and equal production. The simulation results also indicate that the proposed optimization did not have a negative impact on the production capacity of the line or on the continuity of the manufacturing process. The manufacturing system maintained the required level of production while improving the utilization of human resources. This finding confirms that more flexible assignment of operators to workstations can represent an effective tool for increasing labor productivity in assembly systems. In addition to changes in operator utilization, the optimization scenario also affected other monitored parameters of the manufacturing system. Among the important factors is the movement of operators within the production line and the total distance traveled by workers during a work shift. This parameter is particularly important from an ergonomic perspective, as excessive movement between workstations may lead to increased physical workload for operators. A more detailed analysis of operator movement within the manufacturing system is presented in Figure 16, where the values of distances traveled by individual workers during the simulated work shift are shown. These results make it possible to evaluate the impact of the proposed operator rotation on the organization of the work process and to assess whether the optimization measure introduces increased physical workload for workers. Figure 17 shows a comparison of the state before and after optimization, from which the

elimination of 4 operators is evident and from which the increase in work efficiency for the vast majority of operators is evident.

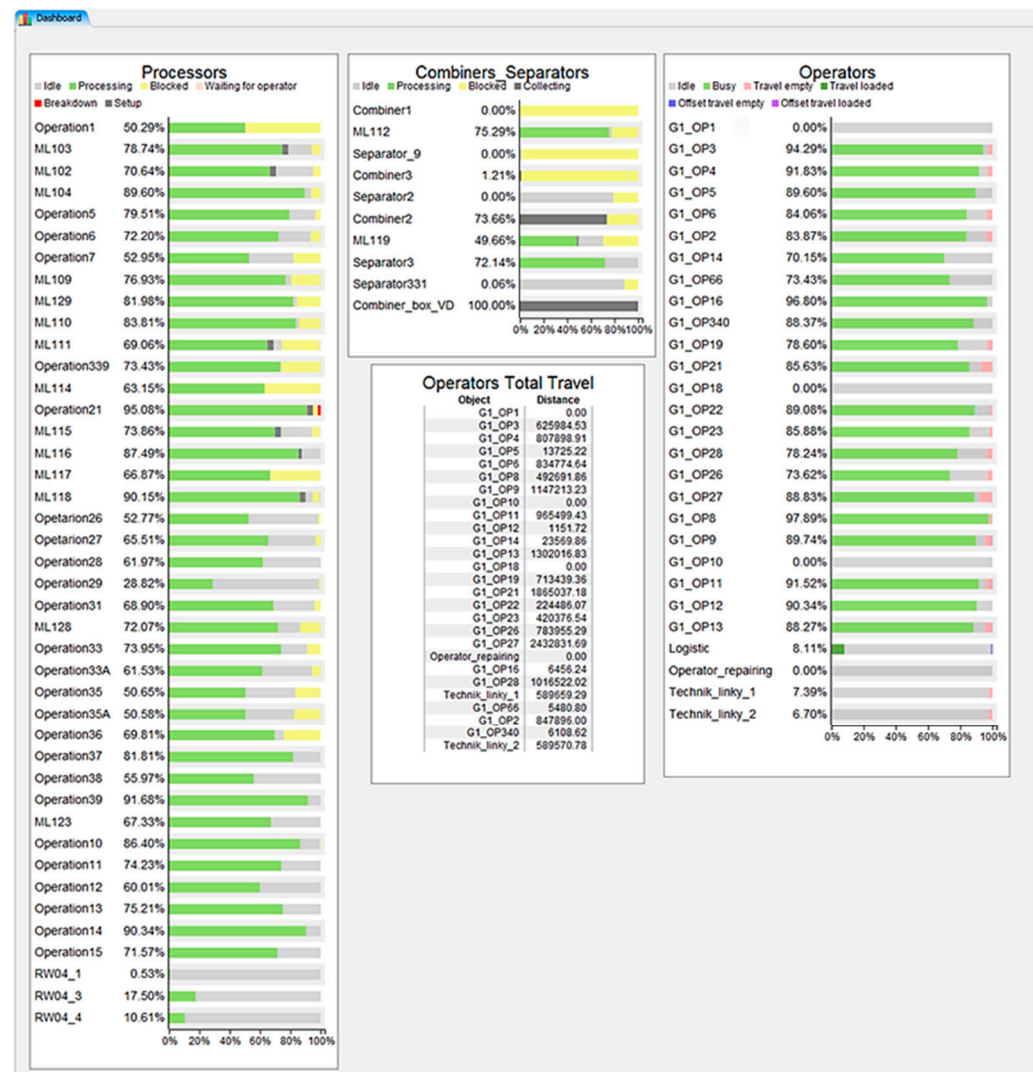


Figure 16. Results of the simulation experiment after the implementation of the intelligent operator rotation model.

Based on the analysis of operator movement, it can be concluded that the optimization scenario based on worker rotation leads to a slight increase in operator mobility, while at the same time enabling more efficient utilization of working time and reducing the proportion of idle time. Operator movements are carried out mainly between workstations located in close proximity, which minimizes time losses caused by transfers between individual workstations. Another monitored indicator is the utilization of individual elements of the manufacturing system. This parameter makes it possible to identify workstations with a high level of workload as well as stations that exhibit a lower level of utilization. The results for the first group of workstations are shown in Figure 18, where a comparison of the states of operators before and after optimization is presented.

Processors	Automat/Manual	Operators before optimization	Busy in % before optimization	Operators after optimization	Busy in % after optimization	In/decrease of % busy
Operation1	Manual	Logistics		Logistics		
ML103	Manual	G1_OP1	79.39			
ML102	Manual	G1_OP3	71.22	G1_OP3	96.81	25.59
ML104	Manual	G1_OP4	90.43	G1_OP4	91.5	1.07
Operation5	Manual	G1_OP5	80.26	G1_OP5	89.53	9.27
Operation6	Manual	G1_OP6	72.73	G1_OP6	82.76	10.03
Operation7	Manual	G1_OP2	53.35	G1_OP2	82.71	29.36
ML109	Automat					
ML129	Automat					
ML110	Automat					
ML111	Manual	G1_OP14	70.47	G1_OP14	70.35	-0.12
ML112	Automat					
Operation339	Manual	G1_OP66	74.19	G1_OP66	73.73	-0.46
ML114	Automat					
Operation21	Manual	G1_OP16	97.73	G1_OP16	97.17	-0.56
ML115	Automat					
ML116	Manual	G1_OP340	88.98	G1_OP340	88.74	-0.24
ML117	Automat					
ML118	Automat					
Operation26	Manual	G1_OP19	52.97	G1_OP19	79.23	26.26
Operation27	Manual	G1_OP21	65.71	G1_OP21	84.43	18.72
Operation28	Manual	G1_OP18	90.43			
Operation29	Manual	G1_OP18				
ML119	Automat					
Operation31	Manual	G1_OP22	68.75	G1_OP22	88.17	19.42
ML128	Automat					
Operation33	Manual	G1_OP23	73.62	G1_OP23	85.96	12.34
Operation33A	Manual	G1_OP28	61.27	G1_OP28	78.7	17.43
Operation35	Automat					
Operation35A	Automat					
Operation36	Manual	G1_OP26	81.58	G1_OP26	77.42	-4.16
Operation37	Manual	G1_OP27	55.69	G1_OP27	87.47	31.78
Operation38	Automat					
ML123	Automat					
Operation10	Manual	G1_OP8	97.27	G1_OP8	97.89	0.62
Operation11	Manual	G1_OP9	83.51	G1_OP9	89.74	6.23
Operation12	Manual	G1_OP10	67			
Operation13	Manual	G1_OP11	83.35	G1_OP11	91.53	8.18
Operation14	Manual	G1_OP12	100	G1_OP12	90.34	-9.66
Operation15	Manual	G1_OP13	79.15	G1_OP13	88.27	9.12
RWD4_1,3,4	Manual	Operator_repairing	8.48			
LineTechnic	Manual	Technik_linky_1	7.39	Technik_linky_1	7.39	
LineTechnic	Manual	Technik_linky_2	6.7	Technik_linky_2	6.7	
		Zmenový majster		Zmenový majster		
Σ operators			28	24		
Average busy %			76.62708333	86.30714286		
					9.680059524	Total increase of busy % on line

Figure 17. Numerical comparison of percentage utilization before and after the implementation of the optimization.

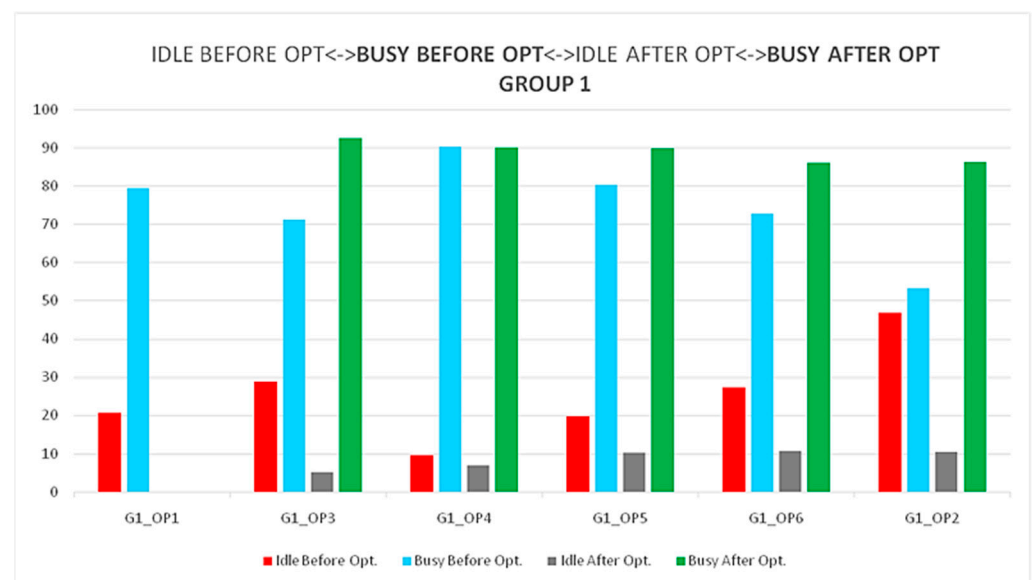


Figure 18. Comparison of operator utilization according to defined groups—Group 1.

From the graph, it can be observed that after the introduction of operator rotation, there was a significant increase in the percentage of working activity for several workers. The numerical expression is that from the original group 1 average operator utilization of 74.5% with a percentage sum of Idle status of 152.4% for the entire group; after optimization with the simultaneous elimination of one operator, the resulting average operator utilization is 88.6% and the sum of Idle status is at the level of 56.69%. Globally, this is an increase in

average utilization by absolute 14.1% while maintaining production, which is a significant improvement. From the graph it is possible to identify that the operator G1_OP1 was eliminated by optimization since it no longer has visualized performance indicators after optimization. The graph also shows the positive impact of optimization on the utilization of operators and thus the increase in the green column at the expense of the blue one and also the decrease in the idle state where the initial higher red column alternates with decreased gray columns. From a visual point of view, such an interpretation is also possible in further evaluations. Operators who, in the original state, exhibited a higher proportion of idle time were involved in operating multiple workstations, thereby increasing their overall utilization. At the same time, the proportion of time during which operators waited for the arrival of a product or for the completion of an operation at the preceding workstation was reduced. This effect is particularly noticeable at workstations where a significant difference between Busy and Idle states was observed in the original configuration. An analogous analysis was also carried out for the second group of workstations, the results of which are presented in Figure 19.

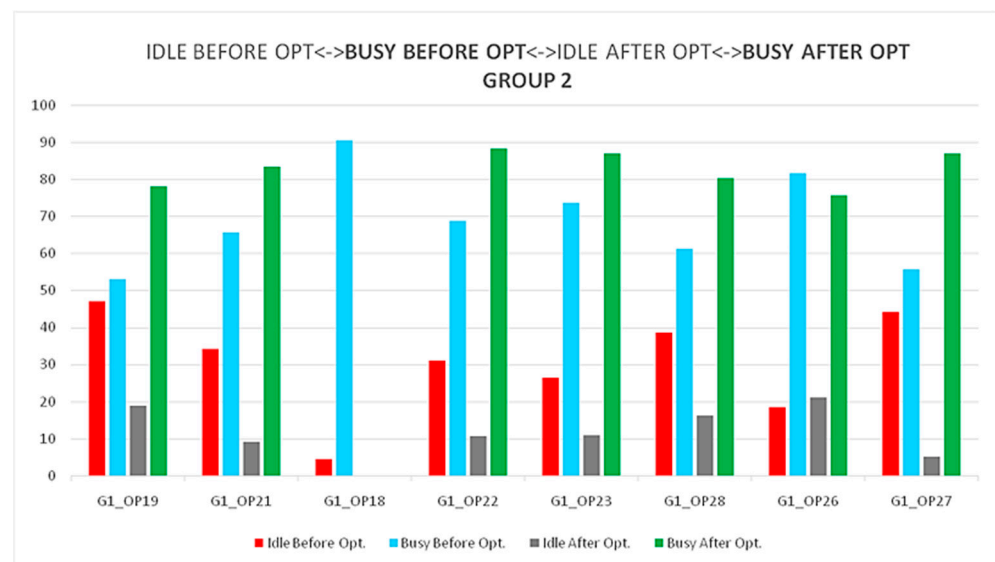


Figure 19. Comparison of operator utilization according to defined groups—Group 2.

In the second group of workstations, a similar trend can be observed as in the previous group. The implementation of operator rotation led to a balancing of workload among individual workers and at the same time to a reduction in the proportion of idle time. Operators who in the original state exhibited a lower percentage of working activity were involved in a broader range of work operations, which increased the efficiency of workforce utilization in this part of the production line.

The numerical expression is that from the original average operator utilization of 68.75% with a percentage sum of Idle status of 244.6% for the entire group 2; after optimization with the simultaneous elimination of one operator, the resulting average operator utilization is 83.05% and the sum of Idle status is at the level of 118.62%. Globally, this is an increase in average utilization by absolute 14.30% while maintaining production, which is also a significant improvement. In this case, the sum of Idle status remained at a relatively high level after optimization, but when trying to possibly eliminate another operator or propose a different rotation, greater distances were encountered, typologically different jobs at the workplace, or affecting the bottleneck or output of the entire line, and therefore the total value of Idle status was left in this case at 118.62%. At the same time, a stabilization of the percentage values of working activity among individual operators can be observed, indicating a more balanced distribution of work tasks. The results of the third group of

workstations are shown in Figure 20, which presents a comparison of operator workload in the last analyzed group.

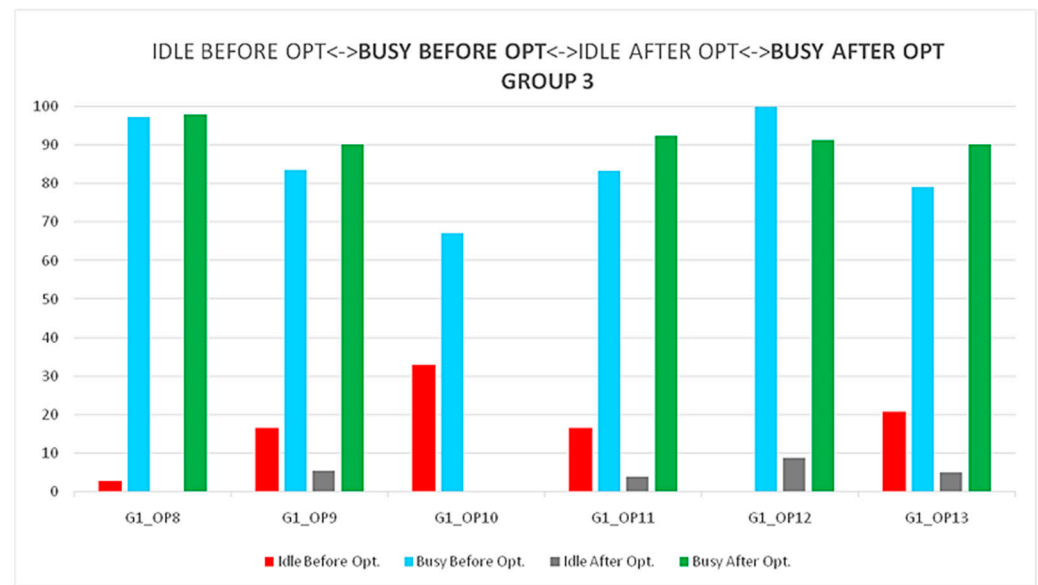


Figure 20. Comparison of operator utilization according to defined groups—Group 3.

In this case as well, a positive impact of the proposed optimization scenario can be observed. The implementation of intelligent operator rotation contributed to a reduction in the proportion of idle time and to an increase in the working activity of operators within the group. The balancing of workload among individual workers also contributes to more stable operation of the manufacturing process and more efficient utilization of human resources. Analogously to the previous groups, the numerical expression is that from the original average operator utilization of 85% with a percentage sum of Idle status of 89.7% for the entire group 3; after optimization with the simultaneous elimination of one operator, the resulting average operator utilization is 91.5% and the sum of Idle status is at the level of 42.2%. Globally, this is an increase in average utilization by absolute 6.50% while maintaining production, which is also a favorable improvement with regard to the total production.

A comparison of the results of all three groups indicates that the implementation of operator rotation represents an effective tool for optimizing work organization on the production line. The proposed solution makes it possible to reduce the proportion of operator idle time, increase the percentage of their working activity, and at the same time maintain the required production capacity of the manufacturing system.

It is also necessary to add that in the previous text the elimination of 3 operators was explained, but in total 4 operators were eliminated. The fourth was an operator from the repair department, and line technicians were proposed for this department, who are necessary to ensure the smooth operation of the line, but usually do not have a high percentage of process utilization. All the mentioned key summarized parameters and results for their quick comparison can be seen in Figure 21 below, which clearly shows the most important outputs and numerical benefits of the introduced concept.

		Before (%)	After (%)	Δ absolute (pp)	Δ relative (%)
Operators utilization (Avg.)			Target after approx. 85%		
	Group 1	74.5	88.6	14.1	18.9
	Group 2	68.75	83.05	14.3	20.8
	Group 3	85	91.5	6.5	7.6
Overall line utilization		76.6	86.3	9.7	12.7
Operators Idle state (Avg. Sum)		Before (%)	After (%)	Δ absolute (pp)	Δ relative (%)
	Group 1	152.4	56.69	−95.71	−62.8
	Group 2	244.6	118.62	−125.98	−51.5
	Group 3	89.7	42.2	−47.5	−53.0
		Before(pcs)	After (pcs)	Δ absolute (pcsp)	Δ relative (%)
Overall number of operators		28	24	−4	−14.3
Defined production standard		1900	1900	N/A	N/A

Figure 21. Summary and quantification of key characteristics.

The optimization of the manufacturing process through intelligent operator rotation primarily resulted in the balancing of workload among individual workers. The proposed solution allows operators to perform work operations at multiple workstations within defined workstation groups. Such an approach reduces the risk of operator idle time and at the same time enables a more flexible response to changes in the workload of individual parts of the production line. The principle of the proposed operator rotation is illustrated in the workstation rotation matrix, which defines the assignment of individual operators to workstations during the production cycle. The matrix also represents a systematic method of work organization in which operators are gradually moved between neighboring workstations within defined groups. The first part of the rotation matrix is presented in Figure 22.

Rotation on the line	G1_OP3	G1_OP4	G1_OP5	G1_OP6	G1_OP2	G1_OP14	G1_OP66	G1_OP16	G1_OP340	G1_OP19	G1_OP21
ML103											
ML102											
ML104											
Operation5											
Operation6											
Operation7											
ML111											
Opetarion339											
Opetarion21											
ML116											
Opetarion26											
Operation27											
Operation28											
Operation29											
Operation31											
Operation33											
Operation33A											
Operation37											
Operation38											
Opetarion10											
Opetarion11											
Opetarion12											
Opetarion13											
Opetarion14											
Opetarion15											
RW04_1											
RW04_3											
RW04_4											
	G1_OP3	G1_OP4	G1_OP5	G1_OP6	G1_OP2	G1_OP14	G1_OP66	G1_OP16	G1_OP340	G1_OP19	G1_OP21

Figure 22. Operator rotation matrix within the production line—Part 1.

The rotation matrix illustrates the relationships between individual operators and the workstations of the production line. The green fields in the matrix represent the workstations at which the operator performs the corresponding operation, while the red fields indicate the workstations that the operator does not operate within the rotation scheme. Such a graphical representation makes it possible to clearly identify the scope of work competencies of individual operators and at the same time provides information about the flexibility of the workforce within the manufacturing system. The second part of the rotation matrix is presented in Figure 23, which complements the overall overview of operator assignments to workstations across the entire production line.

G1_OP22	G1_OP23	G1_OP28	G1_OP26	G1_OP27	G1_OP8	G1_OP9	G1_OP11	G1_OP12	G1_OP13	
										ML103
										ML102
										ML104
										Operation5
										Operation6
										Operation7
										ML111
										Opetarion339
										Opetarion21
										ML116
										Opetarion26
										Operation27
										Operation28
										Operation29
										Operation31
										Operation33
										Operation33A
										Operation37
										Operation38
										Opetarion10
										Opetarion11
										Opetarion12
										Opetarion13
										Opetarion14
										Opetarion15
										RW04_1
										RW04_3
										RW04_4
G1_OP22	G1_OP23	G1_OP28	G1_OP26	G1_OP27	G1_OP8	G1_OP9	G1_OP11	G1_OP12	G1_OP13	

Figure 23. Operator rotation matrix within the production line—Part 2.

The analysis of the rotation matrix shows that individual operators are capable of operating multiple workstations located in their immediate vicinity or characterized by a similar type of work operation. Such a designed work organization makes it possible to increase the flexibility of the manufacturing system while ensuring the continuity of the production process even in the case of short-term fluctuations in the workload of individual workstations. The implementation of the rotation system also contributes to more efficient utilization of the workforce and to the reduction in the total number of operators required to ensure the desired production capacity. The simulation results confirmed that, while maintaining the required production rate, it is possible to reduce the number of operators on the production line and simultaneously increase their average utilization rate, which represents a significant benefit from both an economic and organizational perspective.

In this part, it is still necessary to clarify how the simulation logic and rules will be transferred to the real line. From the defined matrix, it is clear which operator works at which workplace and, in the case of belonging to a group, from the matrix, it is clear within which workplaces he rotates. However, it remains to clarify how the simulation logic of operator control will be transferred to real operation or simply how the operator will know when and to which station he should go if he is serving several of them. Looking at Figure 6, the logic of the call and rotation rules is fundamentally clear, which first calls the operator who is at station X to station X. If there is no operator present at this station, the rule is that station X then calls the first free operator who is competent to work at the given workplace.

The transfer of this logic to real practice was designed and requires the implementation of visualization tools, sensors and a PLC into which the logic of rules and rotation will be inserted and then the PLC will visualize to the operator via the visualization tool which station he is called to.

This specific application scenario of optimization and its model were repeatedly verified by simulation and based on almost identical outputs the optimization was proposed for physical implementation. In the case of this particular line and its subsequent optimization, the reliability of the model results presented in the work was confirmed by experimental repeated simulations and their repeatability of achieving the outputs was confirmed with respect to simplifying assumptions. A detailed and repeated in-depth analysis of the obtained and presented results and such repeated experimental simulation approach excluded randomness of the results and confirmed the practical sufficiency of covering the claims of the simulation conclusions and the proposed optimization for real application and the adoption of the optimization concept for a real existing process in a manufacturing enterprise. From the historical simulation data obtained from the history of the simulation software, it is evident that the optimized process was repeated and subjected to a monthly operation simulation, which means 60 repeated and consecutive simulated shifts with a minimum of manufactured products at the level of 1897 and a maximum at the level of 1905, which in the negative scenario and therefore in the case of fewer products being manufactured represents a deviation of 0.15% from the reference value, which is an acceptable deviation for practice and from the point of view of verification of optimization for practice. As already mentioned, in this case they ensured that the statement about the reliability of the proposed method was made without the need to perform an in-depth complex mathematical-statistical analysis and the correctness was repeatedly experimentally confirmed.

5. Conclusions

The conducted analysis of the manufacturing process and the subsequent development of the simulation model made it possible to comprehensively evaluate the operation of the assembly line from the perspective of the utilization of production resources, particularly human labor. The research found that the simulation model represented an effective tool for the experimental verification of various work organization scenarios without the need to intervene in the real manufacturing process. The basic finding of this research was therefore the finding that modeling and simulation is one of the most suitable tools and approaches for the purposes of process analysis and the design of optimization measures. The experimental approach based on experimental simulation verification of the proposed optimization scenarios has proven to be a suitable way of cost-free verification of the correctness of the system functioning in a different-changed mode of operation according to the proposed optimization. By tuning the operating conditions and their experimental verification, it is possible to reach the optimal scenario from the point of view of the total and particular utilization rate and to the optimal personnel occupation of the line with regard to the quality and required line output. In this case, the free optimization method of the smart rotation type has proven to be suitable and thanks to its design and simulation verification, the optimal scenario from the point of view of all key line factors has been found. The approach mentioned makes it possible to identify inefficient areas of the manufacturing system, analyze the behavior of individual workstations, and design optimization measures before their implementation in practice.

The results of the simulation of the original state of the production line revealed uneven utilization of operators across individual workstations. The analysis of the percentage utilization of workers showed that some operators performed operations almost continuously

with utilization over 95%, while others exhibited a relatively high proportion of idle time and utilization around 50%. The average operator utilization before the implementation of optimization measures reached approximately 76.6%, indicating the existence of reserves in work organization and in the distribution of work tasks among individual workers. At the same time, it was possible to identify workstations with a higher level of workload that represented potential bottlenecks of the manufacturing system and could negatively affect the continuity of the production process. A bottleneck has been defined and confirmed by simulation, which in this case is Operation21, to which Operator 16 is assigned. Based on the obtained results, an optimization scenario based on the principle of intelligent operator rotation between workstations was proposed. The essence of this approach was the creation of workstation groups with a similar nature of performed operations and enabling operators to operate multiple workstations within a defined group. Therefore, 3 groups were created in which the utilization rate in these individual groups was examined, which before optimization was at the level of 74.5%, 68.75% and 85%. Such an organization of work enables a more flexible redistribution of workload among workers while reducing the time during which operators wait to perform the next operation. Simulation experiments confirmed that the implementation of the rotation system leads to a balancing of workload among operators and an increase in their average utilization rate. The implementation of smart rotation increased the average utilization rate of operators in individual groups to 88.6%, 83.05%, and 91.5%, which are significant increases. This simultaneously resulted in an increase in the overall utilization of line operators as a whole from the original 76.6% to the post-optimization 86.3%, which represents a significant increase of almost 10% on average in absolute. By introducing rotation between neighboring workstations, it was possible to reduce the proportion of operator idle time and at the same time increase the flexibility of the manufacturing system. The simulation results also confirmed that even with a reduced number of operators, it is possible to maintain the required production capacity of the line. In the analyzed case, the number of operators could be reduced without negatively affecting the performance of the manufacturing system, which represents a significant economic benefit. Specifically, 4 operators were eliminated, one operator in each created group, as well as an operator dedicated to repairs. His tasks were taken over by line technicians. The introduced eliminations and optimizations did not have a negative impact on the production capacity of the line—approximately 1900 pcs/shift. When designing the optimization solution, it was also necessary to consider practical aspects of implementation in real production. An important factor is particularly the distance between individual workstations, ergonomic requirements of the working environment, and legislative restrictions related to the physical workload of workers. All these aspects were simulated and followed according to the law. They can be seen in Figures 11 and 16. The qualification of operators also plays a significant role, as operating multiple workstations requires a broader range of work skills and an adequate level of worker training. Last but not least, it is necessary to mention that not all operators were included in the optimization, but only those who are physically close to each other during work due to rotation and have similar work characteristics. Other operators were left without optimization, but in the vast majority they had acceptable utilization even before optimization, and after optimization, either their condition improved or the value culminated at the level before optimization.

The scientific contribution of the presented work lies primarily in the application of simulation modeling for the analysis and optimization of work organization in the manufacturing process as an important decision support tool for verifying proposed changes. The developed model made it possible to identify bottlenecks in the manufacturing system and experimentally verify the effectiveness of the proposed optimization measures. The proposed methodology approach and intelligent operator rotation approach represents a

methodological procedure that can also be applied to other types of manufacturing systems with a similar organizational structure. In the broader context of digital engineering, this approach can be considered part of modern manufacturing management concepts that emphasize the use of simulation models and digital twins of manufacturing processes.

Despite the achieved results, certain limitations of the research are permissible. The simulation model was developed on the basis of available technological data from a specific production line, which means that the obtained results are to some extent connected with the specific characteristics of the analyzed production system and they are limitedly transferable to other use cases. This mentioned fact is also perceived by the authors as the most limiting and in a way defining the boundaries of the research. The research and the corresponding optimization were designed for the specifics of a specific process and therefore it is necessary to state that the introduced concept can be a kind of inspiration for processes of similar nature, but it is necessary to keep in mind that when trying to apply a similar optimization model, it is first necessary to perform an in-depth analysis of the process, to determine its characteristics and common features, and only on the basis of the assessed similarity can it be possible to apply a similar form of optimization, but adapted to the specific process. In this research, the simulation and optimization design presented is suitable and optimal, but it is therefore necessary to state that despite the assessment of similarity with the current discovery of common features with the researched line, it may be that the applied optimization when applied to another studied process may not give the same optimal results and a unique and specific analysis of the newly researched process is necessary, into which a methodological model and optimization approach similar to this one but robustly adaptable to the specific process can then be applied. In summary, it is stated that the Smart rotation optimization for another similar process is possible, but after a detailed analysis. The model also worked with deterministic or statistically approximated values of technological times, while in real conditions these times may be influenced by other factors such as operator performance variability, equipment failures or organizational downtimes. Other limitations of the research from another perspective are perceived in the form of simplifying assumptions of the simulation and subsequent optimization, which were listed in detail in the Section 2. In conclusion, the authors mention those with the largest and most fundamental impact, such as unlimited supply of material, absence of unexpected errors, quality of input material, and many others.

From the perspective of future research, it is possible to recommend extending the simulation model with dynamic factors influencing the functioning of the manufacturing system, such as unexpected equipment failures, variability of production times, or disruptions in the logistics and supply chain. A promising direction is also the integration of simulation models with the concept of a digital twin of the manufacturing system, which would enable continuous monitoring and optimization of manufacturing processes in real time. One of the other possible aspects that future research could look at or investigate are areas such as randomly occurring aspects such as the impact of random errors, random outages from a logistics perspective, the quality of input material, or also an experimental proposal to reduce the production standard and also reduce the number of operators and subsequently increase to 4-shift operation with an analysis of efficiency and economic feasibility, verification of the introduction of a higher level of automation and its impact on the system and the design of another optimization scheme, or also possible cooperation with systems in the context of I4.0 or I5.0. An interesting direction of research could also be the introduction of virtual reality in the study of this process and the investigation of the impacts or functioning of the system after optimization in the form of virtual reality. FlexSim simulation offers a very realistic and illustrative simulation and its course, but

with virtual reality the authors can imagine an even better understanding of processes, possible risks by gaining an even better overview of the process.

In conclusion, the use of simulation tools in the analysis and optimization of manufacturing processes represents a significant benefit for modern manufacturing enterprises and is a reliable decision-making and support tool. The implementation of the proposed rotation system and the described methodology can contribute to increased labor productivity, more efficient utilization of human resources, and a reduction in operational costs while maintaining the required production capacity of the manufacturing system.

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Abbreviations

The following abbreviations are used in this manuscript:

DES	Discrete Event Simulation
CAD	Computer-Aided Design
OCRA	Occupational Repetitive Actions Index
WIP	Work in Progress

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