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Assembly line balancing in a digital environment

Andrej Polka [1*], Martin Krajčovič [2], Martin Buzalka [3]

1 *Andrej Polka, Ing., University of Žilina, Faculty of Mechanical Engineering, Department of Industrial Engineering, Univerzitná 8215/1, 010 26 Žilina, Slovakia, andrej.polka@fstroj.uniza.sk*
2 *Martin Krajčovič., prof., PhD., Ing., University of Žilina, Faculty of Mechanical Engineering, Department of Industrial Engineering, Univerzitná 8215/1, 010 26 Žilina, Slovakia, martin.krajcovic@fstroj.uniza.sk*
3 *Martin Buzalka, Ing., University of Žilina, Faculty of Mechanical Engineering, Department of Industrial Engineering, Univerzitná 8215/1, 010 26 Žilina, Slovakia, martin.buzalka@fstroj.uniza.sk*
* *Andrej Polka, Ing., andrej.polka@fstroj.uniza.sk*

Abstract: There are various methods for assembly line balancing, but currently, advanced digital tools and software solutions are increasingly being applied, allowing for the transfer, examination, analysis, and optimization of enterprise systems in a digital form. This article focuses on assembly line balancing in a digital environment using advanced tools. It describes the tools and processes used in line balancing, including their application in digital systems. The presented results highlight the effectiveness of advanced digital tools in addressing this issue, with their efficiency verified through real-world project implementations.

Keywords: assembly; assembly processes; assembly line balancing; digital transformation

Odwzorowanie linii montażowej w środowisku cyfrowym

Andrej Polka [1*], Marin Krajčovič [2], Martin Buzalka [3]

1 *Andrej Polka, Ing., University of Žilina, Faculty of Mechanical Engineering, Department of Industrial Engineering, Univerzitná 8215/1, 010 26 Žilina, Slovakia, andrej.polka@fstroj.uniza.sk*
2 *Martin Krajčovič., prof., PhD., Ing., University of Žilina, Faculty of Mechanical Engineering, Department of Industrial Engineering, Univerzitná 8215/1, 010 26 Žilina, Slovakia, martin.krajcovic@fstroj.uniza.sk*
3 *Martin Buzalka, Ing., University of Žilina, Faculty of Mechanical Engineering, Department of Industrial Engineering, Univerzitná 8215/1, 010 26 Žilina, Slovakia, martin.buzalka@fstroj.uniza.sk*
* *Andrej Polka, Ing., andrej.polka@fstroj.uniza.sk*

Streszczenie: Istnieje wiele metod odwzorowania linii montażowej, jednak obecnie coraz częściej stosowane są zaawansowane narzędzia cyfrowe i rozwiązania programowe, które umożliwiają przenoszenie, badanie, analizę i optymalizację systemów przedsiębiorstw w formie cyfrowej. Artykuł koncentruje się na odwzorowaniu linii montażowej w środowisku cyfrowym z wykorzystaniem zaawansowanych narzędzi. Opisuje narzędzia i procesy, w tym ich zastosowanie w systemach cyfrowych. Przedstawione wyniki podkreślają skuteczność zaawansowanych narzędzi cyfrowych w rozwiązywaniu tego problemu, a ich efektywność została potwierdzona poprzez wdrożenia w rzeczywistych projektach..

Słowa kluczowe: montaż; procesy montażowe; równoważenie linii montażowej; transformacja cyfrowa

1. Introduction

The digital environment is increasingly gaining ground, enabling the use of advanced technologies such as simulations, analytical tools, and artificial intelligence. Traditional balancing methods, based on manual calculations and experience, often face limitations that slow down response times and increase costs. Digital tools and technologies are changing the way assembly lines are planned, optimized, and managed. With real-time data being collected and processed,

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manufacturers can not only optimize workflows but also predict issues before they arise, thereby minimizing downtime and increasing overall productivity.

1.1. Assembly line

An assembly line is an orderly system of workstations and equipment that are chronologically arranged to efficiently perform assembly operations and transform individual components into a finished product. This type of production system is widely used in batch and mass production, where the priority is to optimize production processes and maximize productivity. Each workstation on the assembly line performs a specific operation, ensuring a smooth production flow and minimizing cycle time. [1]

1.2. Line balancing

Line balancing is a process in assembly systems where tasks are allocated to individual workstations in a manner that achieves optimal workload distribution and minimizes inefficiencies. The primary objective of this process is to ensure an even distribution of tasks across all stations as in Figure 1, thereby preventing overloading of any station, which could otherwise result in exceeding the cycle time. Additionally, the process seeks to minimize the total time required to complete the product. Effective line balancing contributes to a smoother production flow, reduces idle time, and enhances overall productivity. By addressing potential bottlenecks and optimizing task assignments, line balancing plays a pivotal role in improving operational efficiency in serial production environments. [2]

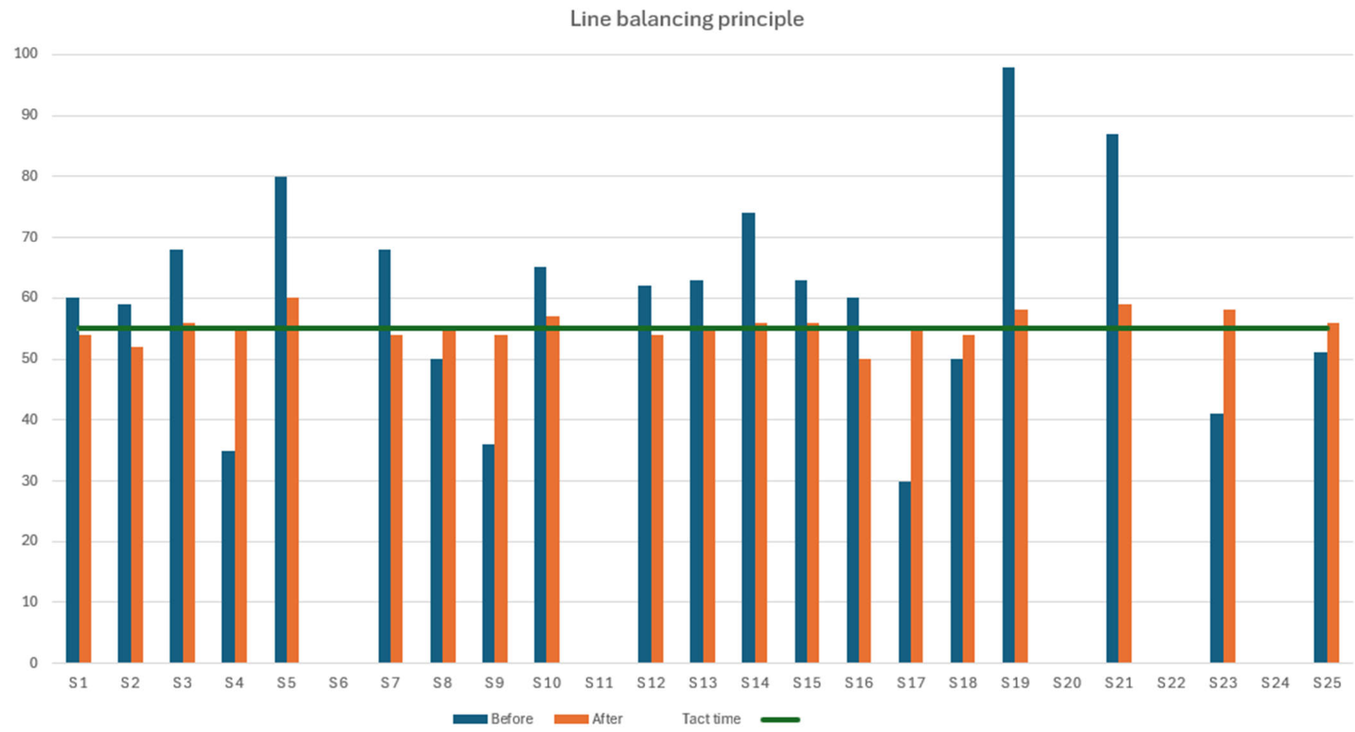

Figure 1. Principle of assembly line balancing [Source: Authors]

1.3. Factors and importance of line balancing

Assembly line systems are widely used in various industries for mass production. Due to the complexity of assembled products, line balancing is crucial for ensuring efficiency and optimizing the overall manufacturing process.

Key factors affecting line balancing include:

- time requirements,
- product variety,
- task variability,
- resource availability,
- ergonomics and safety,
- technical requirements,
- flexibility and scalability,

- cycle time,
- quality and control processes. [3]

The importance of assembly line balancing lies in ensuring an efficient and smooth production process. Assembly line balancing is a key step in organizing workflows and task allocation within the manufacturing environment.
The main benefits of assembly line balancing include:

- more efficient assignment of tasks to individual operators,
- ensuring timely delivery of products in the agreed quality,
- increasing production speed through optimal line balancing,
- determining workforce requirements based on line balancing,
- reducing overall production time,
- increasing profit and reducing costs for the company due to effective balancing,
- ensuring optimal production with minimal downtime,
- reducing the error rate in finished products. [4]

1.4. Digitalization of processes

The digitalization of processes has become an integral part of the modern company environment, bringing significant improvements in efficiency and innovation. An increasing number of companies are transitioning to digital processing of their operations, enabling them to respond more quickly to changing market demands and enhancing their productivity and competitiveness [5].

Digitalization and digital transformation in companies can be understood in various ways, as evidenced by several definitions:

- Digitalization involves the conversion of analog information and processes into digital formats, allowing for more efficient data management and optimization of operational activities.
- Digitalizing refers to the application of digital technologies and data analysis to improve performance, increase profitability, and transform key aspects of business, including processes, competencies, and management models.
- Digital transformation is a complex process where existing business processes are either digitally modified or entirely new ones are created to more effectively respond to changing market demands. [6]
- A digital enterprise is characterized by an environment in which computer and information technologies are key elements, transforming the physical world into virtual models. [7]

2. Line balancing process using advanced digital tool

Advanced digital tools and software solutions designed for the digital transformation of processes enable the efficient management of various aspects of assembly line balancing. These tools facilitate continuous optimization and adjustments to processes, thereby contributing to increased competitiveness and providing the capability to analyse the impacts of changes in a digital environment. Thanks to advanced digital tools, it is possible to simulate and verify each change on the line, allowing for the identification and design of the optimal assembly line configuration.

This section of the article describes the methodological approach to using digital tools for assembly line balancing. This process is divided into three key stages that are essential for the successful implementation of projects aimed at addressing the given issue:

- preparatory phase,
- line modeling,
- line balancing.

2.1. Preparation phase

Within this phase, it is essential to establish and precisely define measurable goals and criteria for assembly line balancing, which will serve as the foundation for evaluating the success of the project. Additionally, during this phase, it is necessary to gather all relevant input data that are crucial for the analysis and subsequent resolution of the project.

2.1.1. Input data

For assembly line balancing and optimization processes, it is essential to have access to high-quality and relevant input data. These data are either collected through real-time monitoring using RTLS (Real-Time Location Systems) or extracted from databases and imported into software tools. After verification and the creation of a digital model of the line, it is possible to proceed with the statistical processing and analysis of these data. The most used input data for assembly line balancing processes include:

- number of operators,
- individual operations,
- technological processes and procedures,
- assembled parts and components,
- component consumption,
- takt time,
- required takt time,
- line capacity,
- component packaging,
- frequency of line supply.

2.2. Line modeling

In this phase, the steps required to create a model of the line in a digital environment using are described using a flowchart Figure 2. This phase marks the beginning of the line balancing process in the digital environment, where it is necessary to create a digital model of the line.

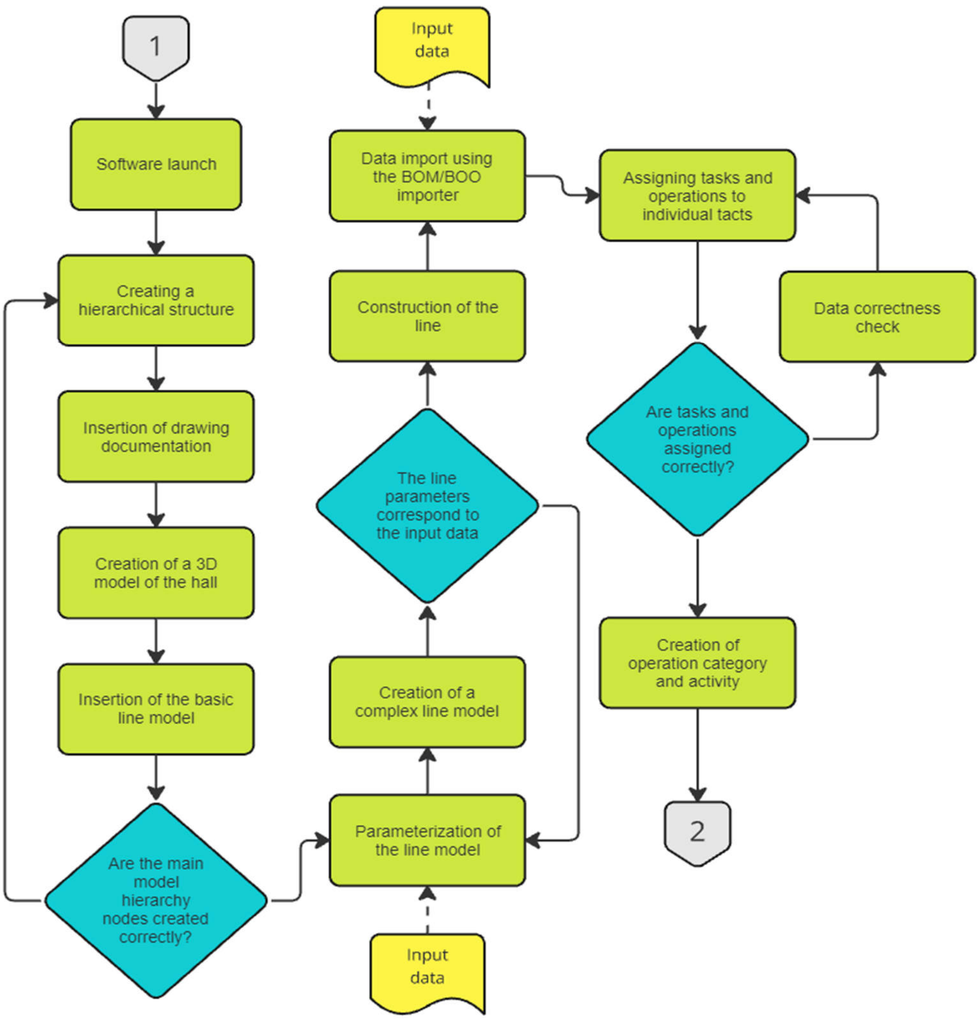

Figure 2. Flowchart - initial stage of the process of creating a digital model for assembly line balancing [Source: Authors]

2.2.1. Project creation and hierarchical structure developmentIn the initial phase of the project, it is necessary to create a hierarchical structure, which is gradually expanded by adding nodes and sub-nodes containing data. The hierarchical structure an example of which is shown in the Figure 3 is a fundamental element of the software, serving to identify individual nodes where the project's objects, components, or processes are located. This structure is then modified by inserting new objects, components, and 3D models from the library or by importing them into the software environment using the "drag and drop" function.

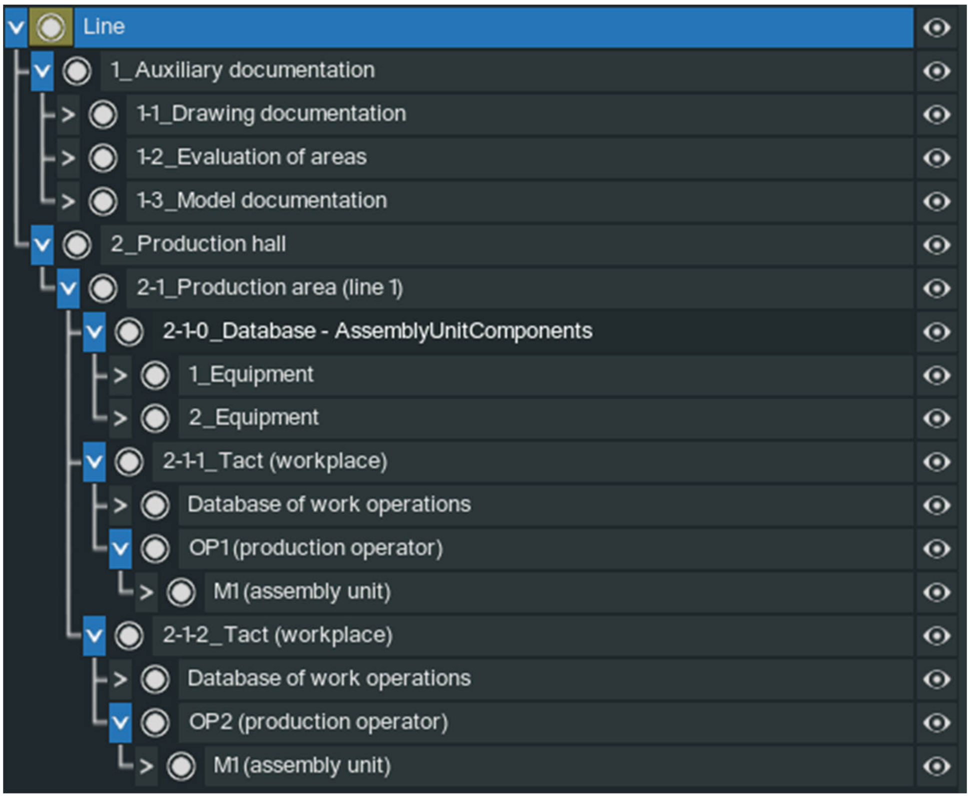

Figure 3. Hierarchical Structure [Source: Authors]

2.2.2. Creating the 3D model of the line, layout, and environment

Based on drawing documentation or a point cloud, a detailed model of the assembly line can be created. In this step, it is necessary to insert and configure the required number of workstations into the software environment. Each station must be assigned parameters such as cycle time, dimensions, and utilization. By duplicating these stations, a complex line model is created, which must then be supplemented with additional elements, such as shelving systems, pallets, and other part consumption locations, to complete the overall layout.

2.2.3. Importing input data

After creating the complex assembly line model, the next steps, which involve setting up the line's processes, can be taken. In this step, it is necessary to import activities and operations and subsequently allocate them to individual operators and cycles. This process is carried out using an importer shown in the Figure 4 that allows the import of input data into the software in the form of xlsx files.

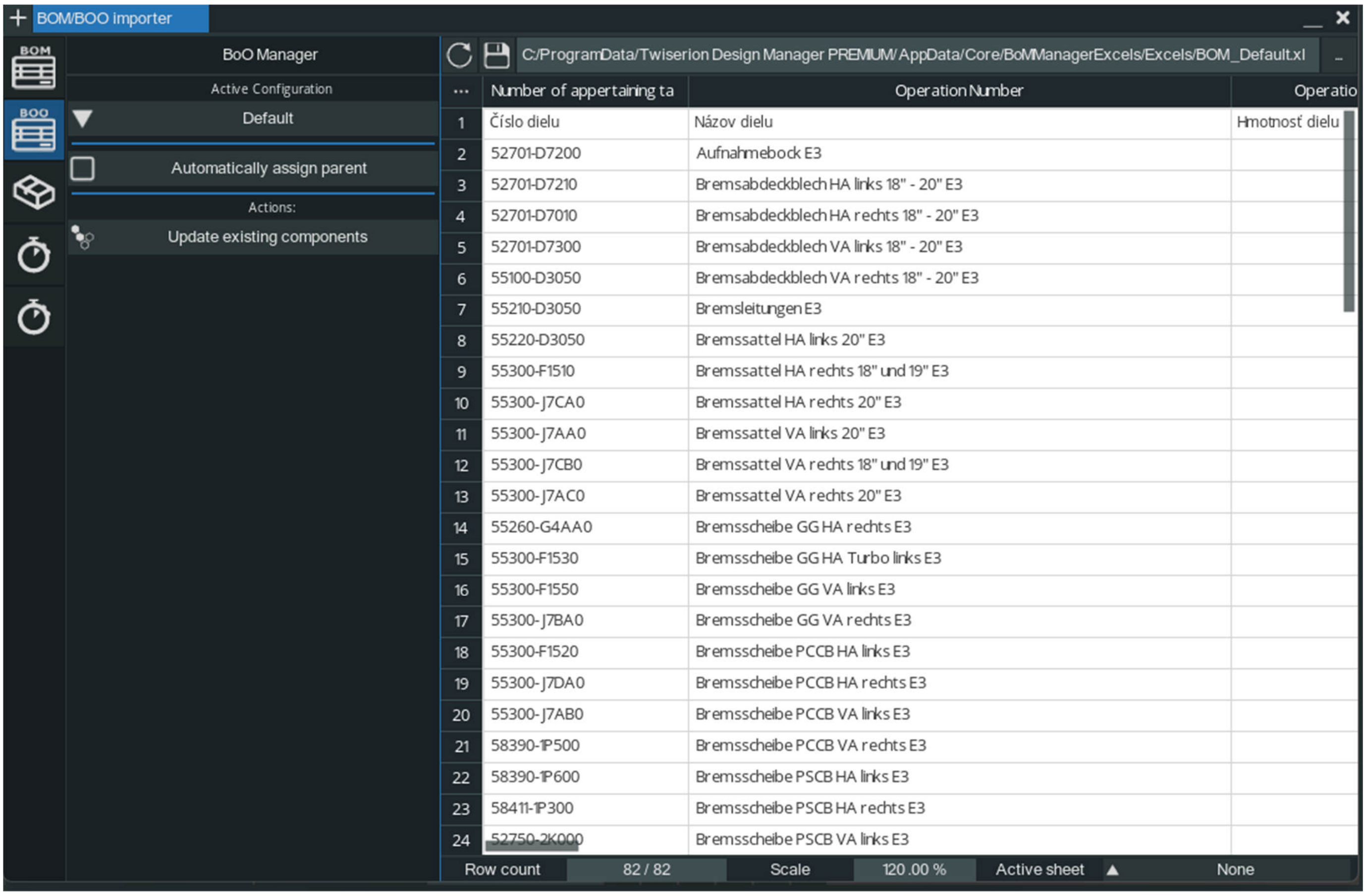

Figure 4. Input data importer tool [Source: Authors]

2.2.4. Assigning operations and classifying activities

After importing input data, such as the individual operations performed on the assembly line, it is necessary to assign them to the appropriate operator. This process can be done either by correctly mapping the configuration during the import or by manually assigning operations to a specific operator or workstation as shown in the Figure 5 based on the technological process. Once the operations are assigned, it is important to categorize them.

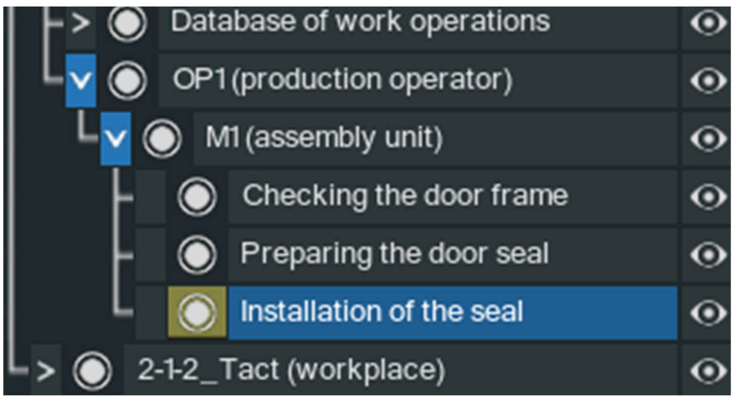

Figure 5. Assigning an operation to operators [Source: Authors]

2.2.5. Creating a categorization of operations

Categorizing operations allows for a detailed visualization of activities on the assembly line, helping to identify value-added operations, essential and necessary tasks, as well as inefficient actions. Within the software tools, it is possible to categorize operations according to the requirements and specific needs of the project being addressed.

2.3. Assembly line balancing

This phase describes the steps and procedures for balancing the assembly line. Using a flowchart Figure 6, the workflow is described using the different tools of the software solution. The outcome of this phase is the creation of a balanced, optimal assembly line design, which is achieved using various software tools.

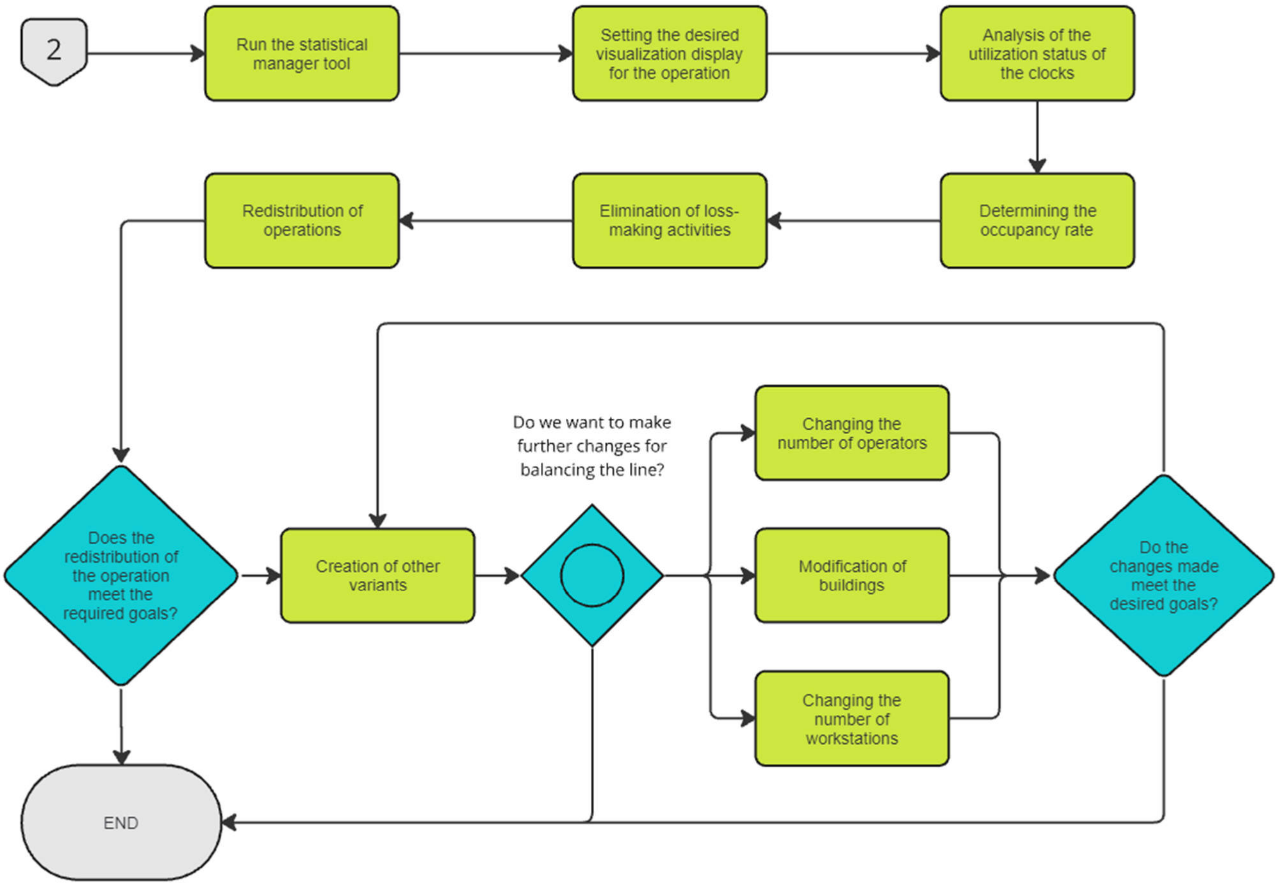

Figure 6. Flowchart - the second stage of the process flow for balancing [Source: Authors]

2.3.1. Statistical manager and working with this tool

This tool allows for the effective resolution of various aspects of the process, including balancing cycle times through logical redistribution of operations, optimizing operator utilization, and eliminating inefficient activities.

The statistical manager an example of which is shown in the Figure 7. is an advanced tool designed for the analysis and visualization of data obtained from various logistical and manufacturing processes. It enables efficient processing and analysis of statistical data regarding resource utilization, which is crucial for identifying areas that require improvement.

Thanks to its ability to provide detailed insights into data, it contributes to the optimization of production, warehouse, and logistics processes.

This intuitive and interactive tool is equipped with an interface of graphs, diagrams, and dashboards that simplify data analysis and optimization. It offers extensive possibilities for process improvement in the following categories:

- forklifts
- persons,
- transport flow,
- workstations,
- machines,
- products,
- traffic of logistical flow,
- pallets.

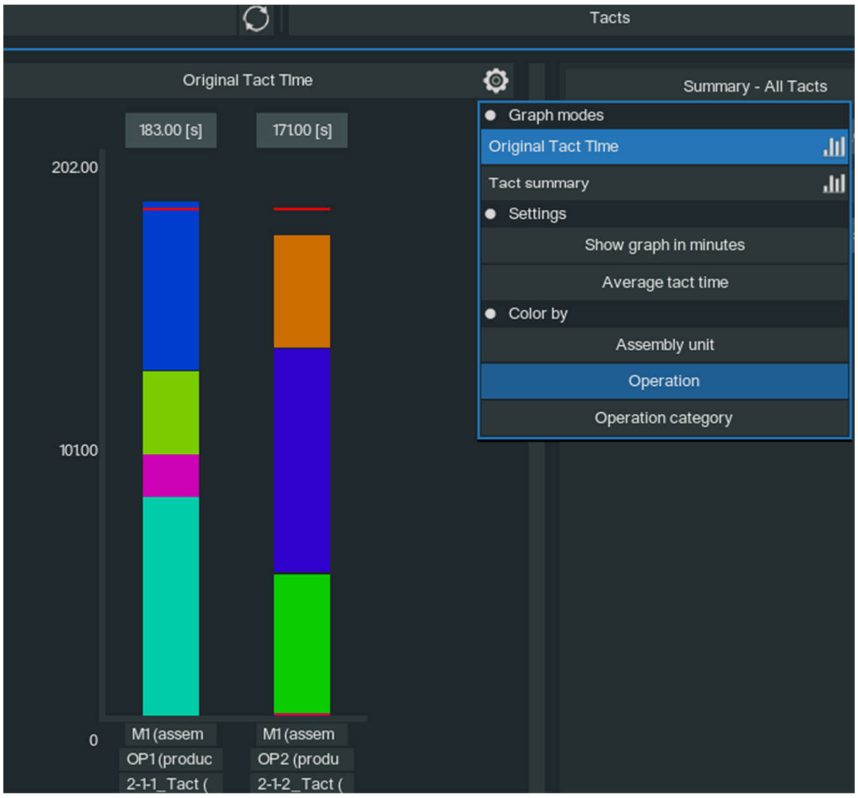

Figure 7. Statistical manager and display visualization selection [Source: Authors]

2.3.2. Determining the utilization rate

This process involves the analysis and quantification of the workforce and resources necessary for the efficient operation of the assembly line. This analysis is crucial for identifying opportunities to reduce overloading and uncover unused capacity at individual cycles. Within the system, utilization measurement is carried out through a statistical tool, where the utilization rate can be visualised as shown in the Figure 8. The process begins with a thorough analysis of the current state of each work tact on the line, assessing the level of load at each workstation. Using an advanced interface, segments where imbalances in workload distribution occur are identified.

Figure 8. Workload of operators at workstations [Source: Authors]

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2.3.3. Eliminating waste and non-value-added activities

The process of balancing assembly lines can also be achieved through the removal of activities that are wasteful and do not add value. Identifying such activities is made possible through advanced visualization.
In the process of assembly line balancing, activities such as waiting, unnecessary movement, and other forms of waste are eliminated, with each removal supported by analysis. By eliminating activities that do not add value, the number of operations is reduced, and the utilization of individual cycle times is optimized. This approach leads to shorter cycle and takt times, thereby increasing the line's capacity and overall productivity.

Two categories of operations were created in the redistribution of operations as shown in the Figure 9.:

- operations marked in green – value-added,
- operations marked in red – wasteful activities.

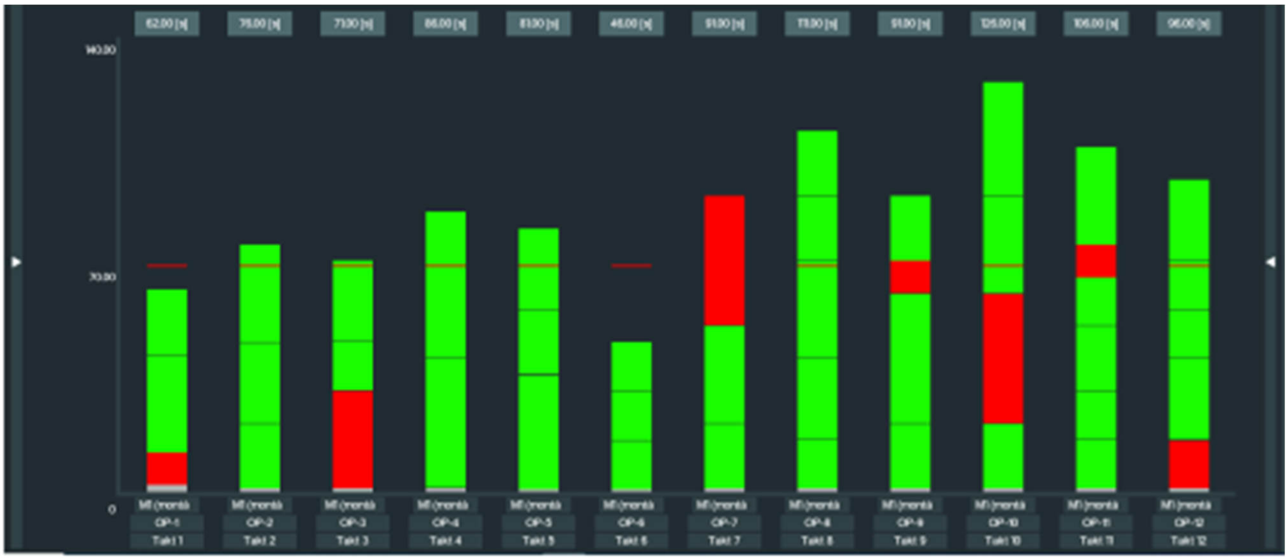

Figure 9. Visualization of the operation category [Source: Authors]

2.3.4. Redistribution of operations and line takt time adjustment

The redistribution of operations is carried out based on logical analysis and optimization of the arrangement of operations between individual cycles. In the Statistical manager shown in Figure 10., the redistribution of operations is performed using the "drag and drop" function. After moving an operation to a different cycle, a new operation with the required parameters is automatically created in the corresponding takt node to which the operation was moved.
When modifying and changing the sequence of operations, it is essential to consider the requirements and constraints related to the assembly and technological process to ensure optimal efficiency and functionality of the line.

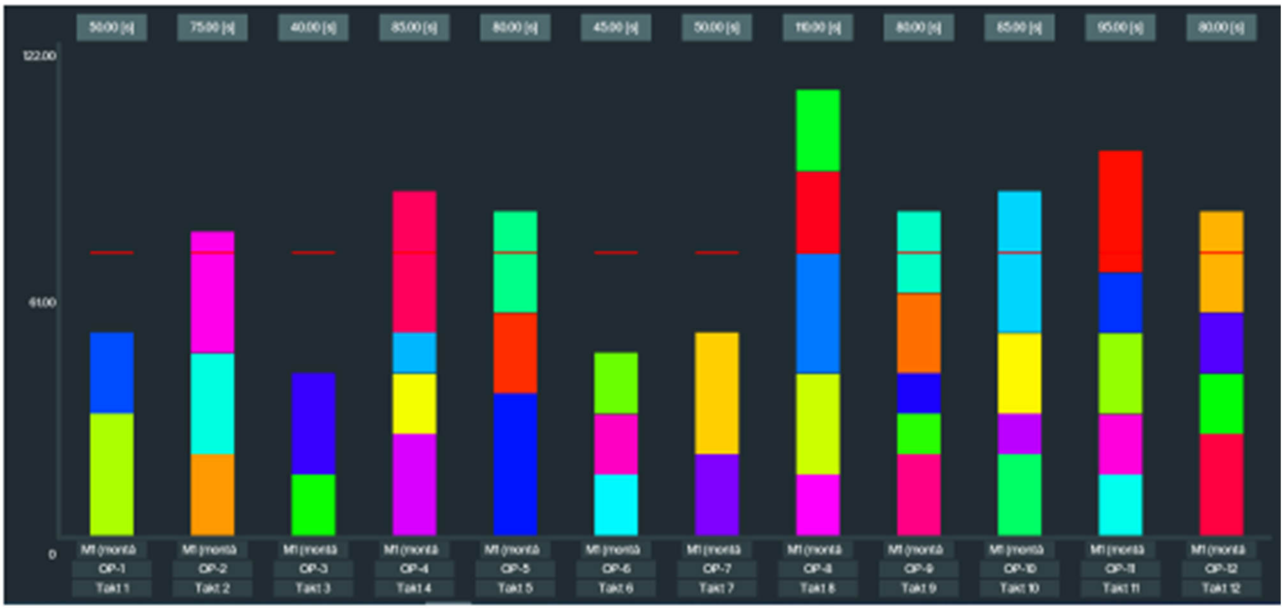

Figure 10. Demonstration of the state of the assembly line before the redistribution operation [Source: Authors]

As part of the project solution for assembly line balancing in an automotive plant, the individual operations were redistributed as follows to achieve a balanced state:

- from WS 3, the operation "Inserting the internal locking mechanism" was moved to WS 2,
- from WS 8, the operation "Assembly of the outer handle" was moved to WS 5,
- from WS 3, the operation "Installing the upper decorative window trim" was moved to WS 2.

Thanks to the redistribution and takt time adjustment of the assembly line, the desired balanced state of the line shown in Figure 11 was achieved, where all cycles maintained the required operator utilization and met the required takt time.

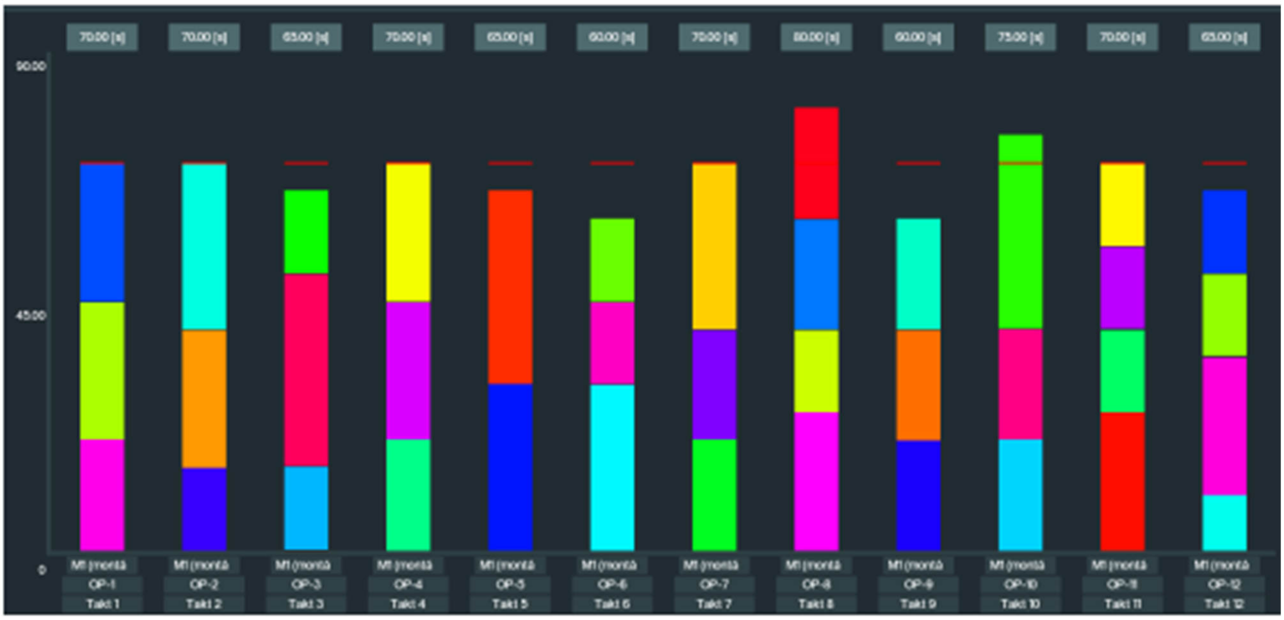

Figure 11. Demonstration of the state of the assembly line after redistributing the operation and creating an optimal design [Source: Authors]

3. Practical verification of the system on the assembly line on selected projects

The project aimed at optimizing the assembly line in automotive focused on balancing the assembly stations to shorten cycle time and streamline the distribution of work operations. For this purpose, advances digital tools were used to

create a digital model of the line based on collected input data, including workflows and operation times. The digital model provided a visualization of the current state of the line, allowing for the identification of inefficient processes and bottlenecks.
Advanced digital tools enabled the simulation and verification of proposed changes without interfering with actual operations. In the digital environment, it was possible to optimize the distribution of activities across workstations, reducing operator overload, increasing production efficiency, and minimizing downtime.
As part of the assembly line balancing project in the automotive industry, four solution variants were proposed Table 1. In the balanced state, it was possible to reduce the number of takt times, which had a positive impact on cost reduction. All proposed variants were thoroughly discussed and evaluated with the aim of selecting the most efficient and optimal solution.

Table 1. Summary of Results for the Assembly Line in the Automotive [Source: Authors]

	Before changes	**Variant 1**	**Variant 2**	**Variant 3**
Required tact time [sec.]	67	61	61	61
Cycle time [sec.]	1346	1158	1195	1214
Tact time [sec.]	67,3	60,95	59,75	60,7
Number of workstations on the line	25	25	25	25
Number of productive workstations	20	19	20	20
Number of operators per tact	2	2	2	2
Number of operators on the line	40	38	40	40
Maximum tact utilization [%]	152	109	107	101
Minimum tact utilization [%]	50	60	40	57
Average tact utilization [%]	91	88	81	88
Changes implemented in assembly	No	Yes	No	Yes

In the final phase of the project, testing of the selected optimized design was conducted directly on the assembly line, with the goal of identifying any shortcomings and allowing for their elimination. During the testing phase, it was determined that no further adjustments were necessary, and the proposed solution is fully ready for implementation into the production process.

Conclusion

The use of digital tools in assembly line balancing brings significant improvements compared to traditional methods. These tools allow simulation and design of various scenarios, real-time analysis of changes, and optimization of work activity layouts based on real data. This approach eliminates the need for physical intervention in operations, minimizing risks and downtime. Integrated statistical tools automatically evaluate the impact of changes, leading to more accurate productivity improvements and continuous enhancement.

Advanced digital tools enable flexible analysis, design, modification, and experimentation with processes without disrupting operations. Creating new project versions based on existing data simplifies the optimization of work operations, the number of operators, the reorganization of workstations, and the optimization of material flow, contributing to the elimination of bottlenecks and minimizing downtime. Analytical tools in the software also enable the standardization of work activities, increasing line efficiency and reducing operator workload.

Overall, digital tools and software solutions provide flexibility, immediate analysis, and optimization of work operations, leading to a significant increase in efficiency and cost reduction compared to traditional approaches.

The article focused on describing the process of line balancing in the digital environment, specifically using the software tool Twiserion Design Manager. The outcome of the article is an overview of tools capable of analysing input data imported into the software and then optimizing this data to achieve the best and optimal solution.

Acknowledgments

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