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Simulation as a Tool for Optimizing Logistics Flows to Increase Assembly Line Productivity

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Abstract: Assembly is one of the key phases of the production process, as it significantly affects productivity and the smoothness of logistics flows. Eliminating logistical and process-related waste therefore represents one of the most effective approaches for improving the performance of assembly systems while simultaneously supporting the smooth flow of materials throughout the entire organization. The paper focuses on the optimization of the intra-company logistics of an assembly line for the production of automatic elevator doors using a discrete simulation method. The digital model of the line was created in the Tecnomatix Plant Simulation environment based on real data on operation times, work distribution and material flows in a system without inter-operational bins. The simulation analysis identified the main bottlenecks caused by uneven worker workload and long cycle times of selected operations. Several improvement options were designed and verified using the trial-and-error method. A significant increase in productivity was achieved by introducing a new workstation and redistributing activities among workers, which increased production from 72 to 81 pieces per shift.

Keywords: Digital twin, discrete-event simulation, intralogistics, workload balancing

1. Introduction

The optimization of material and information flows represents one of the key challenges of modern manufacturing systems, as it directly affects productivity, operational costs, and the ability of enterprises to respond flexibly to changing market demand. Assembly processes, in particular, belong among the most complex and resource-intensive stages of production, where even minor inefficiencies in logistics, workstation balancing, or task allocation can significantly limit overall system performance. As a result, improving assembly logistics has become a strategic priority within the broader context of Industry 4.0 and digital transformation initiatives.

In recent years, digitalization has fundamentally changed the way manufacturing and logistics systems are designed, analyzed, and optimized. Discrete-event simulation (DES) has emerged as a widely adopted method for modeling complex production and intralogistics systems, enabling the evaluation of system behavior under various operational scenarios without disturbing real operations [1,2]. Simulation tools allow detailed representation of workstations, material flows, worker movements, and resource interactions, providing valuable insights into bottlenecks, utilization levels, and system dynamics. Numerous studies confirm that simulation-based approaches significantly support productivity improvement, layout optimization, and throughput enhancement in assembly and manufacturing environments [3-5].

A major advancement in simulation-based optimization is the integration of DES models into the concept of the digital twin. Digital twins represent virtual replicas of physical systems that continuously reflect real operational conditions through data connectivity and real-time updates [6,7]. According to Gallagher [8], in manufacturing logistics digital twins enhance process transparency, enable predictive decision-making, and support adaptive control of material flows. When combined with industrial communication standards such as OPC UA, simulation models can be linked with PLCs, MES, and sensor layers, enabling virtual commissioning and reducing the time and risk associated with deploying new or modified production systems [9-11].

Tecnomatix Plant Simulation is one of the most extensively used DES tools in industrial practice and academic research, particularly for modeling production lines, intralogistics systems, and assembly operations. Its object-oriented architecture supports hierarchical model development, reusable components, and detailed analysis of resource utilization and material flow performance [12]. Recent studies [13-15] demonstrate its applicability in areas such as inventory optimization, layout planning, energy-efficient logistics, and sustainability-oriented decision-making. Furthermore, advances in automated model generation and intelligent simulation techniques are expanding the role of DES toward Industry 5.0, emphasizing human-centric, resilient, and sustainable manufacturing systems [16,17].

Despite the extensive body of literature on simulation and digital twins, many industrial assembly systems still suffer from unbalanced workloads, inefficient task allocation, and rigid logistics configurations, particularly in synchronous lines operating without intermediate buffers. Such systems are highly sensitive to bottlenecks, where prolonged operation times at individual workstations or uneven worker utilization can significantly constrain throughput [18,19]. This highlights the need for detailed, data-driven simulation studies focused on practical assembly-line optimization under real operational constraints.

2. Aim and Data

The aim of the study is to identify bottlenecks in the production and logistics system and to propose such changes in the organization of work and the distribution of workstations that will lead to an increase in line productivity. Through the analysis of the utilization of workstations and workers, the main limitations of the system were identified, in particular the uneven distribution of the workload and long cycle times in selected operations. Subsequently, several improvement options were verified, including the distribution of operations, the transfer of activities among workers, and the expansion of the line with a new workstation and worker.

The concept of the digital twin represents a virtual model of a physical system that is connected to real-world operations in real time and dynamically reflects its current state. Gallagher [8] notes that within industrial logistics and manufacturing this concept has gained a dominant position primarily due to its ability to increase process transparency, support predictive control, and significantly reduce operational costs. The subject of this article is an assembly line for automatic elevator doors. The doors are assembled from components produced at other workstations and supplied through internal material-handling processes as part of intralogistics. The assembly takes place on a line consisting of seven workstations arranged in a single sequence. The line is synchronous and operates without intermediate buffers between stations, which is characteristic of a just-in-sequence production logistics approach. The material flow, managed by logistics workers and intralogistics technology, follows a linear path throughout the assembly line.

Table 1 Operation Times at Workstations. Source: authors

Name	Time [min:sec]	Worker	Cumulated Work Time [min:sec]
Workstation 1	3:48	Worker 1	5:36
Workstation 2	1:48	Worker 1	
Workstation 3	3:43	Worker 2	5:51
Workstation 4	2:08	Worker 2	
Workstation 5	5:47	Worker 3	5:47*
Workstation 6	2:58	Worker 3	
Workstation 7	2:44	Worker 4	2:44

* The operation carried out at workstation No. 6 is automatic testing and therefore is not included in the worker's working time (this also applies to Tables 3, 4 and 5).

The assembly line is operated by four workers performing logistics and production tasks. The first worker manages Workstations 1 and 2, forming the initial segment of the production logistics flow. The second worker operates Workstations 3 and 4, continuing the intralogistics-driven sequence. The third worker handles Workstations 5 and 6, ensuring continuity in material-handling and manufacturing logistics. The fourth worker operates Workstation 7, completing the final assembly stage. In this configuration, the line produces 72 door units per shift, with a net working time of 7 hours and 15 minutes. Operation times, worker allocation, and cumulative manufacturing logistics workload are shown in Table 1. The objective of this study is to propose modifications to the assembly line in order to achieve increased productivity and thus a higher number of units produced per shift.

2.1 Methods and Tools

The methodology for optimizing production material flows using Tecnomatix Plant Simulation is based on standard procedures commonly applied in simulation studies within industrial logistics. According to the recommendations of De Felice and Cimino [2,16], the following methods and tools were selected and applied to address the problem and achieve the defined objective: analysis, modeling, simulation, verification, and the trial-and-error method.

2.1.1 Analysis

This step includes collecting data on manufacturing logistics, material flows, cycle times, production takt times, workstation capacities, downtimes, and transport times. Sujová [6] emphasizes that input data quality significantly affects model accuracy. Table 1 shows that the longest operation is performed by Worker 2, lasting 5 minutes and 51 seconds, which limits line productivity. The second longest task is carried out by Worker 3, at 5 minutes and 47 seconds—the longest single operation in the assembly process. Without it, the line cycle time could be reduced to 3 minutes and 48 seconds. Therefore, achieving the objective of increased units per shift requires focusing on Worker 2 and the operation at Workstation 5, which are the process bottlenecks.

2.1.2 Modeling

Thanks to its object-oriented architecture, Plant Simulation enables the creation of hierarchical models and reusable objects [10,20]. This technique was used to develop a 3D model of the existing assembly line (Figure 1). For better visualization, a 3D representation was created using available tools. While the graphical depiction of workstations does not match their appearance, the dimensions reflect reality, allowing accurate simulation of worker movements and relevant results. Each movement needed to carry out a logistics operation (i.e., moving parts from one workstation to another) takes time during which the worker cannot perform assembly tasks, thereby reducing available work capacity and directly affecting line productivity.

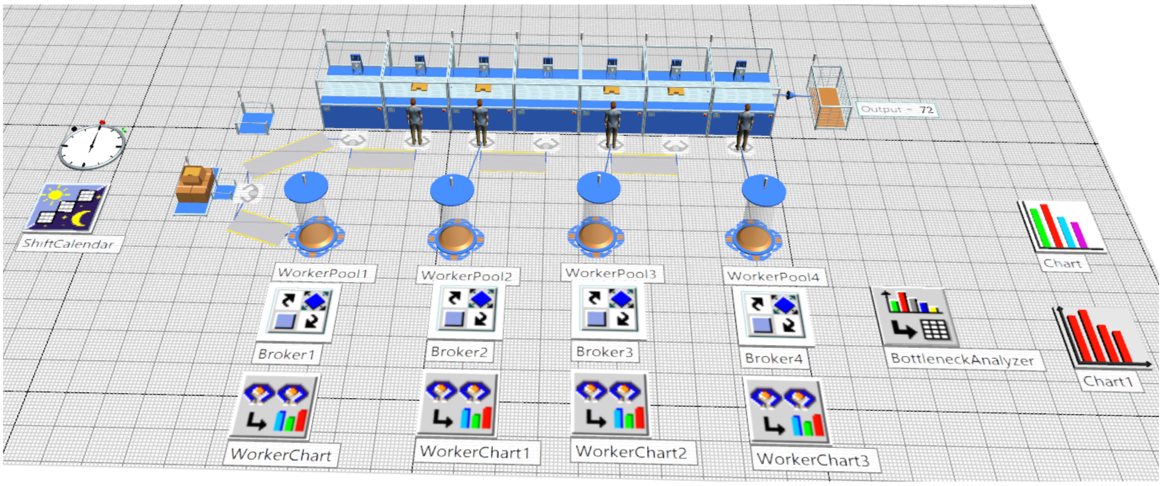

Fig. 1 3D Model of the Original Workstation. Source: authors

2.1.3 Simulation

Simulations were performed on the model in Tecnomatix Plant Simulation. Operation times were assigned to workstations, and worker movements and characteristics such as workstation dependencies, material flow, internal logistics, and work shifts were defined. To reduce simulation time—especially using the trial-and-error method—one shift was simulated.

During an 8-hour shift, workers have a 15-minute break and a 30-minute lunch, giving a net working time of 7 hours and 15 minutes. After setting all parameters, the simulation showed that the assembly line produces 72 elevator doors per shift.

Workstation utilization and engagement with the product are shown in Figure 2. The left side illustrates the percentage of activities at each workstation, including setup, waiting, blocking, and others, while the right side shows the percentage of each workstation's occupancy by the product.

Fig. 2 Resource Statistics and Occupancy. Source: authors

From the figure, it can be observed that the most heavily utilized workstation is Workstation 5, which corresponds to the operation with the longest duration. The utilization of this workstation reaches 88.32%. The most blocked resource is the component supply source, which is expected, as additional components can only be delivered once Workstation 1 is freed. Workstation 1 becomes available only after the assembled product is moved to Workstation 2, which in turn requires the sequential transfer of preceding products to subsequent stations, since the line operates without intermediate buffers. The actual transfer of materials from the source to Workstation 1 takes a very short time; therefore, blocking constitutes the largest share of the source's activity (up to 90.62%).

The exact numerical values of the percentage shares are presented in Table 2. The workstations in the table are arranged from the highest to the lowest share of productive work. Regarding the utilization of individual workers' time, this is illustrated in Figure 3.

Table 2 Percentage Distribution of Activities at Workstations. Source: authors

String	resource	working	waiting	blocked	Pause
1	root.Station4	92.42	7.58	0.00	0.00
2	root.Station	62.86	37.14	0.00	0.00
3	root.Station2	60.13	39.87	0.00	0.00
4	root.Station5	47.45	52.55	0.00	0.00
5	root.Station6	41.34	58.66	0.00	0.00
6	root.Station1	27.73	72.27	0.00	0.00
7	root.Station3	18.96	36.59	44.45	0.00
8	root.Source	0.00	0.00	90.62	9.38
9	root.Drain	0.00	100.00	0.00	0.00
10	root.Buffer	0.00	100.00	0.00	0.00
11	root.Buffer1	0.00	99.28	0.72	0.00

This represents the percentage share of individual activities within each worker's total available time. The graphs show that productive work occupies nearly 90% of the time for Workers 1, 2, and 3. For Worker 4, productive work accounts for approximately 40% of the time. The remaining time is spent waiting for components to arrive from the preceding workstation.

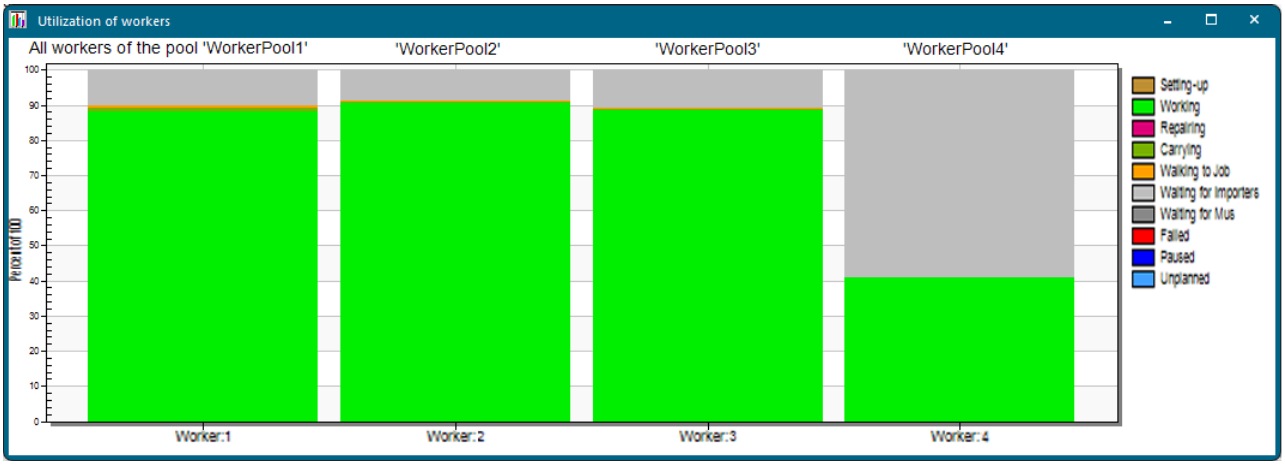

Fig. 3 Utilization of workers. Source: authors

2.1.4 Verification

Validation involves verifying whether the model accurately represents the real process. Simulation indicators are compared with real-world metrics, such as throughput, work-in-progress (WIP), and workstation utilization. According to authors [19,21,22], verification ensures the internal correctness of the model, including the accuracy of flows and operation sequences. Errors can occur when defining relationships and interactions between workers, materials, and machines; if undetected, they may invalidate results. In this case, the number of doors produced per shift was used as the verification metric. The simulation of the original state showed 72 doors per shift, matching actual production, confirming the model's accuracy and suitability for further simulations.

2.1.5 Trial-and-Error Method

The trial-and-error method was used to develop proposals for improving the productivity of the assembly line. The outputs include indicators such as line takt time, throughput, waiting times, capacity utilization, and energy consumption [14,15]. Based on these indicators, the optimal solution variant can be recommended. Several improvement variants were proposed:

1. Variant – Splitting Operation 5, which lasts 5 minutes and 47 seconds, into two separate operations. The first operation has a duration of 3 minutes and 17 seconds, and the second lasts 2 minutes and 30 seconds. An additional workstation was added to the line to perform the second operation. Table 3 shows the operation times for each workstation and the corresponding workers.

Table 3 Operation Times at Workstations – Variant 1. Source: authors

Name	Time [min:sec]	Worker	Cumulated Work Time [min:sec]
Workstation 1	3:48	Worker 1	5:36
Workstation 2	1:48	Worker 1	
Workstation 3	3:43	Worker 2	5:51
Workstation 4	2:08	Worker 2	
Workstation 5	3:17	Worker 3	5:47*
New Workstation	2:30	Worker 3	
Workstation 6	2:58	Worker 3	
Workstation 7	2:44	Worker 4	2:44

The assumption was that better balancing of the operation times across the workstations would improve the line's throughput. However, after modifying the model and running the simulation, it was found that this adjustment had no impact on increasing productivity. The bottleneck remained the total working time of Workers 2 and 3, as the proposed change did not affect these durations.

2. Variant – Since the first variant did not lead to improvement, it was proposed to modify it so that Worker 4, whose utilization is around 40%, would take over part of Worker 3's tasks. This includes work at the new workstation and operation of Workstation 6, where the only required action is inserting a component, while all other processes are automated. The operation times for each workstation and worker are shown in Table 4. The simulation model was updated and rerun. Although the workload distribution among workers changed, overall productivity did not

increase. The reason is that Worker 2 still required 5 minutes and 51 seconds to complete their tasks.

3. Variant – Upon a detailed review of Table 4, it was decided to modify Variant 2 by introducing an additional worker into the process and redistributing tasks among the workers. The proposed redistribution and corresponding operation times are presented in Table 5. The tasks assigned to the new worker are highlighted in green.

Table 4 Operation Times at Workstations – Variant 2. Source: authors

Name	Time [min:sec]	Worker	Cumulated Work Time [min:sec]
Workstation 1	3:48	Worker 1	5:36
Workstation 2	1:48	Worker 1	
Workstation 3	3:43	Worker 2	5:51
Workstation 4	2:08	Worker 2	
Workstation 5	3:17	Worker 3	3:17
New Workstation	2:30	Worker 4	4:14*
Workstation 6	2:58	Worker 4	
Workstation 7	2:44	Worker 4	

The new worker takes over tasks at Workstations 2 and 4. The total duration of their work is 3 minutes and 56 seconds. Adding a new worker also has an impact on the internal logistics of processes.

Table 5 Operation Times at Workstations – Variant 3. Source: authors

Name	Time [min:sec]	Worker	Cumulated Work Time [min:sec]
Workstation 1	3:48	Worker 1	3:48
Workstation 2	1:48	NewWorker	3:56
Workstation 3	3:43	Worker 2	3:43
Workstation 4	2:08	NewWorker	3:56
Workstation 5	3:17	Worker 3	3:17
New Workstation	2:30	Worker 4	4:14*
Workstation 6	2:58	Worker 4	
Workstation 7	2:44	Worker 4	

After updating the simulation model and running the simulation, it was found that this variant increased productivity to 81 units per work shift. Since this variant resulted in an improvement, it will be described in greater detail.

3. Results and Discussion

The proposed Variant 3 is illustrated in Figure 4. As previously mentioned, this variant includes the addition of a new workstation and an extra worker, so the line is now operated by five workers. The individual operations are redistributed among the five workers, as shown in Table 5.

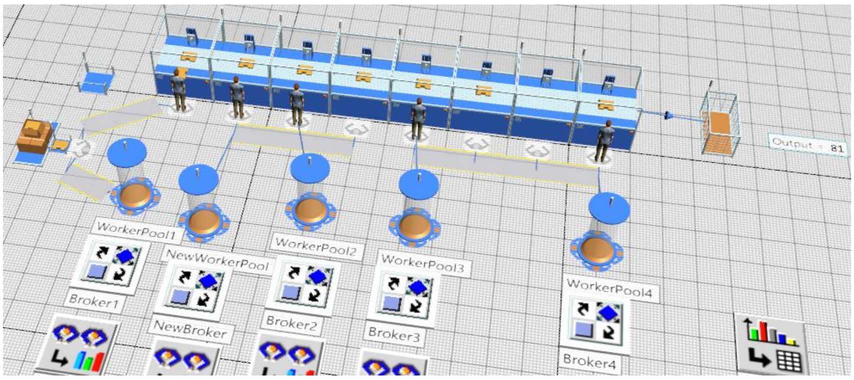

Fig. 4 3D Model of the New Workstation. Source: authors

Figure 5 shows the utilization of the workstations and their occupancy by the product. The exact percentage values are presented in Table 6.

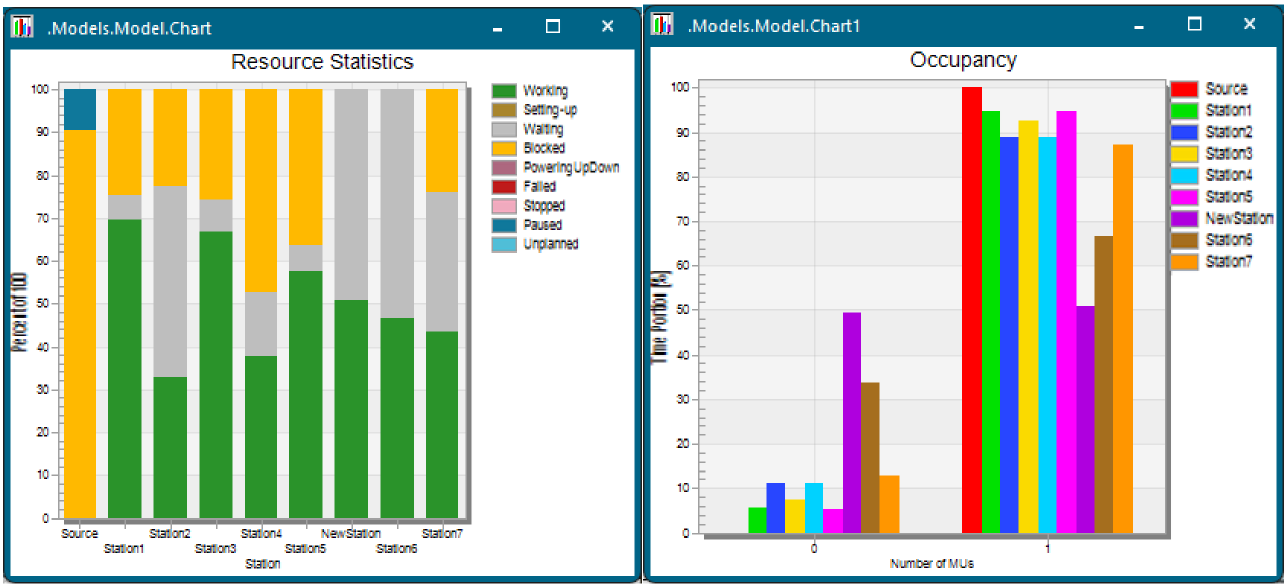

Fig. 5 Resource Statistics and Occupancy. Source: authors

The overall percentage of productive work decreased at some workstations and increased at others, due to the redistribution of tasks among the workers.

Table 6 Percentage Distribution of Activities at Workstations – New Variant. Source: authors

String	resource	working	waiting	blocked	Pause
1	root.Station1	69.67	5.50	24.83	0.00
2	root.Station3	66.59	7.44	25.97	0.00
3	root.Station5	57.46	6.02	36.52	0.00
4	root.Station6	50.68	49.32	0.00	0.00
5	root.Station7	46.48	53.52	0.00	0.00
6	root.NewStation	43.23	32.88	23.89	0.00
7	root.Station4	37.78	14.93	47.29	0.00
8	root.Station2	32.62	44.80	22.58	0.00
9	root.Source	0.00	0.00	90.62	9.38
10	root.Drain	0.00	100.00	0.00	0.00
11	root.Buffer	0.00	100.00	0.00	0.00
12	root.Buffer1	0.00	8.27	91.73	0.00

The overall utilization of all five workers is shown in Figure 6.

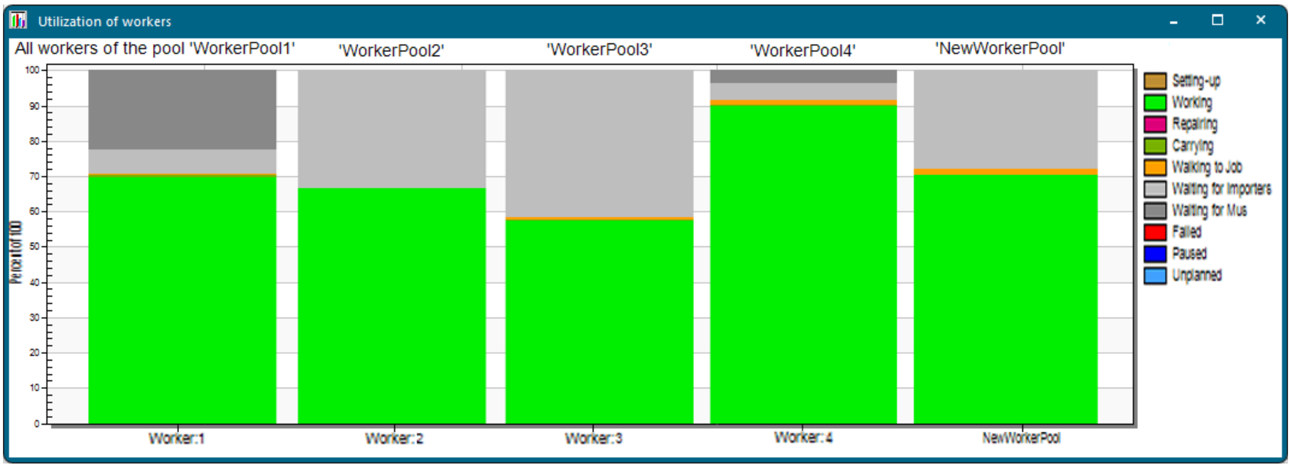

Fig. 6 Utilization of workers. Source: authors

The results of the simulation experiments showed that simply balancing operations without changing staffing did not lead to an increase in productivity. Significant improvements occurred only after the introduction of a new workstation and the redistribution of activities among five workers, which allowed the elimination of key bottlenecks. Compared to the original variant, the workload of Workers 1, 2, and 3 decreased, while the workload of Worker 4 increased, despite the addition of a new worker. This is due to the redistribution of tasks among the workers.

The proposed variant increased production from the original 72 to 81 pieces per work shift while maintaining the fluidity of the material flow. The paper confirms that simulation tools and the digital twin concept represent an effective means for analysis, optimization and decision support in the field of production logistics and assembly processes.

4. Conclusion

Several authors [4,5,19,20] confirm that the optimization strategy used by the integrated digital twin of manufacturing leads to significant improvements in operational performance in several system performance indicators and logistics flow of materials.

Based on the conducted analysis, modeling, and simulation experiments in Tecnomatix Plant Simulation, it was confirmed that the primary constraints of the original assembly line were the operations performed by Workers 2 and 3, whose long task cycles determined the overall line takt time and limited its production logistics throughput. Through the gradual application of the trial-and-error method and testing of multiple modification variants, it was verified that simply splitting operations or reallocating tasks within the existing intralogistics workflow did not achieve the desired increase in productivity. Significant improvement was achieved only with the third variant, which included the addition of a new workstation and an extra worker, enabling the effective redistribution of time-consuming operations. This change led to a more balanced workload distribution within the production logistics system and reduced the time burden on critical workstations. As a result, line throughput increased from 72 to 81 units per shift, representing a substantial step toward higher productivity. Based on the experiments conducted, it can be concluded that optimizing the assembly process using simulation tools is an effective approach for identifying bottlenecks and designing realistic improvements. The proposed Variant 3 represents a suitable solution that enhances assembly line performance while ensuring better workload balance among workers.

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