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SYSTEMATIC OPTIMIZATION OF A MULTI-MODEL INDUSTRIAL ASSEMBLY LINE THROUGH LINE BALANCING AND SIMULATION

Abstract: *Assembly line optimization remains a key challenge in production engineering, especially in environments with product diversity, variability, and space constraints. This paper presents a practical study on optimizing a multi-model industrial assembly line using real production data. The approach integrates line balancing, reduction of non-value-added activities, layout reconfiguration, and simulation-based validation to improve performance without major investments. The process was modeled in Plant Simulation to evaluate initial and improved configurations. Results indicate that partial optimization yields limited gains, while full implementation leads to reduced operating times, improved workload balance, enhanced stability, and increased output capacity. The study highlights the importance of considering real industrial constraints and the value of simulation as a decision-support tool.*

Key words: *assembly line, line balancing, process optimization, simulation, Lean Manufacturing.*

1. INTRODUCTION

In recent years, manufacturing systems have undergone significant transformations driven by increasing market competitiveness, product diversification, and the need for higher operational efficiency. Traditional rigid production systems are progressively being replaced by flexible manufacturing environments capable of handling variable production volumes and multiple product variants within the same assembly line. In this context, multi-model assembly lines have become widely adopted in modern industry, offering adaptability but also introducing higher levels of complexity in process management and line balancing [1].

Assembly line balancing represents one of the most studied problems in production engineering due to its direct influence on productivity, resource utilization, and production stability. The main objective of line balancing is to distribute tasks among workstations in such a way that idle times are minimized and workstation workloads are as close as possible to the line takt time [2]. However, although numerous mathematical and optimization models have been proposed in the literature, many of these approaches consider idealized production environments with deterministic operation times and limited variability. In real industrial settings, operational performance is strongly influenced by human factors, equipment limitations, layout constraints, and process variability, aspects that are often insufficiently addressed by purely theoretical models [3].

Recent research emphasizes the importance of integrating practical constraints into assembly line design and optimization. Mixed-model production systems, in particular, face challenges related to workload variability, bottleneck propagation, and synchronization between consecutive operations, all of which can negatively affect production flow and overall efficiency [4]. In addition, Lean Manufacturing principles have demonstrated significant potential in reducing waste, minimizing non-value-added activities, and improving flow continuity through layout redesign and process simplification [5]. Nevertheless, the successful implementation of such approaches requires detailed analysis of real production data and validation through simulation or experimental studies.

Simulation-based analysis has become an increasingly important tool for evaluating assembly line performance before implementing physical changes in industrial environments. Digital models allow engineers to test different optimization scenarios, identify bottlenecks, and assess the impact of operational modifications without disrupting production activities. Studies show that combining simulation with line balancing techniques can significantly improve decision-making and reduce implementation risks in complex manufacturing systems [6].

The present study addresses the optimization of a real multi-model industrial assembly line operating under practical constraints such as limited space, mandatory operation sequences, and technological limitations. The research focuses on identifying workload imbalances, reducing non-value-added activities, and reorganizing the production layout in order to improve line performance. A simulation model was developed to evaluate both the initial configuration and the proposed improvement stages, enabling the validation of the optimization strategy before implementation. The results demonstrate that substantial improvements in productivity and process stability can be achieved through systematic balancing and layout reconfiguration without major technological investments.

The main contribution of this work lies in bridging the gap between theoretical assembly line balancing methods and real industrial practice by integrating operational data analysis, Lean Manufacturing principles, and simulation-based validation into a coherent optimization framework applicable to real production environments.

2. THEORETICAL FRAMEWORK

Assembly lines are sequential systems in which overall performance depends on the synchronization of workstations. Line balancing aims to distribute tasks evenly so that the processing time at each station is as close as possible to the line takt time [7].

The takt time is defined as:

$$T = \frac{T_{disponible}}{Q} \qquad (1)$$

where Q represents the production demand.

An imbalance leads to idle times and the accumulation of intermediate inventories, negatively affecting overall efficiency.
The line efficiency is expressed as:

$$E = \frac{\sum t_i}{n \cdot t} \qquad (2)$$

where n represents the number of stations.

Recent studies highlight that operational variability is the main factor limiting the performance of mixed-model assembly lines [8], [9].

The methodology combines direct process analysis with continuous improvement methods, including: (1) measurement of operation times, (2) material flow analysis, (3) bottleneck identification, (4) simulation of operation redistribution, and (5) performance evaluation after optimization. To visualize task distribution, an operation time analysis was employed (Fig.1).

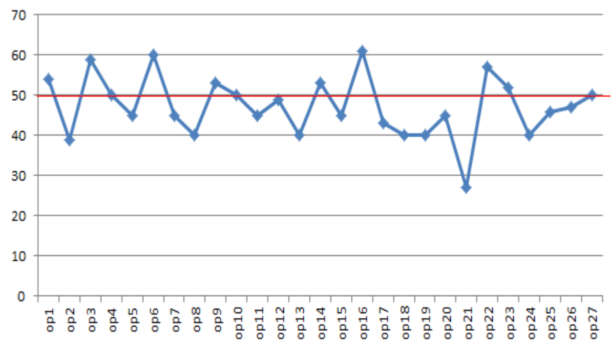

Figure 1 Analysis of operation times

3 ANALYSES OF THE INITIAL SITUATION

The process evaluation revealed significant imbalances between workstations, which had a direct impact on overall system performance. Several stations were found to be overloaded, resulting in uneven workload distribution and increased pressure on operators, while others experienced high levels of idle time. These discrepancies led to local accumulations of partially processed products, disrupting the continuity of the production flow and reducing operational stability. As a consequence, fluctuations in the production rate were observed, indicating that the system was operating below its optimal efficiency and highlighting the need for workload redistribution and process optimization.

Each workstation is assigned specific operations that must be performed in a defined sequence, with each operation characterized by an average execution time.

Based on the process description, the operations can be classified into six categories: assembly, verification (safety testing), quality control (QC), cleaning, product identification, and packaging.

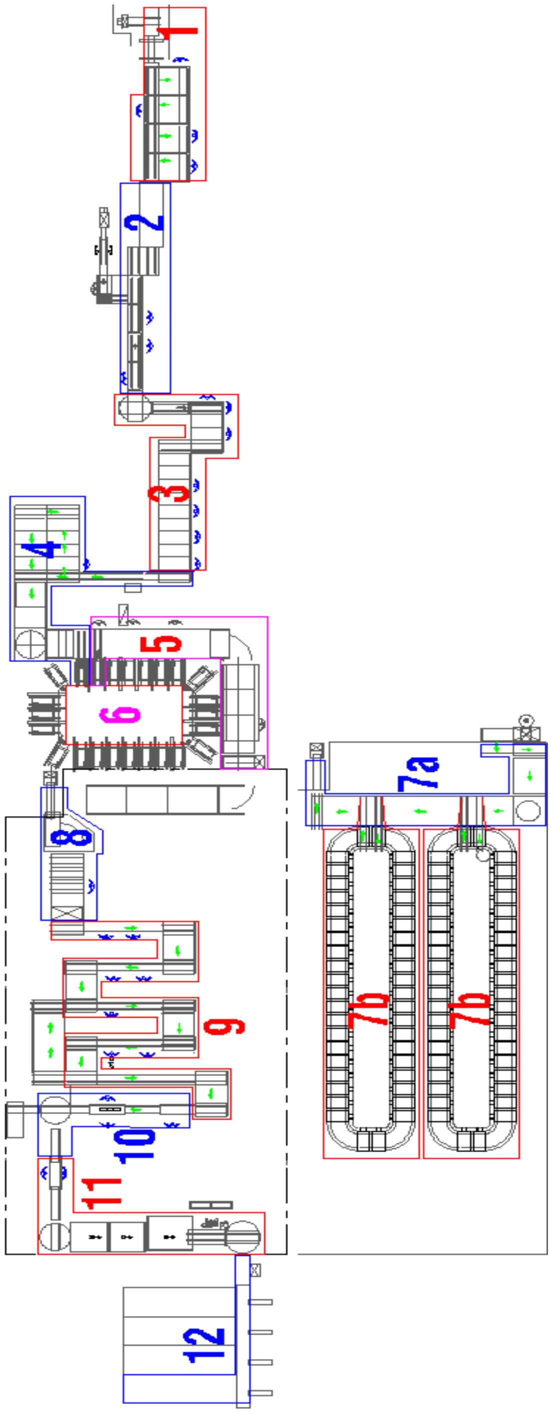

Figure 2 Assembly line

To enable a more detailed analysis of the assembly process, the line was divided into 12 work zones (Fig. 2) due to its complexity.

- **Zone 1:** operations op1 – op3
- **Zone 2:** operations op4 – op6
- **Zone 3:** operations op7 – op12
- **Zone 4:** operation op13
- **Zone 5:** operations op14 – op16
- **Zone 6:** vacuuming area for the products

- **Zone 7:** area where the functional testing of the products is performed automatically; no operator is required
- **Zone 8:** operation op18
- **Zone 9:** operations op19 – op24
- **Zone 10:** operations op25 – op26
- **Zone 11:** operation op27
- **Zone 12:** area dedicated to product identification according to model and transfer to the warehouse.
- The analysis showed that variability in operational times leads to the propagation of bottlenecks throughout the entire production flow.

3.1. Optimization Proposal

The redistribution of tasks aimed to align the duration of each workstation more closely with the line takt time. Operations with longer processing times were either divided into smaller elements or reassigned to other stations in order to achieve a more balanced workflow. In addition, efforts were made to reduce non-value-added activities by eliminating unnecessary movements, redundant handling operations, and waiting times between stations. These adjustments contributed to improving flow continuity and increasing overall process efficiency.

Following the balancing of the assembly lines, the time required to perform operations was reduced by approximately 37%. The total operating time decreased from an initial value of 1182 seconds to 738 seconds after the implementation of the optimization measures.

In certain situations, increasing the number of operators was necessary to ensure an adequate balance of tasks. In the initial configuration, the assembly line consisted of 28 workstations operated by 34 operators, as well as two rework stations staffed by two operators. Following the redistribution of operations, it was determined that 30 workstations operated by 38 operators were required, together with a single rework station staffed by one operator and an additional workstation located outside the line in zone 2. The purpose of this additional workstation is to prepare the upper damper, which is subsequently positioned and assembled on the conveyor by other operators.

The product moving through the continuous flow follows a zigzag path. To optimize the available space, a layout arranged in an "L" shape is proposed instead of a straight-line configuration. In continuation of the first zone, operators are positioned in a linear arrangement, while the transition area is removed to allow the workstations to be aligned in a straight line and to improve flow continuity. The vacuum carousel is equipped with 24 vacuum pumps, generating a takt time of 37.5 seconds for a vacuum cycle of 900 seconds. Since increasing the vacuum speed of the refrigeration units is not feasible, the adopted solution involved the introduction of additional vacuum stations. This approach had to consider several constraints, including the requirement for an even number of vacuum stations and the limited space allocated to this area. Although achieving a takt time of 24 seconds would require the installation of 12 to 14 additional vacuum pumps, spatial limitations allowed for the implementation of only eight new vacuum stations. As a result, the new takt time of the vacuum station was reduced to 28 seconds. This solution required modifications to the layout in that area, including changes in the arrangement of the vacuum stations and the repositioning of adjacent workstations.

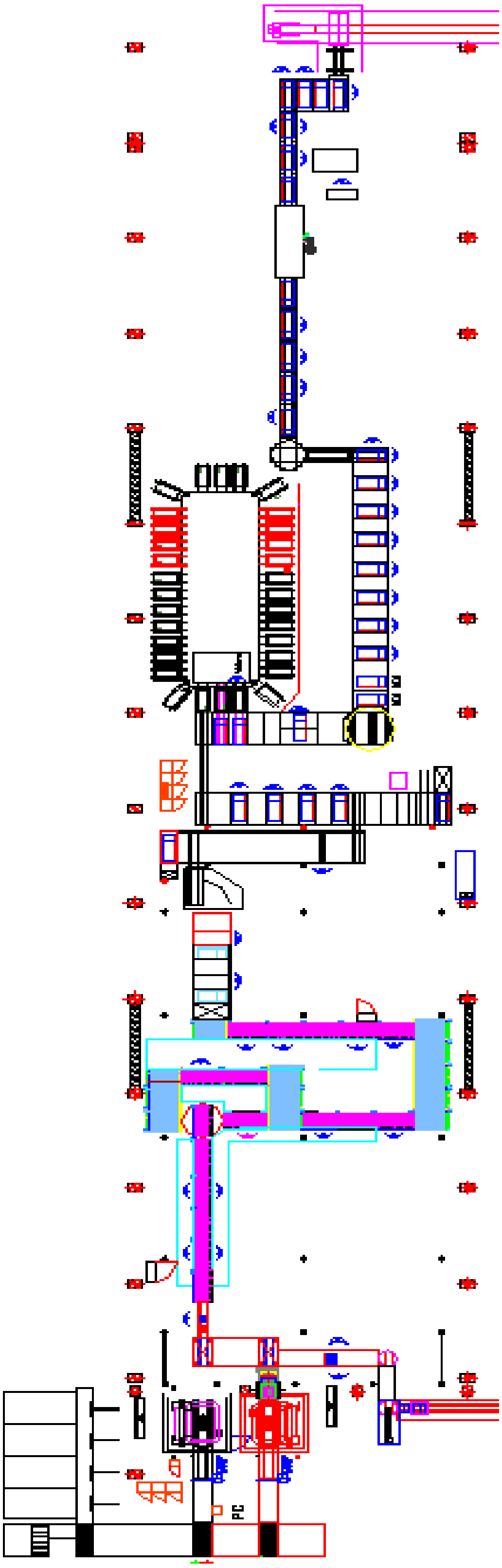

Figure 3 Assembly line reconfiguration

Table 1

Activity report for the unimproved assembly line

Mean Life Time	Throughput	TPH	Production	Transport	Storage	Value added
32:08.9143	343	56	73.04%	26.96%	0.00%	68.69%

In addition, a reconfiguration of the workstations into a "U"-shaped layout is proposed in order to further improve material flow and space utilization.

The partial reconfiguration of the layout reduced transport distances in accordance with Lean Manufacturing principles [10]. Figure 3 illustrates the concept of the proposed line reconfiguration.

Another essential step in the optimization process involved reconfiguring the layout of the workstations within the available space. The main objective was to reduce the distance traveled by the product along the production flow in order to minimize auxiliary time and improve overall operational efficiency.

To ensure the correct implementation of the proposed solutions, a simulation of the entire assembly line was carried out. The solutions were implemented in two stages, as their application required time and a full shutdown of the assembly line for an extended period was not feasible. The optimization process started from the final work zones and progressed upstream in order to avoid major bottlenecks within the production flow. The first improvements were introduced in zones 11, 10, 9, and 8, while the second stage included zones 7, 6, 5, 4, 3, 2, and 1.

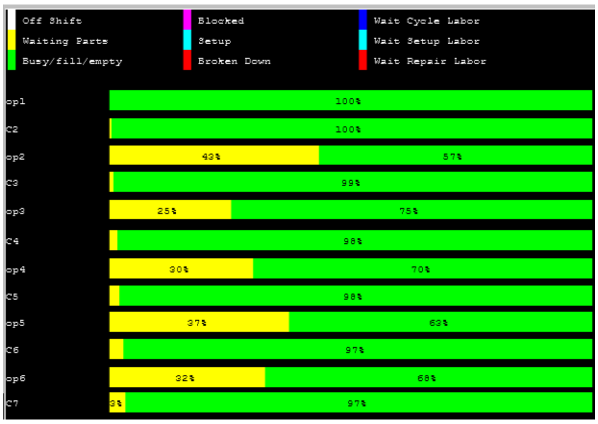

Figure 4 Assembly line simulation

Before initiating the required modifications, simulations were performed for both the initial configuration and the two implementation stages. The assembly process was modeled and simulated using Plant Simulation software.

To validate the developed virtual model, the first simulation was conducted using the initial configuration of the assembly line, prior to the implementation of the proposed improvements.

Within an interval of 21,930 seconds, representing the effective working time of one shift, the simulation indicates a production output of 343 units. Under real operating conditions, the average production recorded over the past three years is 311 units per shift. Therefore, the simulation results are close to the actual production data, which confirms the validity of the model.

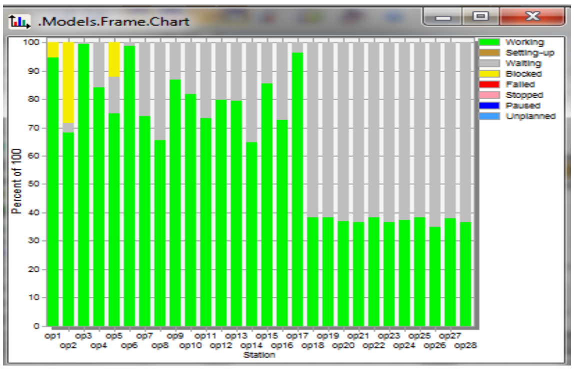

Figure 5 Operator efficiency

As indicated by the activity report corresponding to the first stage of improvements, a significant increase in the number of produced units cannot be expected, since the assembly process remains constrained by upstream limitations. However, a reduction in the average operating time across the entire line can be observed, decreasing from 32.8 seconds to 28.22 seconds.

Production capacity decreased from 73.04% to 69.31% as a result of operators in the optimized zones not working at maximum capacity (Fig. 5). Thus, starting from operation station 18, operators function at approximately half of their available capacity.

In the second stage, an extended model was developed to simulate the assembly process under conditions where all proposed optimization measures were fully implemented. The purpose of this model was to evaluate system performance in a scenario in which all improvements were applied across the entire line, allowing the analysis of their cumulative impact on production flow, workstation balancing, and resource utilization. Through this simulation, the overall effects of the optimization on production capacity, process stability, and operational efficiency were assessed.

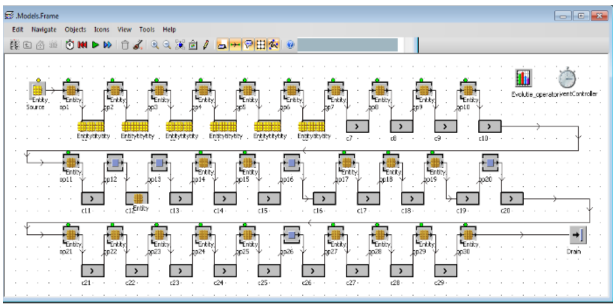

Figure 6 Improved assembly line simulation

It can be observed that, under the improved configuration, productivity increases to 93 units per hour, corresponding to an output of approximately 565 units during a single work shift. This result demonstrates a significant enhancement in the overall performance of the assembly line compared to the initial state. The average operating time reaches 26.12 seconds, indicating that the process operates close to the target takt time of 25 seconds established for the line. The reduction in cycle time reflects a better balance of workloads across workstations and a more stable production flow, with fewer interruptions and reduced idle periods. Overall, the results suggest that the implemented optimization measures contribute to higher efficiency, improved resource utilization, and increased production capacity while maintaining process stability

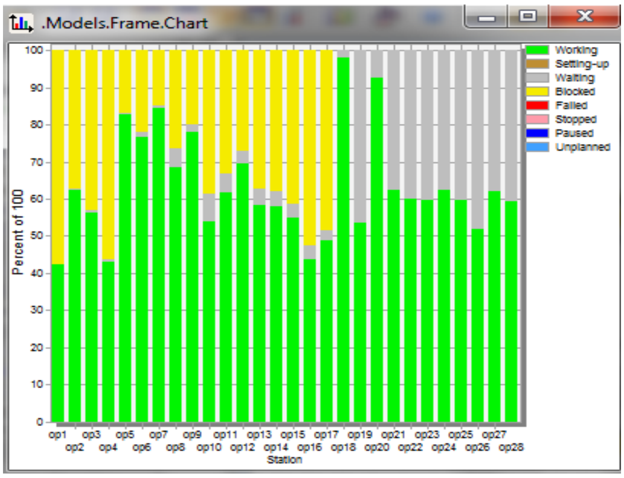

Figure 7 Operator status after improvement

As shown in the graph in Figure 5, workstations 1 to 17 are blocked due to the long durations of operations 18 (refrigerant charging and vacuum testing) and 20 (electrical safety testing), which have operating times of 37.5 and 35.5 seconds, respectively. These operating times could be reduced by introducing additional conveyors; however, this solution cannot be implemented due to limited available space.

The systematic design and balancing of assembly lines represent, in this case, a complex process, determined both by the high number of operations and by the constraints imposed by the available space. Additional limitations are related to the mandatory sequence of operations and the specific conditions required for carrying out each activity.

In order to reduce the assembly line takt time, it was necessary to implement an integrated set of measures, including the elimination of operations that did not add value to the final product, increasing the number of operators in overloaded workstations, reducing the distances between successive operators, eliminating unnecessary transfers, and repositioning the transfer conveyors to ensure the shortest and most efficient product path. In addition, increasing the number of vacuum stations in both the functional testing area and the refrigerant charging area contributed significantly to improving the overall performance of the line. The implementation of the proposed solution involved several stages, including modifying the design layout, updating instructions and technical specifications, and archiving the revised project version.

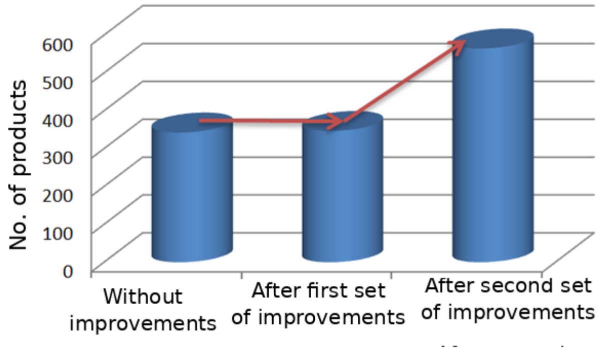

Figure 8 Operator status after

Before implementing the identified solutions, it was considered necessary to simulate the assembly process in order to anticipate how the system would respond to the proposed changes and to evaluate their impact on overall performance. The simulation results showed that the first set of modifications did not generate a significant increase in productivity, as their effects were limited by constraints existing in the upstream section of the line. A major improvement in performance became visible only after optimizing the second half of the assembly line located upstream, when the production flow became more balanced and stable. According to the simulation results, production is expected to increase from 343 units to approximately 565 units per shift, highlighting the positive impact of the full implementation of the optimization measures.

7. CONCLUSIONS

This study addressed the optimization of a multi-model industrial assembly line operating under real production constraints. The research highlighted the gap between theoretical assembly line balancing models and the complexity of practical industrial environments, where operational variability, spatial limitations, and technological constraints significantly influence system performance.

The results demonstrate that substantial improvements can be achieved through systematic task redistribution, reduction of non-value-added activities, and partial layout reconfiguration, without requiring major technological investments. The balancing process led to a significant reduction in total operating time and improved workload distribution across workstations. Although the first stage of optimization produced limited productivity gains due to upstream constraints, the full implementation of the proposed measures resulted in a considerable performance increase.

Simulation played a key role in validating the proposed solutions before their implementation. The virtual model accurately reflected real production data, confirming its reliability as a decision-support tool. Under the improved configuration, productivity increased from 343 units per shift to approximately 565 units per shift, while the average operating time approached the target takt time. These results confirm that a structured and data-driven optimization approach can significantly enhance production capacity, process stability, and resource utilization.

At the same time, the study underlines the importance of considering practical limitations such as space availability, equipment constraints, and mandatory operation sequences when designing optimization strategies. Future research may focus on further reducing bottlenecks in technologically constrained stations and integrating real-time data monitoring to support adaptive line balancing in dynamic production environments.

Overall, the findings confirm that systematic assembly line design, supported by simulation and Lean Manufacturing principles, represents an effective pathway toward achieving higher operational efficiency in complex industrial systems.

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