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Optimizing Sewing Line Balancing in Apparel Manufacturing through Digitalization

Bülent Koç[1]*, Selin Hanife Eryürük[1]

[1] Istanbul Technical University, Faculty of Textile Technologies and Design, Textile Engineering Department, Istanbul, Türkiye
* Corresponding author. E-mail: kocbul18@itu.edu.tr

Abstract
This study presents an innovative software system for optimizing sewing line balancing in apparel manufacturing, addressing challenges posed by dynamic production demands, such as fluctuating order sizes and varying product styles. By Integrating real-time data with lean principles, the system utilizes a parallel station position-weighted algorithm and dynamically assigns operators based on current task metrics. This real-time data integration for operator assignment is the system's key innovation. A case study demonstrated significant improvements: line efficiency increased from 79.68% to 88.31%, and per-operator output rose by 10%. These results highlight the potential for substantial efficiency gains in apparel manufacturing.

Keywords
Apparel Manufacturing, Digitalization, Process Monitoring Devices (PMDs), Digital Lean, Digital Line-Balancing.

1. Introduction

The garment industry faces intense competition and rapid changes, driven by fluctuating order sizes, increasing product variety, and shorter lead times. This dynamic environment makes optimizing production processes crucial for cost-effectiveness, product quality, and operational efficiency. Sewing, a labour-intensive process often exceeding 35% of total production costs, presents unique challenges due to its inherent complexity [1]. Effective task allocation across various workstations, each managed by operators with varying skill levels, is critical for maintaining production efficiency. Improper assignments can lead to increased labour costs, higher work-in-progress, extended cycle times, and reduced throughput. Therefore, floor managers must meticulously oversee task configuration and distribution to minimize inefficiencies and optimize production outcomes [2].

Sewing line balancing, a core component of lean manufacturing, aims to systematically eliminate inefficiencies such as idle time, bottlenecks, and uneven task distributions [3]. Optimizing task allocation improves workflow efficiency and reduces cycle times. However, achieving a perfectly balanced line with uniform cycle times remains challenging due to variable task durations and the complexity of sewing operations. The primary goal is to minimize discrepancies in task distribution, preventing any single operation from becoming a bottleneck.

The optimization of assembly line operations, often referred to as the Assembly Line Balancing Problem, has long been a critical challenge in the manufacturing industry. This problem involves the assignment of various tasks to workstations in a way that minimizes idle time and maximizes production efficiency. Over the years, researchers have developed a wide range of approaches to address this problem, including exact algorithms, heuristic methods, and simulation-based techniques [4]. Among these, task parallelism has emerged as a promising strategy. By enabling multiple tasks to be executed simultaneously across different stations, this approach effectively reduces idle time and mitigates bottlenecks, leading to enhanced overall production efficiency [5].

Traditional manual evaluations of sewing line balancing often lead to inconsistencies and delays. However, Industry 4.0 and digital transformation have enabled more dynamic and adaptive line configurations. Integrating IoT technologies, sewing machines, and software systems allows real-time data collection and process monitoring, facilitating rapid identification and correction of bottlenecks [6,7].

This study introduces a novel software solution for optimizing sewing line balancing in the apparel industry, utilizing the parallel station position weighted line balancing method and real-time performance data from process monitoring devices. Unlike existing solutions, our system dynamically adjusts the workload among operators. This approach enhances workflow balance and aligns with lean manufacturing principles by reducing waste and increasing operational flexibility. The system demonstrates the potential of digitalization to improve efficiency, competitiveness, and sustainability in the apparel sector.

2. Literature Review

The assembly line balancing problem (ALBP) remains a critical challenge in manufacturing optimization, focusing on the efficient assignment of tasks to machines and operators with varying skill levels. Effective line balancing minimizes bottlenecks, optimizes resource utilization, and enhances operational efficiency, allowing manufacturers to adapt quickly to market fluctuations, thereby fostering innovation and competitiveness [8]. Traditional line balancing models often prioritize minimizing the number of workstations for a given cycle time or vice versa. However, these rigid optimization criteria, compounded by inherent sequencing and zoning constraints, often result in a predetermined line-balancing structure. This lack of flexibility limits the potential to optimize for other critical factors, such as capacity and workload imbalances across workstations [9,10].

In sewing line planning, time data collection plays a critical role in enhancing operational efficiency. Various studies have emphasized the impact of time and motion on productivity, while others have highlighted how standard minute values (SMV) can help eliminate bottlenecks and improve efficiency in production workflows [11,12]. Techniques for sewing line balancing have gained prominence over other process improvement methods, including Lean manufacturing [13-15], Lean Six Sigma [16,17], and Six Sigma [18]. These balancing techniques must navigate multiple constraints, such as task assignments, task precedence, cycle times, and resource limitations, making the process complex and challenging [19,20]. While many performance measures focus on minimizing the number of workstations in straightforward assembly line scenarios, simulation studies have proven invaluable for refining balancing methodologies [21,22]. Research has highlighted essential factors, including system design, bottleneck identification, and resource allocation. Comparisons between heuristic and simulation-based methods in sewing line balancing reveal that both approaches effectively balance assembly lines [23,24].

Heuristic techniques, particularly the ranked positional weight (RPW) method, the largest candidate rule, and the computer method for sequencing operations for assembly lines (COMSOAL), have been extensively studied and applied in sewing line balancing [25]. Their effectiveness in optimizing straight-line balancing has been well-documented in ready-to-wear assembly lines [26]. Notably, a comparison among these methods showed that the largest candidate rule performed best overall, enhancing efficiency [27]. The efficient assembly of complex products, such as trousers, is a critical challenge in manufacturing, as it directly impacts productivity and profitability. The RPW method, developed by Helgeson and Birnie in 1961, remains a popular heuristic technique for optimizing assembly processes [28,29]. When applied to manual techniques, the RPW method has been shown to significantly outperform other approaches, reaching 95.1% efficiency and a 19.84% smoothness index. This study applies the RPW heuristic to the complex assembly process of trousers, with a focus on task distribution based on precedence and time requirements.

Process monitoring device (PMD) technology has become a pivotal tool in modern production planning, providing real-time workflow monitoring through sensors on sewing machines. This real-time monitoring capability enables immediate adjustments based on performance fluctuations, proving particularly advantageous for small-batch or single-item production by reducing cycle times and enhancing overall efficiency [30,31]. PMDs continuously track production processes, optimizing task assignments according to operator performance and enabling rapid responses to dynamic production needs, thus offering greater flexibility and efficiency compared to traditional methods.

Building on these advancements, this study introduces a digital sewing line balancing model that incorporates process monitoring device technology for real-time rescheduling based on live performance data. This approach aims to enhance production efficiency while aligning with broader digital transformation trends in the textile industry, such as the shift towards Industry 4.0 and data-driven manufacturing [32]. By emphasizing waste reduction and continuous improvement, the adoption of digital lean principles is essential for the ongoing digital evolution within the industry, as it enables businesses to remain competitive and adapt to rapidly changing market demands [33].

The persistent challenge of optimizing assembly line balancing in the labour-intensive garment industry has driven the exploration of diverse methodologies, encompassing simulations, heuristic methods, and genetic algorithms. This study contributes to this ongoing pursuit by introducing a novel model that seamlessly integrates digital technologies with established lean production principles. This integration is not merely a technological advancement but represents a paradigm shift towards a more agile, efficient, and responsive production environment. The positive impacts observed in garment production, particularly in line efficiency and workload optimization, suggest that this model holds considerable promise for application across a spectrum of industries grappling with similar challenges.

3. Theoretical Framework

This section will individually evaluate three key components that elucidate how digitalization can enhance sewing line balancing. By analyzing each component, we aim to provide a clear understanding of their specific contributions to improving operational efficiency in apparel manufacturing. This examination will highlight the integral role of digitalization in optimizing production processes.

3.1. Real-Time Data Collecting and Performance Management with Process Monitoring Devices (PMDs)

This section emphasizes the critical role of process monitoring devices (PMDs) in real-time data collection and performance management within manufacturing, particularly in the apparel industry. By capturing live data from production lines, PMDs enhance operational efficiency, support data-driven decision-making, and promote continuous workflow improvement. Their integration is essential for the digital transformation of manufacturing, fostering agile and competitive production environments.

As illustrated in Figure 1, PMDs centralize the digitalization of production processes by continuously collecting real-time data directly from machines, enabling immediate adjustments to optimize production activities.

To better understand the impact of PMDs, it is essential to explore their specific functions in various aspects of manufacturing. The role of PMDs in real-time data collection is pivotal, enabling a seamless digital transformation across production lines. Additionally, PMDs facilitate the dynamic calculation of operator performance, providing actionable insights into productivity levels. By implementing real-time performance tracking, organizations can engage in proactive maintenance management, thus ensuring smoother operations and minimizing downtime. Collectively, these elements highlight how PMDs serve not only as monitoring tools but also as significant enablers of enhanced operational performance in the apparel manufacturing sector.

(1) Role of PMD in Real-Time Data Collection and Digital Transformation:

Process monitoring devices (PMDs), utilizing internet of things (IoT) technologies, connect machines and systems to facilitate real-time data exchange and process automation, which are essential for optimizing sewing line balancing. Real-time data captured through wi-fi, RFID, and automated quantity tracking enables continuous monitoring of production activities. This information provides critical insights into operator performance, quality, and production output, facilitating dynamic adjustments to operator assignments and task allocation to improve line balance.

Sewing machines equipped with PMDs serve as prime examples of effective hardware and IoT integration,

Fig. 1. Process Monitoring Device (PMD)

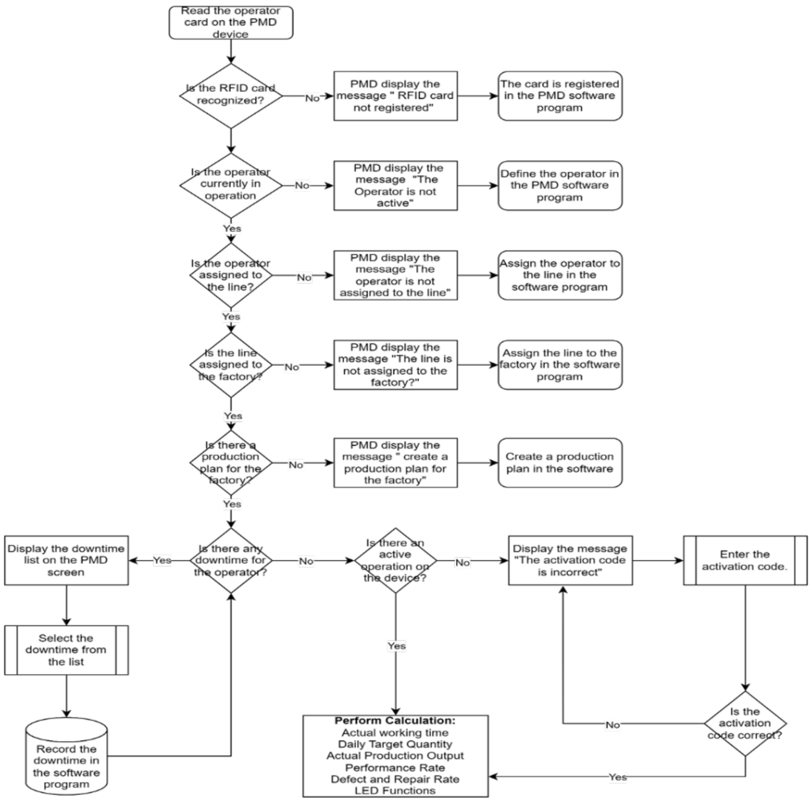


Fig. 2. Dynamic Workflow Optimization Framework for PMD

encouraging stakeholders to adopt various methodologies for developing integrated software solutions. The integration of process monitoring devices with IoT, cloud computing and software application offers significant potential for optimizing sewing line balancing in apparel manufacturing. Consequently, these advancements help manufacturers retain a competitive edge in today's

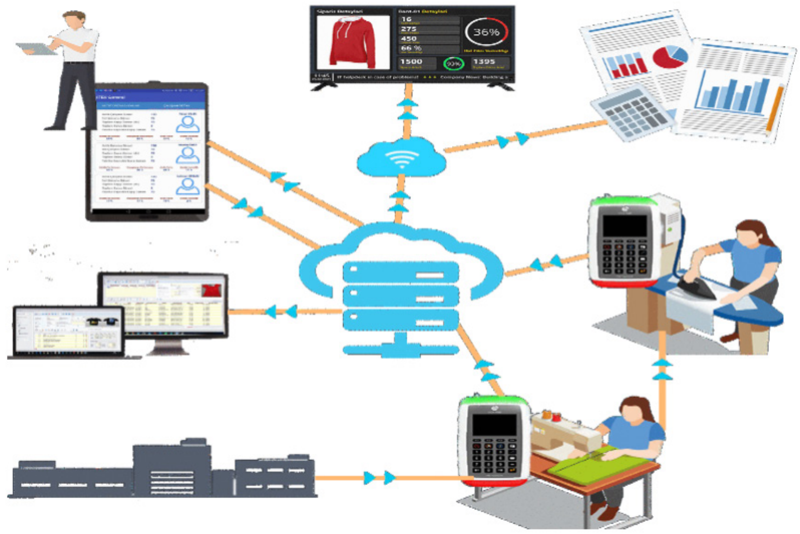


Fig. 3. Overview of Digitalization in Garment Manufacturing

market [34]. Figure 3 illustrates the interconnectedness of these technologies and their impact on operational effectiveness in garment manufacturing.

(2) Dynamic Calculation of Operator Performance:
Monitoring operator performance is crucial for improving production efficiency in digital manufacturing. The PMD system captures real-time data on working times, production output, and standard operation times, enabling objective assessments [35]. Upon scanning their RFID card, an operator's task details are linked to performance data on the server. The system logs key metrics such as standard times, actual working times, and production quantities, while tracking task start and stop times, including pauses or interruptions like machine downtime or breaks, along with their specific causes. These comprehensive data enable accurate evaluations of operator performance.

Performance metrics are dynamically calculated and displayed on the PMD screen using the following formulas:

$$Performance=(Production\ Time(min.))/(Actual\ Working\ Time(min.))\times 100 \quad (1)$$

$$Production\ Time=Production\ Quantity(pcs.)\times Smv(min.) \quad (2)$$

$$Actual\ Working\ Time=(Time\ at\ measurement-Start\ of\ Shift-Downtimes) \quad (3)$$

Example of Performance Calculation:

Details	Values
Start of Shift	08:00
Time at Measurement	12:00
Downtime	30 minutes
Production Quantity	250 pieces
Standard Minute Value (SMV)	0.5 min/pcs

The calculations would be as follows:

Calculations	Formula	Details
Production Time	250pcs × 0.5min/pcs	125 min
Time Difference	12:00 − 08:00 = 4hours	240 min
Actual Working Time	240min − 30min	210 min
Performance Calculation	((125 min)/(210 min)) ×100	59.5%

Performance metrics are dynamically calculated and displayed on the PMD screen using established formulas that consider standard time, actual time, and units produced. These calculations are performed every minute and with each unit counted, providing real-time feedback to operators. While an operator's RFID card is active, the system continuously records performance data. Upon card removal or machine shutdown, the performance value is transmitted to the server and stored in the database by the PMD Control Program.

(3) Real-Time Performance Tracking and Proactive Maintenance Management**:**
Process monitoring devices (PMDs) provide real-time feedback on operator performance, enabling managers to identify inefficiencies and track progress toward production goals. By capturing key metrics such as working time and production volume, PMDs allow operators to compare their performance with predefined standards. The system also detects interruptions, enabling quick corrective actions to improve efficiency and maintain competitiveness in the apparel industry.

PMDs are crucial for managing machine failures and planning maintenance. When a machine breakdown occurs, operators can log the fault using the PMD, which transmits the data to a central system, alerting technicians for prompt repairs. By integrating PMDs with total productive maintenance (TPM) principles, manufacturers can use proactive fault detection and predictive maintenance to reduce downtime and enhance equipment reliability. The data collected also help refine maintenance strategies, advancing TPM's goals of improved efficiency, minimized downtime, and optimized operations for sustainability [36].

3.2. Developed Software Algorithm

The parallel station weighted line balancing algorithm developed in this study serves as an advanced tool for optimizing workforce distribution across the assembly line. Its primary objective is to minimize the number of operators assigned to each workstation while addressing capacity constraints and workload imbalances. By incorporating key parameters such as workstation capacity, operator skills, and task location weights, the algorithm effectively redistributes tasks to create a more balanced and efficient operational flow. This approach enhances production processes, leading to improved outputs and smoother overall operations.

To facilitate efficient operation of this algorithm, three essential datasets were utilized:

- *Production Data:* This includes real-time production quantities collected through process monitoring devices (PMD), operators' working times, standard minute values (SMV), production cycle times, and performance data at workstations. These data serve as critical inputs for optimizing the workload distribution.
- *Workstation Data:* Analysis of workstation capacity, cycle times for tasks performed at each station, available resources, and operational requirements inform the organization of workload distribution among stations.
- *Operator Data:* These data encompass each operator's skill level, past performance, working speed, and tasks suitable for assignment. Operators are allocated to various workstations based on their skill and performance metrics.

The algorithm development process begins with the capacity algorithm, which determines the optimal number of operators assigned to each station. This process is informed by the specific needs of each workstation and the skill levels of operators. Balancing efforts account for operator workload, workstation capacity, and task duration to ensure an efficient allocation of resources. The steps involved in this process are outlined as follows:

1. Task Duration Calculation: The time allocated to tasks at each workstation (ti) is determined using the standard minute value (SMV), which acts as a benchmark in the production process. The SMV is calculated based on the average performance values for each task, obtained from the factory database by considering task descriptions, operation types, and the machinery used. Consequently, dynamic task durations are established based on the operators' performance levels, ensuring that production times reflect real-time efficiency metrics.

$$ti=smvi/Performance \tag{4}$$

2. Cycle Time Determination: Cycle time (tc) is the total duration required to finish a task at a workstation, covering the processing time, inter-station movements, adjustments, and operator changeovers. It is closely associated with the takt time, which establishes the production rate based on customer demand to ensure output meets the required levels [37].

$$\text{Takt time (tc)=(Daily Working Time (C))/(Daily Customer Demand (Q))} \tag{5}$$

For instance, with a daily working time of 540 min and a customer demand of 1,330 units, the cycle takt time can be calculated as:

$$tc=(540\ min.)/(1330\ pcs.)=0{,}406\ \text{min/pcs.}$$

3. Calculation of Required Operator Number (Ni): The required number of operators to be assigned to a workstation (Ni) is calculated using the following formula:

$$Ni=ti/tc \tag{6}$$

This formula demonstrates the relationship between task time (ti) and operator capacity. The calculated value of Ni indicates the minimum theoretical number of operators needed at a station. To enhance efficiency and reduce resource allocation, only the integer part of this value is used. For instance, if the task time (ti) is 2.5 minutes and the cycle time (tc) is 0.65 minutes, the calculation for the number of operators would be as follows:

$$Ni=ti/tc$$

$$Ni=2.5/0.8=3.84$$

In this scenario, only three operators would be assigned to the workstation, ensuring efficiency without unnecessary resource use.

Following the capacity analysis, the ranked positional weight algorithm is employed to optimize task distribution based on dependency relationships and the calculated "position weight" of each task. This method ensures optimal assignments to workstations and incorporates the following components:

(1) Position Weight Calculation:

The position weight (Wi) for each task is determined by summing the unassigned duration of the task and the unassigned durations of its dependent subsequent tasks:

$$\text{Wi=(Unassigned duration of the task+ sum of unassigned durations of subsequent dependent tasks)} \tag{7}$$

The position-weighted assembly line balancing method prioritizes tasks according to their position weights, assigning the task with the highest position weight first. At each step, the unassigned task with the highest position weight is assigned to the next available workstation. This assignment continues for tasks that meet specified conditions, effectively balancing the assembly line by considering both the position weights of tasks and their dependency relationships [38].

Several critical steps govern this process:

i. All tasks on the assembly line must be assigned to workstations, each assigned to only one workstation.
ii. The total durations of tasks assigned to each workstation must not exceed the cycle time, thereby determining the minimum number of workstations based on the factory's daily working hours.
iii. For a task to be assigned to a workstation, all prior tasks must be assigned to either a previous or the same workstation, ensuring a smooth and continuous workflow.

(2) Task Assignment Using the Ranked Positional Weight Algorithm:

After implementing the ranked positional weight algorithm, the task assignment phase begins. In this stage, tasks with higher position weights are prioritized for assignment, ensuring that allocations are made based on their sequential importance. The software algorithm employs the parallel station position weight method to minimize the unassigned durations of tasks according to their designated position weights.

This optimization algorithm considers the priorities, capacities, and positions of specific tasks and workstations, effectively enhancing productivity. By reducing unassigned durations, the algorithm ensures a more efficient distribution of tasks across workstations, optimizing their utilization. This approach mitigates potential imbalances along the assembly line and streamlines workflows, resulting in improved overall operational efficiency.

The strategic application of specific position weights within this method enables a more calculated allocation of tasks. By emphasizing the positions of workstations, the algorithm aims to achieve a balanced process, optimizing task durations while maintaining harmony throughout the production line.

3.3. Verification Process

Verification is a critical element of the theoretical framework that ensures the developed software algorithm and data collection methods produce accurate and reliable outcomes. This process encompasses rigorously validating the effectiveness of the algorithm through empirical testing and performance analysis. Key operational metrics, such as line efficiency, balance delay, and labour productivity, are meticulously compared before and after the implementation of the algorithm [39,40].

Line Efficiency: This crucial metric gauges the overall effectiveness of the sewing line within the defined cycle time (Takt time). High line efficiency is indicative of well-balanced workstations and adherence to operational standards, directly contributing to improved productivity. The formula for calculating line efficiency is as follows:

$$\textit{Line Efficiency}(\%) = (\textit{Sum of actual task times})/((N \times tc)) \qquad (8)$$

– The sum of actual task times represents the total time spent on task completion, measured in minutes, based on the performance of work elements. These data are essential for assessing resource utilization efficiency.
– tc represents the cycle takt time, a critical component that ensures production aligns with customer demand.
– N denotes the total number of stations (operators) calculated after the balancing process, emphasizing the algorithm's impact on workforce distribution.

By optimizing line efficiency, organizations can minimize waste and ensure that each operator effectively contributes to the production process, thereby promoting a culture of continuous improvement.

Balance Delay: This metric quantifies the deviation from an ideally balanced state, highlighting any workload imbalances between workstations. A lower balance delay signifies a more equitable distribution of tasks among operators, thereby enhancing overall efficiency. The formula for balance delay is expressed as:

$$\textit{Balance Delay}(\%) = ((N \times tc - \textit{Sum of actual task time}))/((N \times tc)) \qquad (9)$$

By minimizing balance delay, companies can streamline operations, reduce stress at specific workstations, and promote a more harmonious work environment.

Smoothness Index: The smoothness index serves as an important reflection of workload distribution across workstations. A lower smoothness index is indicative of a more balanced production flow, which is essential for minimizing disruptions in the manufacturing process. The formula for calculating the smoothness index is as follows:

$$\textit{Smoothness Index}\ (\%) = \frac{\sqrt{\sum_{i=1}^{n}(tc - ti)^2}}{tc \times N} \qquad (10)$$

Labour Productivity: This metric evaluates the average production output per operator, serving as a key indicator of workforce productivity. A higher output per person suggests more efficient use of labour resources and better task allocation. The formula for calculating production output per person is as follows:

$$\textit{Labour productivity} = (\textit{Total Production Quantity})/N \qquad (11)$$

Where: The total production quantity is the total number of units produced during a specific period. N is the total number of operators working during that period.

4. Research Study

This experimental study was conducted in a large-scale apparel factory in Turkey, which had been operating for 20 years and specializes in high-quality knitted garments for export to Europe. The facility had previously been examined in studies on lean production and digitization, reflecting a strong awareness of these concepts among floor managers. The main objective of this study was to develop a software-based methodology to optimize the sewing line for producing the 'D6250 trouser model, illustrated in Figure 4 .

Table 1 provides comprehensive details on the sewing work elements, outlining the specific task sequences involved, the types of machinery employed for each task, and their associated standard times. This information is essential for understanding the production workflow and identifying areas for potential optimization in the sewing process.

To enhance understanding of the operational flow, Figure 5 presents a workflow diagram that aligns with the established task sequence. This diagram visually represents the progression of tasks within the sewing process, highlighting the relationships and dependencies among various work elements. By outlining the workflow, stakeholders can better grasp how each task contributes to the overall production system, facilitating the identification of areas for improvement and optimization.

Task Number	Operation	Machine	SMV (min)
1	Belt Ironing	Ironing Board	0.296
2	Elastic Joining	Elastic Feeding	0.206
3	Belt Elastic Marking	Manual	0.264
4	Elastic Holding	Flatlock	0.560
5	Belt Joining	Lockstitch	0.294
6	Belt Closing	Flatlock	0.496
7	Cuff Ribbing Attachment	Lockstitch	0.698
8	Front Panel Attachment	Lockstitch	0.480
9	Front Seam Joining (x2)	Lockstitch	0.599
10	Back Panel Joining	Lockstitch	0.555
11	Inner Seam Joining	Lockstitch	0.867
12	Belt Attachment + Thread Cleaning	Overlock	0.618
13	Belt Cuff	Coverstitch	0.591
14	Hem Bartack (x2) + Thread Cleaning	Bartack	0.345
15	Label Attachment	Flatlock	0.315
16	Label Removal (x9) + Turning & Stacking	Manual	0.309
17	First Control	Manual	0.505
18	Ironing	Ironing Board	0.587
19	Quality Control	Manual	0.606

Table 1. Sewing Work Elements, Machine Types, and Standard Minute Values for the D6250 Trousers

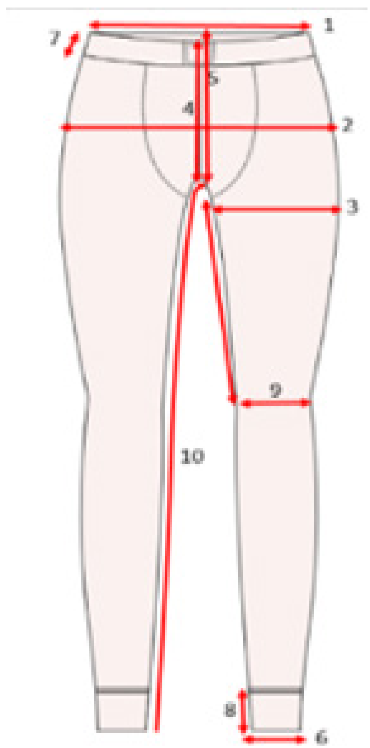


Fig. 4. Image of the D6250 Ladies' Trouser Model

In this study, the parallel station position weighted line balancing method was employed to enhance the efficiency of the sewing line. This method analyzes workstations with fixed capacities derived from cycle times and optimizes unallocated operational times utilizing a position-weighted balancing technique. After establishing the daily target quantity, illustrated in Figure 6, the cycle time necessary for effectively balancing the line is computed. This process ensures that each workstation is aligned with production goals, facilitating a smoother workflow and maximizing output while minimizing idle time.

By clicking the "Calculate" button, the system computes the required number of operators for each task (Ni) by dividing the task duration (ti) by the cycle time (tc). This calculation helps to determine the optimal allocation of resources needed to meet production goals. After completing the calculations, users can save the results by selecting the "Save" option. The detailed capacity calculations for each operation, including the number of operators required and their respective task durations, are summarized in Table 2.

Following this step, users proceed to the "Detail Page" option within the software. The fault-balancing module of the software dynamically adjusts to real-time conditions in the manufacturing environment by leveraging performance data collected for job elements within designated time frames. Updated standard minute values (SMV) are computed by factoring in the performance efficiency of each job element. For instance, consider the job element "ironing belt," which has a standard time of 0.296 minutes and an average performance value of 63%. Through proportional analysis, the actual task time for this element is determined to be 0.470 minutes.

Operator assignments are established by taking the integer part of the calculated operator number required for each job element. Specifically, if the required number of operators for element 1 (N1) is 0.751, then no operator will be assigned (Na1). Conversely, if the required operator number for element 7 (N7) is calculated to be 1.484, one operator will be assigned (Na7). A detailed breakdown of these calculations is presented in Table 3, which clarifies the process of deriving operator assignments from the performance data.

The software presents unallocated durations for each job element, serving as a foundation for further optimization through the use of positional weights. In the interface depicted in Figure 7, users can input the priority rankings of operations, unallocated times, and relational dependencies among tasks. Once this information is entered, the progress icon activates the ranked positional weight (RPW) calculation method. This method effectively assigns job elements by prioritizing those with the highest positional weight, ensuring that critical tasks are completed first. The positional weight for each element is determined by considering both its task duration and the remaining durations of subsequent tasks.

The ranked positional weight (RPW) method organizes job elements based on their positional weights, beginning with those that possess the highest values. Unassigned tasks are systematically assigned to the next available workstation, ensuring optimal resource

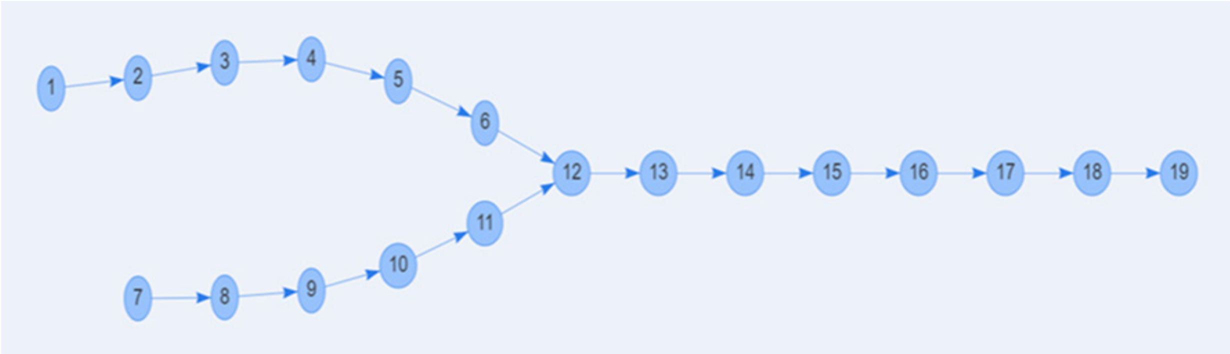


Fig. 5. Sewing Process Workflow Chart for the D6250 Trousers

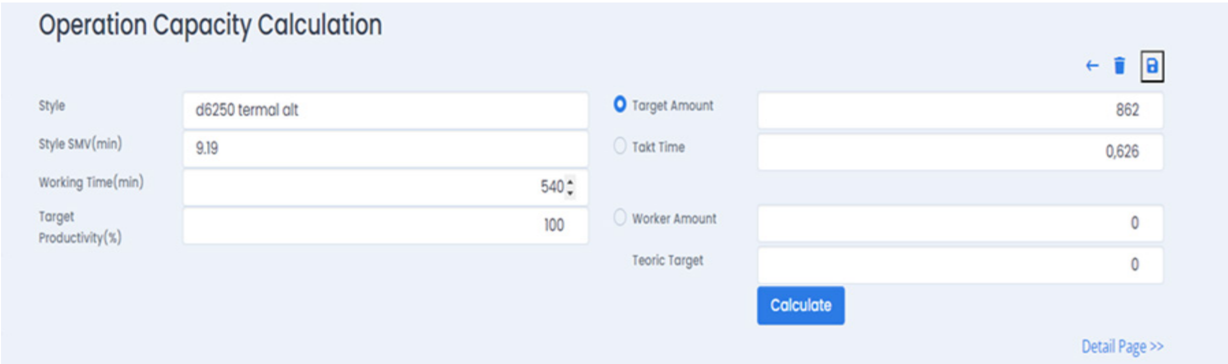


Fig. 6. Software Algorithm Optimization Interface

Task Number	Operation	Machine	SMV (min.)	Hourly Amount	Capacity (Employee/ Machine)	Working Hours
1	Belt Ironing	Ironing Board	0.296	202.70	0.47	4.23
2	Elastic Joining	Elastic Feeding	0.206	291.26	0.33	2.97
3	Belt Elastic Marking	Manual	0.264	227.27	0.42	3.78
4	Elastic Holding	Flatlock	0.560	107.14	0.89	8.01
5	Belt Joining	Lockstitch	0.294	204.08	0.47	4.23
6	Belt Closing	Flatlock	0.496	120.97	0.79	7.11
7	Cuff Ribbing Attachment	Lockstitch	0.698	85.96	1.11	9.99
8	Front Panel Attachment	Lockstitch	0.480	125.00	0.77	6.93
9	Front Seam Joining (x2)	Lockstitch	0.599	100.17	0.96	8.64
10	Back Panel Joining	Lockstitch	0.555	108.11	0.89	8.01
11	Inner Seam Joining	Lockstitch	0.867	69.20	1.38	12.42
12	Belt Attachment + Thread Cleaning	Overlock	0.618	97.09	0.99	8.91
13	Belt Cuff	Coverstitch	0.591	101.52	0.94	8.46
14	Hem Bartack (x2) + Thread Cleaning	Bartack	0.345	173.91	0.55	4.95
15	Label Attachment	Flatlock	0.315	190.48	0.50	4.50
16	Label Removal (x9) + Turning & Stacking	Manual	0.309	194.17	0.49	4.41
17	First Control	Manual	0.505	118.81	0.81	7.29
18	Ironing	Ironing Board	0.587	102.21	0.94	8.46
19	Quality Control	Manual	0.606	99.01	0.97	8.73

Table 2. Capacity Calculations Based on Task Durations of Work Elements for the D6250 Trousers Model

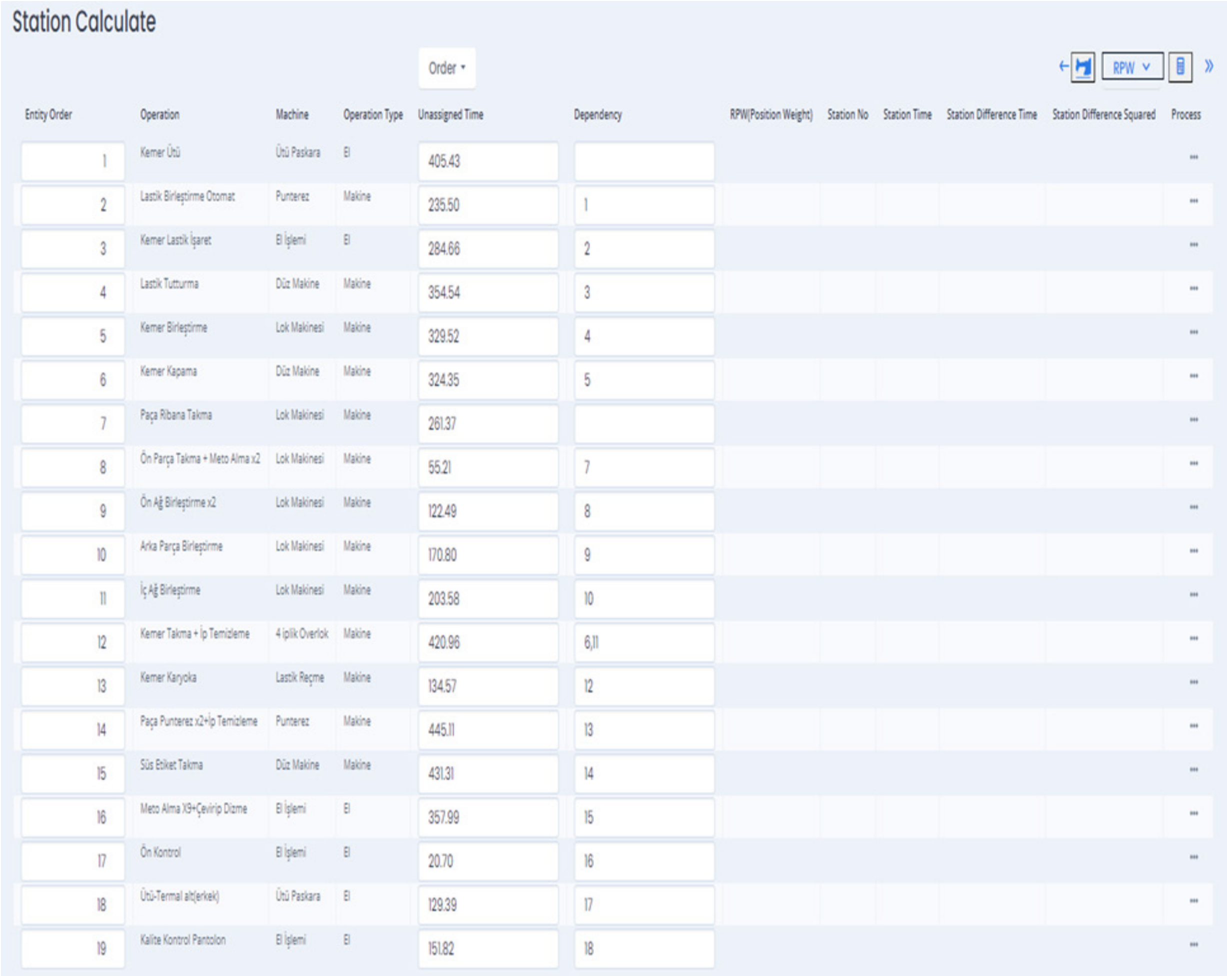
Task Number	Operation	Machine	SMV (min.)	Performance %	Actual SMV (min.)	Takt Time (min.)	Required Operator	Assigned Operator	Leap Operator	Unassigned Time (min.)
1	Belt Ironing	Ironing Board	0.296	63.00	0.470	0.626	0.751	0	0.751	405.43
2	Elastic Joining	Elastic Feeding	0.206	75.00	0.273	0.626	0.436	0	0.436	235.50
3	Belt Elastic Marking	Manual	0.264	80.00	0.330	0.626	0.527	0	0.527	284.66
4	Elastic Holding	Flatlock	0.560	54.00	1.037	0.626	1.657	1	0.657	354.54
5	Belt Joining	Lockstitch	0.294	77.00	0.382	0.626	0.610	0	0.610	329.52
6	Belt Closing	Flatlock	0.496	50.00	1.002	0.626	1.601	1	0.601	324.35
7	Cuff Ribbing Attachment	Lockstitch	0.698	75.00	0.929	0.626	1.484	1	0.484	261.37
8	Front Panel Attachment	Lockstitch	0.480	70.00	0.690	0.626	1.102	1	0.102	55.21
9	Front Seam Joining (x2)	Lockstitch	0.599	78.00	0.768	0.626	1.227	1	0.227	122.49
10	Back Panel Joining	Lockstitch	0.555	67.00	0.824	0.626	1.316	1	0.316	170.80
11	Inner Seam Joining	Lockstitch	0.867	101.00	0.862	0.626	1.377	1	0.377	203.58
12	Belt Attachment	Overlock	0.618	56.00	1.114	0.626	1.780	1	0.780	420.96
13	Belt Cuff	Coverstitch	0.591	76.00	0.782	0.626	1.249	1	0.249	134.57
14	Hem Bar Tack (x2)	Bar Tack	0.345	30.00	1.142	0.626	1.824	1	0.824	445.11
15	Label Attachment	Flatlock	0.315	63.00	0.500	0.626	0.799	0	0.799	431.31
16	Label Removal (x9)	Manual	0.309	75.00	0.415	0.626	0.663	0	0.663	357.99
17	First Control	Manual	0.505	78.00	0.650	0.626	1.038	1	0.038	20.70
18	Ironing	Ironing Board	0.587	76.00	0.776	0.626	1.240	1	0.240	129.39
19	Final Control	Manual	0.606	42.00	1.428	0.626	2.281	2	0.281	151.82

Table 3. Capacity Algorithm Application Based on the Cycle Takt Time for the D6250 Trousers Model

allocation throughout the production line. This approach enhances line balancing by taking into account task dependencies and priorities, which facilitates more efficient operation assignments. By effectively managing these elements, the RPW method contributes to smoother workflows and increased productivity. Detailed calculations that support this methodology are illustrated in Figure 8, providing a clear overview of the prioritization and allocation process.

Upon completing the analysis, users can view the Line Optimization results and Yamazumi charts by clicking the "OK" icon located next to the "List" label in the digital line balancing program, as illustrated in Figure 9. This feature allows users to easily access and review the outcomes of their optimizations, providing valuable visual insights into line efficiency and workload distribution. The Yamazumi charts explicitly display task durations and the allocation of resources, facilitating a comprehensive understanding of the production line's performance and areas for further improvement. The Yamazumi philosophy emphasizes achieving balance and efficiency in process structuring, which helps optimize workflows, improve workforce allocation, and enhance overall process efficiency [41]. The outcomes derived from these calculations are visually represented in Figure 10, showcasing the effectiveness of the implemented optimization strategies. This visual representation supports informed decision-making and strategic adjustments to the manufacturing process.

Upon finalizing the process, there is a detailed overview of assigned operators in conjunction with station data shown in Table 4. This table strategically outlines the allocation of operators to various stations, considering their prior tasks, machine operating skills, and individual performance metrics. By harnessing data-driven insights, each assignment is thoughtfully designed to enhance operational efficiency and ensure optimal performance on the production line. The table includes task durations for each station after optimization,


Station Calculate

Order

RPW

Entity Order	Operation	Machine	Operation Type	Unassigned Time	Dependency	RPW(Position Weight)	Station No	Station Time	Station Difference Time	Station Difference Squared	Process
1	Kemer Ütü	Ütü Paskara	El	405.43							...
2	Lastik Birleştirme Otomat	Punterez	Makine	235.50	1						...
3	Kemer Lastik İşaret	El İşlemi	El	284.66	2						...
4	Lastik Tutturma	Düz Makine	Makine	354.54	3						...
5	Kemer Birleştirme	Lok Makinesi	Makine	329.52	4						...
6	Kemer Kapama	Düz Makine	Makine	324.35	5						...
7	Paça Ribana Takma	Lok Makinesi	Makine	261.37							...
8	Ön Parça Takma + Meto Alma x2	Lok Makinesi	Makine	55.21	7						...
9	Ön Ağ Birleştirme x2	Lok Makinesi	Makine	122.49	8						...
10	Arka Parça Birleştirme	Lok Makinesi	Makine	170.80	9						...
11	İç Ağ Birleştirme	Lok Makinesi	Makine	203.58	10						...
12	Kemer Takma + İp Temizleme	4 iplik Overlok	Makine	420.96	6,11						...
13	Kemer Karyoka	Lastik Reçme	Makine	134.57	12						...
14	Paça Punterez x2+İp Temizleme	Punterez	Makine	445.11	13						...
15	Süs Etiket Takma	Düz Makine	Makine	431.31	14						...
16	Meto Alma X9+Çevirip Dizme	El İşlemi	El	357.99	15						...
17	Ön Kontrol	El İşlemi	El	20.70	16						...
18	Ütü-Termal alt(erkek)	Ütü Paskara	El	129.39	17						...
19	Kalite Kontrol Pantolon	El İşlemi	El	151.82	18						...

Fig. 7. Operation Priority and Dependency Input Screen for Ranked Positional Weight (RPW) Calculation

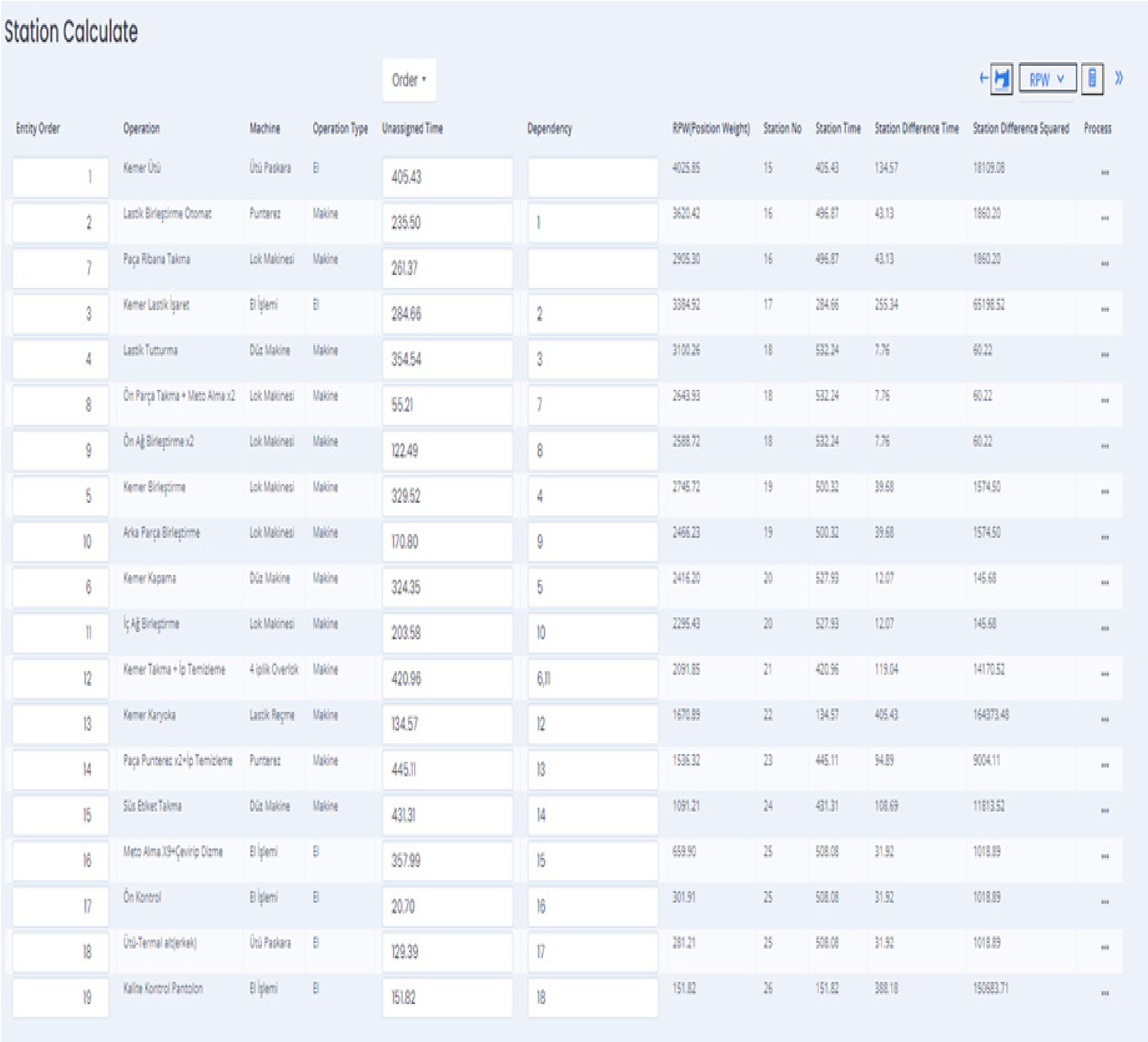
as well as the specific or multiple tasks designated to each operator. This structured methodology not only promotes an efficient workflow but also equips managers with the information necessary to make informed decisions that foster continuous improvement in the production environment.

Finally, Figure 11 offers a detailed visual representation of the total operation durations assigned to each workstation. These graphical analyses are crucial for evaluating the performance and efficiency of the line-balancing process, facilitating the swift identification of any potential inefficiencies. The red columns indicate the stations where Kaizen initiatives will be implemented. By providing clear insights into operational dynamics, these visuals empower floor managers to take timely corrective actions, thereby fostering a culture of continuous improvement and striving for operational excellence. Such insights not only aid in optimizing current workflows but also inform future planning and resource allocation strategies, ultimately enhancing overall productivity and effectiveness in the manufacturing environment.

5. Result and Discussions

The assembly layout for the D6250 women's trouser model, shown in Figure 12, provides a visual representation of the existing configuration of the sewing line. This layout serves as an essential reference point for assessing operational performance and identifying areas for potential improvements. By analyzing the current arrangement of workstations and workflow, floor managers can pinpoint bottlenecks and inefficiencies, allowing for targeted adjustments that enhance the overall effectiveness of the production process. This baseline configuration is crucial for measuring the impact of any subsequent optimizations or changes made to the sewing line.

Optimizations can lead to substantial enhancements in manufacturing operations. By offering a comprehensive comparison of metrics, Table 5 illustrates not only the effectiveness of the applied algorithm but also emphasizes the importance of data-driven decision-making in the optimization process. The increases observed in production output and line efficiency reflect an improved utilization of resources and personnel, suggesting that the algorithm successfully streamlined workflows. Furthermore, this analysis lays the groundwork for continuous improvement initiatives, enabling the organization to adapt to changing demands and maintain



Station Calculate

Entity Order	Operation	Machine	Operation Type	Unassigned Time	Dependency	RPW(Position Weight)	Station No	Station Time	Station Difference Time	Station Difference Squared	Process
1	Kemer Ütü	Ütü Paskara	El	405.43		4025.85	15	405.43	134.57	18109.08	...
2	Lastik Birleştirme Otomat	Punteriz	Makine	235.50	1	3620.42	16	496.87	43.13	1860.20	...
7	Paça Ribana Takma	Lok Makinesi	Makine	261.37		2905.30	16	496.87	43.13	1860.20	...
3	Kemer Lastik İşaret	El İşlemi	El	284.66	2	3384.92	17	284.66	255.34	65198.52	...
4	Lastik Tutturma	Düz Makine	Makine	354.54	3	3100.26	18	532.24	7.76	60.22	...
8	Ön Parça Takma + Meto Alma x2	Lok Makinesi	Makine	55.21	7	2643.93	18	532.24	7.76	60.22	...
9	Ön Ağ Birleştirme x2	Lok Makinesi	Makine	122.49	8	2588.72	18	532.24	7.76	60.22	...
5	Kemer Birleştirme	Lok Makinesi	Makine	329.52	4	2745.72	19	500.32	39.68	1574.50	...
10	Arka Parça Birleştirme	Lok Makinesi	Makine	170.80	9	2466.23	19	500.32	39.68	1574.50	...
6	Kemer Kapama	Düz Makine	Makine	324.35	5	2416.20	20	527.93	12.07	145.68	...
11	İç Ağ Birleştirme	Lok Makinesi	Makine	203.58	10	2295.43	20	527.93	12.07	145.68	...
12	Kemer Takma + İp Temizleme	4 iplik Overlok	Makine	420.96	6,11	2091.85	21	420.96	119.04	14170.52	...
13	Kemer Karyoka	Lastik Reçme	Makine	134.57	12	1670.89	22	134.57	405.43	164373.48	...
14	Paça Punteriz x2+İp Temizleme	Punteriz	Makine	445.11	13	1536.32	23	445.11	94.89	9004.11	...
15	Süs Etiket Takma	Düz Makine	Makine	431.31	14	1091.21	24	431.31	108.69	11813.52	...
16	Meto Alma X9+Çevirip Dizme	El İşlemi	El	357.99	15	659.90	25	508.08	31.92	1018.89	...
17	Ön Kontrol	El İşlemi	El	20.70	16	301.91	25	508.08	31.92	1018.89	...
18	Ütü-Termal alt(erkek)	Ütü Paskara	El	129.39	17	281.21	25	508.08	31.92	1018.89	...
19	Kalite Kontrol Pantolon	El İşlemi	El	151.82	18	151.82	26	151.82	388.18	150683.71	...

Fig. 8. Calculation of the Ranked Positional Weight (RPW) Method for Optimizing Operation Assignments

Fig. 9. Screen Displaying Optimization Result Values

a competitive edge in the industry. Overall, the findings underscore the critical role of strategic optimizations in driving operational success and ensuring sustainable growth.

The results demonstrate that the optimization algorithm significantly improved operator efficiency in comparison to traditional methods while effectively reducing imbalances along the production line. Key findings from this study include the following:

1) *Substantial Increase in Line Efficiency*: The optimization algorithm achieved an 8.63%

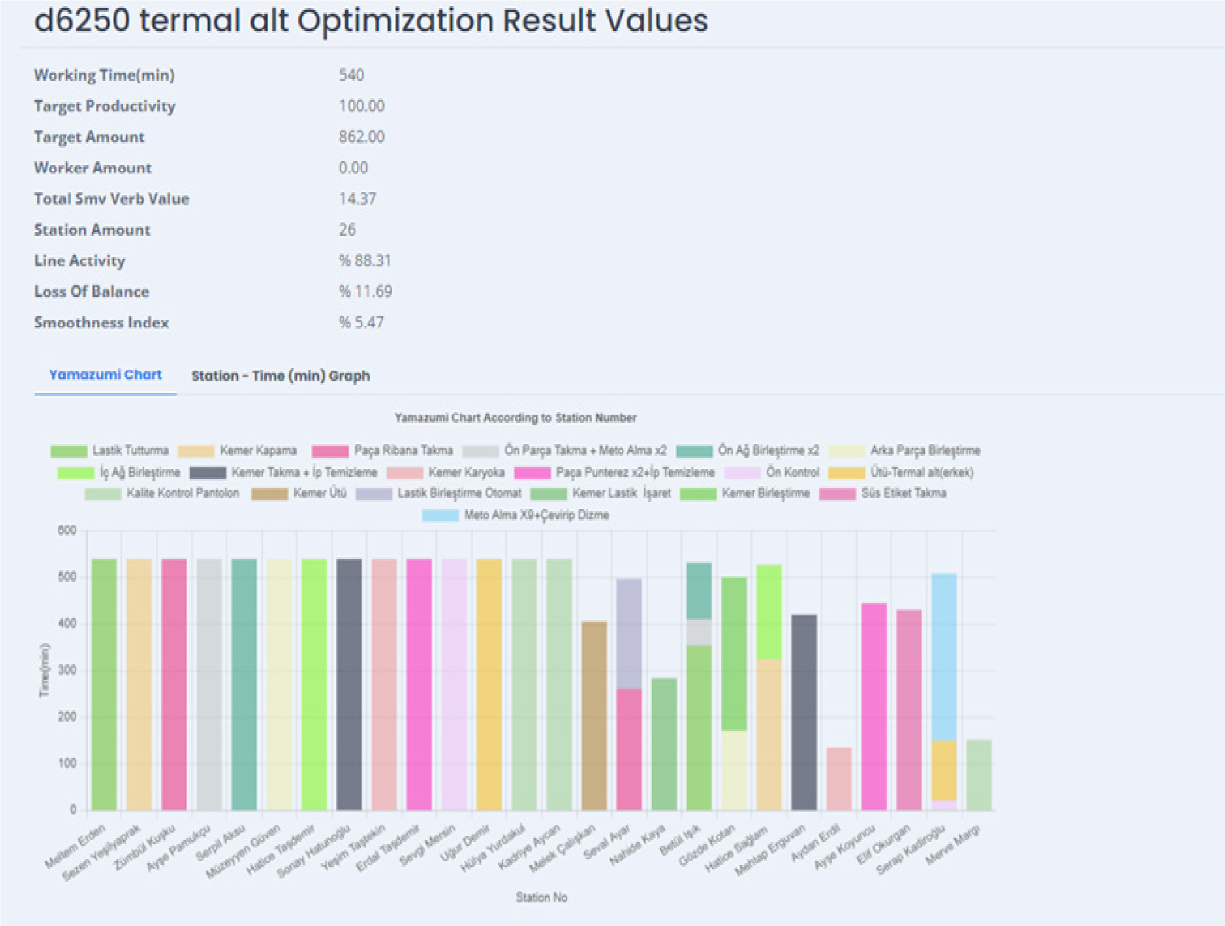


Fig. 10. Access Interface for Line Optimization Results and Yamazumi Chart in the Digital Line Balancing Program

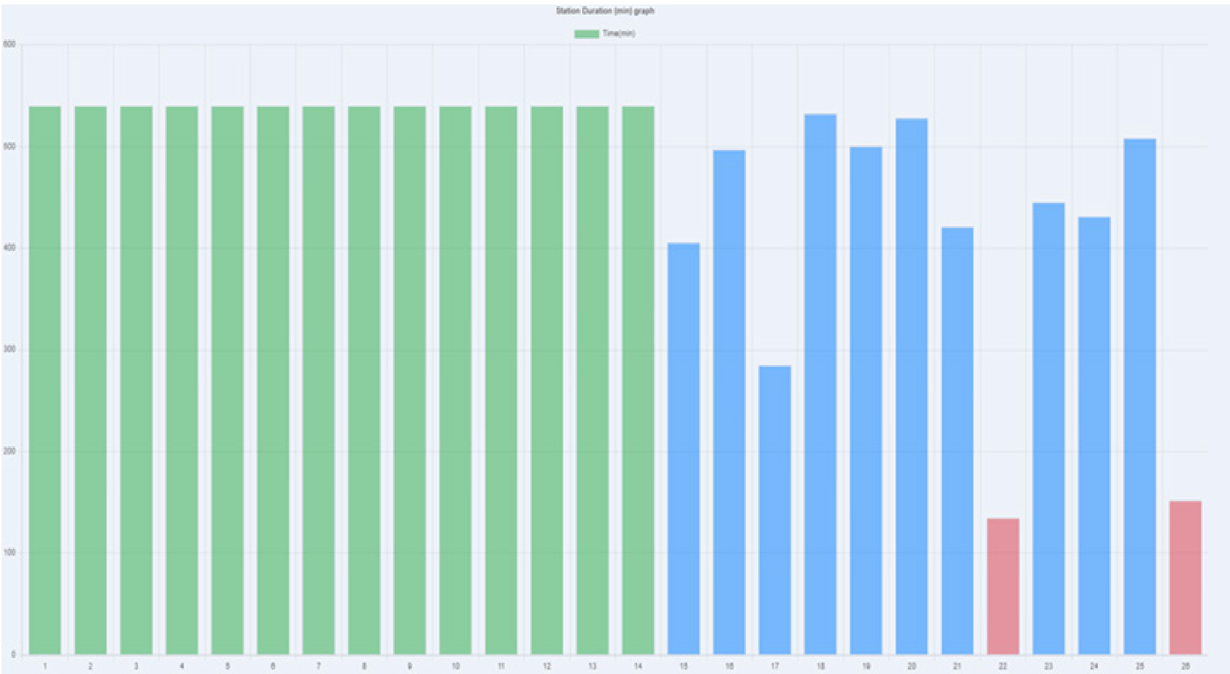


Fig. 11. Total Durations of Operations Assigned to Workstations

Task	Station Number	Operation	Machine	Operator	Station Time (min)
1	15	Belt Ironing Ironing Board	Ironing Board	M.C.	405.43
2	16	Elastic Joining	Elastic Feeding	S.A.	235.5
3	17	Belt Elastic Marking	Manual	N.K	284.66
4	1	Elastic Holding	Flatlock	M.E	540
4	18	Elastic Holding	Flatlock	B.I	354.54
5	19	Belt Joining	Lochstitch	G.K	329.52
6	2	Belt Closing	Flatlock	S.Y	540
6	20	Belt Closing	Flatlock	H.S	324.35
7	3	Cuff Ribbing Attachment	Lockstitch	Z.K	540
7	16	Cuff Ribbing Attachment	Lockstitch	S.A.	261.37
8	4	Front Panel Attach+ Label Removal	Lockstitch	AY.P.	540
8	18	Front Panel Attach+ Label Removal	Lockstitch	B.I	55.21
9	5	Front Seam Joiningx2	Lockstitch	SE.A.	540
9	18	Front Seam Joiningx2	Lockstitch	B.I	122.49
10	6	Back Panel Joining	Lockstitch	M.G	540
10	19	Back Panel Joining	Lockstitch	G.K	170.8
11	7	Inner Seam Joining	Lockstitch	H.T	540
11	20	Inner Seam Joining	Lockstitch	H.S	203.58
12	8	Belt Attachment + Thread Cleaning	Overlock	S.H	540
12	21	Belt Attachment + Thread Cleaning	Overlock	MH.E.	420.96
13	9	Belt Cuff Coverstitch	Coverstitch	Y.T	540
13	22	Belt Cuff Coverstitch	Coverstitch	AY.E.	134.57
14	10	Hem Bartack x2 + Thread Cleaning	Bartack	ER.T	540
14	23	Hem Bartack x2 + Thread Cleaning	Bartack	AY.K	445.11
15	24	Decorative Label Attachment	Flatlock	EL.O.	431.31
16	25	Label Removal X9 + Turning and Stacking	Manual	SE.K.	357.99
17	11	First Control	Manual	SV.M.	540
17	25	First Control	Manual	SE.K.	20.7
18	12	Ironing	Ironing Board	UG.D.	540
18	25	Ironing	Ironing Board	SE.K.	129.39
19	13	Fınal Control	Manual	HU.Y.	540
19	14	Fınal Control	Manual	KA.A.	540
19	26	Fınal Control	Manual	ME.M	151.82

Table 4. Task Times for Assigned Operators and Workstations

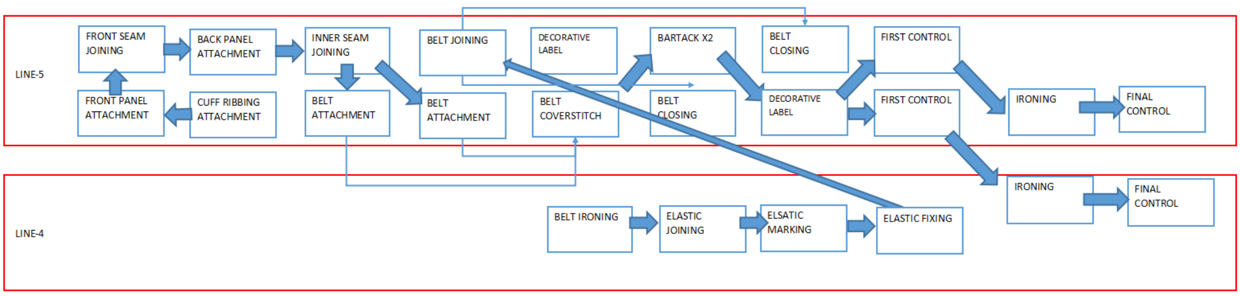


Fig. 12. Current Sewing Line Layout for the D6250 Trouser Model

Operational Metric	Before Optimization	After Optimization	Difference	Percentage Change
Daily Production Quantity	718 pieces	862 pieces	+144 pieces	+20.06%
Daily Working Time	540 minutes	540 minutes		
Total Actual Standard Time	14.37 minutes	14.37 minutes		
Line Efficiency	79.68%	88.31%	+8.63%	+10.83%
Number of Current Operators	24 employees	26 employees	+2 people	+8.33%
Labour Productivity	30 pieces	33 pieces	+3 pieces	+10%

Table 5. Comparative Analysis of Key Production Metrics Before and After Optimization

improvement in line efficiency. By optimizing workload distribution across the production line, operator performance markedly increased, resulting in more effective resource utilization and a smoother, more balanced workflow.

2) *Increased Labour Productivity*: The optimization led to a 10% increase in production per operator, illustrating the positive impact of more efficient workload management. This enhancement indicates that each operator could contribute more effectively to the overall production process, boosting productivity without incurring additional labour costs.
3) *Adaptive Workforce Management*: The slight increase in the number of operators from 24 to 26 reflects the optimization process's flexibility in addressing changing production needs. This adjustment facilitated the achievement of higher production targets while maintaining a balanced workflow. Such adaptability is crucial for sustaining efficiency in dynamic production environments.

Further analysis of workstation times, shown in Figure 11, highlighted areas for potential improvement through Kaizen principles. Specifically, workstations 22 and 26 (marked in red) present opportunities for task reassignment, enabling a single operator to manage both stations. This adjustment could reduce the total number of operators to 25 while still meeting production targets, illustrating the continuous improvement potential within the production process.

The findings from this study demonstrate the significant impact of the optimization algorithm on both production line efficiency and operational performance. By aligning workflow strategies with lean manufacturing principles, the system was able to achieve higher productivity while minimizing waste. The identification of additional improvement opportunities, particularly through Kaizen, suggests the potential for ongoing refinements that can further enhance production flexibility and responsiveness.

Overall, the results emphasize the importance of integrating digital tools and methodologies into traditional manufacturing processes. Optimization algorithms provide immediate efficiency gains while promoting a culture of continuous improvement. In the apparel manufacturing sector, characterized by demand fluctuations and rapid market changes, agility and ongoing process enhancement are vital for sustaining a competitive advantage.

6. Conclusion

This study highlights the transformative potential of digitalization in optimizing sewing line-balancing processes. Organizations embracing digital technologies can achieve substantial reductions in operational costs while simultaneously enhancing production flexibility and cultivating a more responsive manufacturing environment [42]. Within the framework of lean production systems, fostering employee engagement and developing multi-skilled operators are essential drivers of operational improvement. Unlike many other industries, sewing line balancing relies heavily on operator-managed workstations, underscoring the critical need for a workforce proficient in operating multiple machines [43]. Rotational training and comprehensive skill development programs are vital to achieving these objectives [44]. Floor managers play a pivotal role in this process by actively promoting operator flexibility and supporting the acquisition of cross-functional skills aligned with lean production principles. This strategic approach not only elevates operational capabilities but also fosters a culture of collaboration and problem-solving within production teams.

Future research should prioritize the integration of advanced simulation applications to enhance the algorithm's capacity for optimizing workflows. By simulating various production scenarios, organizations can better assess algorithm performance, identify potential bottlenecks, and implement proactive improvements [45]. These simulation-based evaluations refine task prioritization and enable more flexible and efficient workflow adjustments. Moreover, integrating real-time data from process monitoring devices (PMD) with simulation tools will allow algorithms to dynamically adjust workflows based on actual performance data. This system can simulate various corrective actions and select the most appropriate options, thereby improving both efficiency and responsiveness.

Another key area for improvement is the strategic recruitment and development of operator profiles. By defining the optimal skill sets required for high line efficiency, organizations can enhance their hiring practices and attract candidates with the necessary competencies. Additionally, digital sewing line balancing systems designed from a lean perspective have the potential to reduce downtime caused by model changes through real-time production data analysis. This capability supports timely decision-making and improves product quality by enhancing first-pass accuracy.

The synergy between lean-based digitalization and real-time production management equips garment manufacturers with the agility needed to respond swiftly to fluctuating customer demand. This combination not only provides a competitive advantage but also ensures sustainable success in dynamic market conditions. The digital tools and methodologies explored in this study, particularly the optimization algorithm, significantly contribute to improving business operations by enabling real-time data collection and analysis. Furthermore, the integration of production monitoring devices (PMD) enhances competitiveness through rapid interventions, optimized maintenance schedules, and improved operational efficiency [46].

This study's exploration of a digitally-driven sewing line layout characterized by strategically positioned workstations operating in concert with optimized workflows reveals promising avenues for future research in production management. This innovative approach, underpinned by digital line balancing techniques, has demonstrated the potential to significantly enhance the effectiveness and efficiency of industrial processes. The organizational improvements and workstation optimizations identified through this research provide a solid foundation for further investigation into refining and elevating industrial processes across a range of manufacturing sectors.

In conclusion, the successful implementation of digital transformation strategies and lean production methodologies significantly enhances the efficiency of sewing line processes, offering businesses sustainable competitive advantages. As the apparel industry continues to evolve, future studies concentrating on the practical application of these digital and process-oriented improvements will contribute to a broader transformation in manufacturing practices. By leveraging these strategic advantages, organizations can confidently navigate the complexities of the industry landscape, foster innovation, and continuously refine their operational processes to achieve greater efficiency.

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Ethical Compliance

The research related to human use complies with all the relevant national regulations, institutional policies is in accordance with the tenets of the Helsinki Declaration, and has been approved by the author's institutional review board or an equivalent committee.

Declaration of Conflicting Interests

The author(s) declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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