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Improving Production Efficiency of NC-212 Aircraft Outer Wing Assembly Using Value Stream Mapping and Kaizen Approach

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ABSTRACT

Manual aircraft wing assembly is characterized by long lead times, process variability, and waste that reduce production efficiency. This study aims to improve the NC-212 Outer Wing Left-Hand (LH) assembly process by applying lean manufacturing through Value Stream Mapping (VSM), root-cause analysis, and Kaizen-based improvements. Primary data were collected through direct observations, time studies, and interviews across 12 assembly stations. The current-state analysis identified waiting due to pending parts, unnecessary transportation, defects, and manpower imbalance as the dominant sources of waste. Based on Five-Whys and 5W+1H analyses, improvement strategies and takt time-based workforce allocation were developed to optimize production flow. The proposed future state reduced assembly lead time from 75 to 59 working days (21.3%) and increased average labor utilization to 96.16% through workload balancing and reduced idle time. The main contribution of this study is the application of VSM-based lean improvement integrated with takt time-based manpower scheduling for a high-mix, low-volume aerospace assembly environment. The proposed framework provides practical guidance for improving workflow synchronization and supporting continuous improvement in aircraft manufacturing systems.

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1. Introduction

The manufacturing industry plays a pivotal role in driving national economic growth, particularly in emerging economies such as Indonesia. In 2017-2023, the manufacturing sector contributed 18.67% to the national Gross Domestic Product (GDP), reaffirming its position as one of the primary pillars of economic development (Statista, 2025). Beyond its macroeconomic contribution, the manufacturing sector is essential for strengthening industrial resilience, expanding employment, and increasing global competitiveness (Logesh & Balaji, 2021). As global competition intensifies, manufacturing companies are required to continuously improve their operational performance, particularly in terms of product quality, production flexibility, efficiency, and lead time reduction (Purnama et al., 2023).

In this situation, the implementation of an effective and efficient production system becomes crucial, especially in high-complexity industries such as aerospace manufacturing. Aircraft production

requires high precision, strict quality control, long process chains, and synchronization across multiple departments. These characteristics make the aircraft manufacturing process particularly vulnerable to waste, such as defects, delays, excessive transportation, and inefficient workflow, which can significantly increase production lead time and reduce reliability. Therefore, improving process efficiency and minimizing non-value-added activities are critical for maintaining competitiveness and ensuring timely product delivery. Lean manufacturing provides a systematic approach for identifying and eliminating waste throughout the production process (Agustin & Ernawati, 2025; Aucasime-Gonzales et al., 2020; Basiru et al., 2023; Kaukonen, 2025; Lee et al., 2025).

Extensive research has shown the effectiveness of lean manufacturing tools in improving productivity across various industrial settings. For example, Aucasime-Gonzales et al. (2020) reported a 13% improvement in Overall Equipment Effectiveness (OEE) and a 22.5% reduction in setup time in a tire manufacturing company. Lean tools have also been used to reduce waste in electrical component manufacturing Chaudhary et al. (2020), while Alfiansyah & Kurniati (2018) applied the Waste Assessment Model (WAM) to identify critical sources of inefficiencies in glove production. Rahman (2021) applied lean-based analysis and reported major wastes in defects (16.49%), transportation (16.36%), and processing (14.82%). Across these studies, Value Stream Mapping (VSM) consistently emerges as a key tool for visualizing workflow, quantifying value-added and non-value-added activities, and identifying improvement opportunities (Ahmad et al., 2022; Wang et al., 2024).

However, despite the widespread adoption of lean manufacturing in various industrial sectors, its application in aerospace manufacturing remains limited. Previous studies have primarily focused on mass-production or semi-automated industries, whereas empirical investigations in high-mix, low-volume aircraft assembly environments are still scarce (Garre et al., 2017; Kundgol et al., 2021). Most existing studies emphasize repetitive production systems and mainly concentrate on improving machine utilization, setup time, and production efficiency in conventional manufacturing environments (Diaz et al., 2017; Kundgol et al., 2021). Consequently, their findings may not be directly applicable to aircraft assembly processes, which involve manual operations, complex product structures, strict quality requirements, and strong interdependencies among workstations (Seth et al., 2017).

In particular, existing studies have not systematically modelled the value stream of structural aircraft components, such as wings, spars, and leading-edge assemblies, based on direct observations in real industrial settings (Diaz et al., 2017). This gap is important because aircraft manufacturing involves manual, skill-intensive, and high-precision operations that generate waste characteristics different from those found in conventional manufacturing systems. Unlike conventional high-volume manufacturing, aircraft assembly is characterized by long production cycles, low production volumes, and high process variability, requiring improvement strategies that prioritize workflow synchronization and manpower coordination rather than machine utilization alone (Forno et al., 2014; Seth et al., 2017). Consequently, the limited availability of empirical evidence restricts the development of lean improvement strategies that are specifically tailored to aerospace production environments (Garre et al., 2017; Kundgol et al., 2021).

To address this gap, the present study investigates the Outer Wing Left-Hand (LH) assembly process of the NC-212 aircraft manufactured in Indonesia. Using Value Stream Mapping and supporting lean analysis techniques, this study identifies dominant sources of waste, evaluates current process performance, and proposes improvement strategies aimed at reducing lead time and improving process flow. The novelty of this study lies in the implementation of VSM-based lean manufacturing in a low-volume aerospace production environment through a takt-time-based workforce scheduling approach tailored to manual aircraft assembly operations.

This study contributes to the literature in three ways. First, it provides one of the few empirical VSM-based analyses conducted directly within an Indonesian aerospace manufacturing environment, specifically focusing on the NC-212 aircraft. Second, it integrates VSM with takt time analysis, manpower balancing, and Kaizen principles to develop improvement strategies tailored to large-scale

manual aircraft assembly processes. Third, it offers new insights into waste characteristics, workflow behavior, and inefficiency drivers in the Outer Wing LH assembly process, which have not been previously documented in the literature.

2. Method

The methodology of this study is designed to systematically identify production waste and formulate effective improvement strategies within the Outer Wing LH assembly process of the NC-212 aircraft. A structured lean-manufacturing–based approach was employed, combining direct observation, time measurement, historical production data analysis, and in-depth interviews with assembly supervisors to obtain comprehensive insights into the current condition of the production line. The research framework integrates Value Stream Mapping (VSM) to visualize material and information flow, waste identification tools to classify non–value-added activities, and the 5W+1H technique to determine the root causes of inefficiencies. VSM provides a systematic framework for visualizing production flows, identifying waste, and supporting improvement initiatives within lean manufacturing systems (Andreadis et al., 2017). Furthermore, the proposed improvements are developed through Kaizen principles and manpower optimization aligned with takt time to ensure synchronized workflow and enhanced productivity.

This study adopts an applied research design using a case study approach to analyze and improve the production performance of the Outer Wing Left-Hand (LH) assembly process of the NC-212 aircraft at PT Dirgantara Indonesia. The research focuses on identifying waste, mapping production flow Table 2 and Table 3, and designing improvement strategies using Lean Manufacturing and Value Stream Mapping (VSM) principles. The use of VSM in case-based manufacturing research enables the visualization of production activities and the identification of opportunities for reducing non-value-added activities (Carvalho et al., 2019). The overall methodology integrates qualitative field observations and quantitative time-based analysis to evaluate production efficiency. The methodological framework consists of five primary stages: First, problem identification. Second, data collection (primary and secondary). Third, current state mapping. Fourth, waste analysis & Continuous Improvement Evaluation. Fifth, future state mapping & improvement proposal.

2.1. Data Collection Methods

Primary Data were collected directly from the production floor through direct observation, interviews, and time studies. Direct observations were conducted to examine the Outer Wing LH assembly process, including activity sequences, operator movements, material flow, and equipment utilization. Actual process times, delays, material movement frequency, and manpower allocation were also recorded during the observation period. In addition, semi-structured interviews were conducted with supervisors and senior assembly technicians to obtain information regarding bottlenecks, defect causes, part availability issues, and workflow characteristics. Time studies were performed to measure cycle time (CT), lead time (LT), setup time, waiting time, and takt time based on annual aircraft demand and available working hours. Secondary data were obtained from company production records, including historical time logs, process sheets, standard operating procedures (SOPs), and material availability records, as well as technical manuals related to the NC-212 assembly process and previous literature supporting lean manufacturing concepts and Value Stream Mapping implementation. These data sources were used to support process verification and data triangulation to ensure the accuracy and reliability of the measurements.

2.2. Data Processing and Analysis

1. Takt Time Calculation

Takt time represents the maximum allowable time to produce one unit to meet customer demand. It is calculated using in Eq. (1).

$$Takt\ Time\ = \frac{Available\ Production\ System}{Customer\ Demand} \quad (1)$$

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From company data, 4 units of NC-212 were ordered; the available production period was 12 months. Thus, takt time is approximately 60 working days per unit, which becomes the performance benchmark.

2. Cycle Time Calculation

Cycle time (CT) is defined as the total time required by a workstation to complete one unit of output, from the beginning to the completion of all assigned tasks at that station. In this study, the CT of each assembly station was determined using standard process sheets and verified through direct observations and time studies conducted in the NC-212 Outer Wing LH assembly area. The cycle time was obtained by summing the duration of all activities performed within each workstation according to the actual production sequence. The cycle time for station i is computed as in Eq. (2).

$$CTi = \sum_{j=1}^{ni} tij \tag{2}$$

where tijt_{ij}tij represents the time required for operation j at station i, and nin_ini denotes the total number of operations at that station.

3. Lead Time Calculation

Lead time (LT) refers to the total elapsed time required for one complete unit to progress through the entire assembly process, from the release of the first component from inventory to the final completion of the Outer Wing LH assembly. Unlike cycle time, which measures performance at a single workstation, lead time represents the performance of the entire value stream by incorporating value-added (VA) processing time, necessary but non–value-added (NNVA) activities, and non–value-added (NVA) delays such as waiting, queueing, and part shortages. Lead time for the overall process is calculated as follows in Eq. (3).

$$LT = \sum_{k=1}^{m} (CTk + Wk) \tag{3}$$

where CT_k denotes the cycle time at workstation k, W_k represents the waiting time or queue between consecutive workstations, and mis the total number of workstations involved in the Outer Wing LH assembly process.

2.3. Development of the Current State Value Stream Mapping

Current-state Value Stream Mapping (VSM) was developed using primary data collected from direct observations, time studies, production records, and interviews with supervisors in the Outer Wing LH assembly area. The mapping covered twelve major assembly stations, including rear spar assembly, forward spar assembly, wing box assembly, leading-edge assembly, integration work, pruebas, and final equipado. For each station, cycle time, waiting time, manpower allocation, work-in-progress conditions, and material movement information were recorded. These data were then integrated into the current-state VSM to visualize both material flow and information flow throughout the production process. The current-state map was subsequently used to distinguish value-added (VA), necessary non-value-added (NNVA), and non-value-added (NVA) activities. In addition, delays, queues, transportation activities, and work-in-progress accumulation were identified to detect bottlenecks and potential sources of waste. The resulting VSM provided a baseline representation of the existing production system and served as the foundation for subsequent waste analysis and future-state improvement design.

2.4. Value Stream Mapping (VSM)

Value Stream Mapping (VSM) utilizes was employed to visualize material and information flows throughout the NC-212 Outer Wing LH assembly process. The mapping was developed using cycle time, waiting time, manpower allocation, and work-in-progress data collected from direct observations, production records, and interviews with supervisors. The resulting current-state map was used to identify bottlenecks, quantify value-added and non-value-added activities, and provide the basis for future-state improvement design. The standardized VSM symbols adopted in this study are presented in Fig. 1 and Fig. 2.

In this study, annual customer demand for four NC-212 aircraft units was used to calculate takt time and establish the production target. The current-state VSM was then constructed by mapping the sequence of twelve assembly stations, recording cycle times, waiting times, manpower allocation, and material movement information. The resulting map enabled the identification of bottlenecks and waste sources, which subsequently served as the basis for designing the future-state VSM.

Once all processes and flows are documented, the VSM is completed by adding lead-time bars at the bottom of the map. These bars differentiate value-added time (VA) from non–value-added time (NVA), enabling clear visualization of inefficiencies across the system. The material flow timeline typically includes cycle time, processing time, queue time, and waiting time, while the information flow illustrates how instructions and schedules are transmitted. Finally, all flows—material, information, and timing, are connected into a cohesive diagram, forming a comprehensive representation of the current-state production system. This structured flow enables engineers to identify bottlenecks, quantify waste, and design a future-state VSM that supports lean transformation.

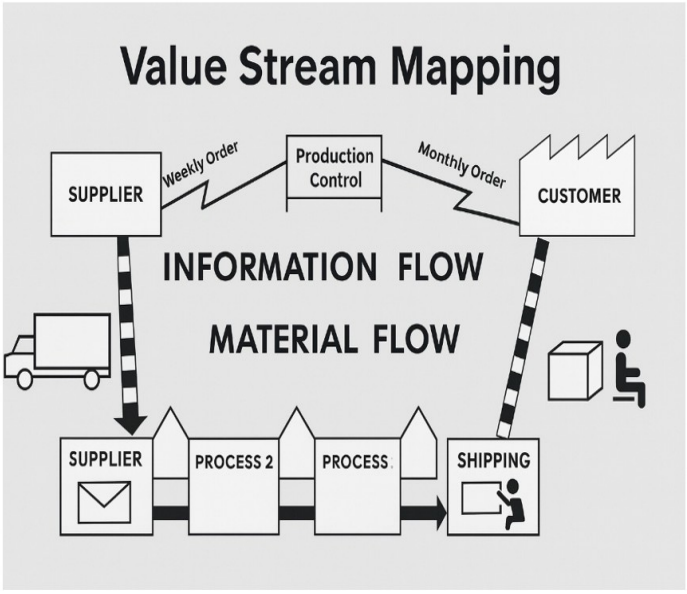


Fig. 1. Value Stream Mapping template showing material and information flows within a production system.

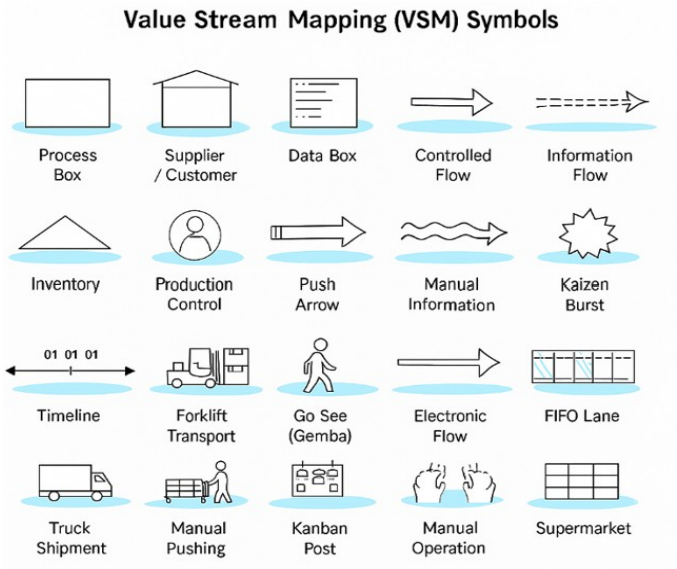


Fig. 2. Standard VSM symbols used to represent processes, inventories, and information flow.

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2.5. Process Time Classification and Waste Identification

1. Process Time Classification

All assembly activities were classified into three categories, namely value-added (VA), necessary but non–value-added (NNVA), and non–value-added (NVA). Value-added activities refer to operations that directly transform the product according to customer requirements. Necessary but non–value-added activities are required under current system constraints but do not directly add value, such as inspection and transportation activities. Meanwhile, non–value-added activities represent pure waste, including waiting, unnecessary movements, and delays (Bizuneh & Omer, 2024). The classification was established based on direct field observations, standard operating procedures (SOPs), and expert judgment obtained from production supervisors.

2. Waste Identification

Waste identification was conducted to determine the dominant waste categories affecting the assembly process. The analysis was initially based on the seven-waste (Muda) framework, which evaluates overproduction, waiting, motion, defects, transportation, inventory, and overprocessing (Liu & Yang, 2020). Subsequently, the identified dominant wastes were analyzed using the 5W+1H approach to determine their characteristics, locations, responsible personnel, occurrence conditions, underlying causes, and potential corrective actions. Further root-cause investigation was performed using Five-Why Analysis and Fishbone (Ishikawa) Diagrams. The Five-Why Analysis was applied to identify the causes of critical defects, such as buckling skin and skin deformation, whereas the Fishbone Diagram categorized the sources of problems into six dimensions: Man, Method, Material, Machine, Measurement, and Environment.

2.6. Design of Future State Mapping and Continuous Improvement Strategy (Kaizen)

Based on the waste analysis carried out in the current production system, a future-state Value Stream Mapping (VSM) model was developed to represent a more efficient and streamlined assembly process (Gopi et al., 2020). The improvement design incorporates the reduction and elimination of non–value-added (NVA) activities, optimization of manpower allocation using takt-time-based scheduling, and the introduction of parallel processing to achieve better line balancing. Additional enhancements include the implementation of safety stock to minimize waiting caused by part shortages, reduction of transportation time through improved layout and material handling tools, and the refinement of standard operating procedures (SOPs) to prevent defect occurrences. Collectively, these modifications create a more synchronized and leaner production flow, ensuring that the future-state map reflects a significantly improved operational performance compared to the current-state condition.

To ensure that the proposed future-state design is operationally feasible, workforce allocation was determined quantitatively based on takt time and workstation cycle time. The required number of operators for each workstation was calculated by comparing the measured cycle time with the takt time according to in Eq. (4).

$$Ni = [\frac{CTi}{TT}] \tag{4}$$

where N_i is the required number of operators at workstation i, CT_i is the cycle time of workstation i, and TT denotes the takt time. The ceiling function ensures that the resulting manpower requirement is expressed as an integer. Stations with cycle times exceeding takt time were identified as bottlenecks and became the primary candidates for manpower redistribution.

Workforce balancing was then performed by reallocating operators from stations with excess capacity to stations whose cycle times exceeded takt time. The balancing efficiency was evaluated using line balancing efficiency (LBE), expressed as in Eq. (5).

$$LBE = \frac{\sum_{i=1}^{n} CT_i}{n \times CT_{max}} \times 100\% \tag{5}$$

where CT_{max} represents the maximum cycle time among all workstations and nis the number of workstations. A higher LBE indicates a more balanced production line and lower idle time between stations.

Parallel processing was introduced for activities that exhibit low precedence dependency and can be executed simultaneously without affecting assembly quality. The resulting equivalent cycle time for parallel operations was estimated as in Eq. (6).

$$CT_{parallel} = \max(CT_1, CT_2, \dots, CT_m) \quad (6)$$

where CT_1, CT_2,… CT_m represent the cycle times of tasks executed concurrently. This approach reduces the overall processing duration because the completion time is governed by the longest parallel activity instead of the sum of individual task durations. The future-state VSM was subsequently constructed by incorporating the revised manpower allocation, parallel processing mechanisms, and waste elimination initiatives. The expected lead time of the improved system was calculated using in Eq. (7).

$$LT_{future} = \sum_{k=1}^{m}(CT_{k,new} + W_{k,new} \quad (7)$$

where $CT_{(k,new)}$ and $W_{(k,new)}$ denote the improved cycle time and waiting time at workstation k, respectively. The difference between current-state and future-state lead time was used to evaluate the effectiveness of the proposed improvements quantitatively.

Based on the identified wastes and root-cause analysis results, improvement alternatives were developed using Kaizen principles. These improvements included manpower reallocation based on takt time, implementation of safety stock to reduce waiting caused by part shortages, reduction of transportation activities, and refinement of standard operating procedures to minimize defect occurrence. The proposed improvements were incorporated into the future-state VSM to evaluate their potential impact on production flow and lead time reduction.

The feasibility of the proposed future-state design was validated by comparing the projected lead time with the takt-time target and ensuring that all manpower reallocations complied with existing process precedence constraints. The proposed schedule and improvement scenarios were also reviewed with production supervisors to confirm their operational applicability within the NC-212 Outer Wing LH assembly environment. This study was conducted with permission from the company, and all information obtained from observations, interviews, and production records was used solely for academic purposes. Confidential company information was treated appropriately to maintain research integrity and protect organizational interests.

3. Results and Discussion

The results and discussion in this section present a comprehensive evaluation of the current assembly performance and the effectiveness of the proposed lean improvement strategies for the NC-212 Outer Wing LH production line. The findings are organized to highlight the identification of waste, quantification of value-added and non–value-added activities, and the impact of process redesign on overall productivity. By integrating Value Stream Mapping, waste analysis, and takt-time–based manpower reallocation, this study provides empirical insights into how lean principles can be systematically applied in the aircraft structural assembly environment, an area that remains underexplored in existing literature. The discussion emphasizes both the operational and managerial implications of the improvements, offering a comparative analysis between the pre-improvement and post-improvement conditions to demonstrate measurable gains in lead time, worker performance, and value-added activity. These results reinforce the relevance of lean and Kaizen methodologies in enhancing production efficiency, aligning with IJIE's focus on integrated engineering solutions and practical contributions to industrial advancement.

3.1. Data Collection

Data collection in this study was carried out through direct observation in the Outer Wing LH assembly hangar of the NC-212 aircraft to understand the production process and record time-related

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data. In addition to field observations, interviews were conducted with supervisors responsible for overseeing the assembly operations to obtain detailed process information. Secondary data were also collected from the company's historical records, including production process documentation and time data for each activity involved in assembling the Outer Wing LH of the NC-212 aircraft. The following section presents the process data for the Outer Wing LH assembly.

Table 1. Assembly Activities (Production Process)

No.	Activity Name	Duration	Start	Sub-Activities (Hours)
1	REAR SPAR LH	11.71 Days	First Week	Setting the spar and fitting on jig (32 Hours) Mixing of sealant (1 Hour) Enlarge all previous diameter bonding F (40 Hours) Painting (14 Hours) Identification (1 Hour) Final inspection (1 Hour)
2	FORWARD SPAR LH	10 Days	First Week	Setting the fillets, profiles, webs and fitting (16 Hours) Enlarge all previous drilling to definitive size (24 Hours) Mixing sealant (1 Hour) Install, fitting, bushing and fastening (16 Hours) Painting (14 Hours) Identification (1 Hour) Final identification (1 Hour)
3	LEADING EDGE (OUTBD) LH	15 Days	First Week	Setting position of ribs and skin jig (32 Hours) Enlarge all previous drilling (48 Hours) Painting (14 Hours) Checking leading edge assembly (8 Hours) Identification (1 Hour) Final inspection (1 Hour)
4	SUB ASSY RIBS & SMALL ASSY	15 Days	First Week	-
5	OUTER WING BOX LH	30 Days	Third Week	-
6	LEADING EDGE (INBD) LH	20 Days	Fourth Week	Setting position of ribs and skin jig (32 Hours) Enlarge all previous drilling (48 Hours) Painting (14 Hours) Checking leading edge assembly (8 Hours) Equipado (32 Hours) Identification (1 Hour) Final inspection (1 Hour)
7	MIDDLE SPAR LH	7 Days	Fourth Week	-
8	SUPPORT FLAP	10 Days	Sixth Week	-
9	WING LET	10 Days	Sixth Week	-
10	OUTER WING INTEGRATION LH	25 Days	Ninth Week	-
11	PRUEBAS	14 Days	13th Week	-
12	EQUIPADO	10 Days	13th Week	-

As seen in Table 1 provides a comprehensive breakdown of the assembly activities involved in constructing the Outer Wing LH of the NC-212 aircraft. Each major assembly stage, such as Rear Spar LH, Forward Spar LH, Leading Edge (Outboard and Inboard), Outer Wing Box, and Wing Integration, is presented alongside its total duration and starting week in the production schedule. Several activities, particularly those related to spar and leading-edge assemblies, include detailed sub-processes such as jig fitting, drilling enlargement, painting, sealant preparation, component installation, and final inspections. These sub-activities are expressed in hours to offer a more precise

representation of labor requirements and processing time. The structure of the table highlights how specific stages require intensive manual work, extensive alignment procedures, and multiple layers of inspection to ensure structural accuracy.

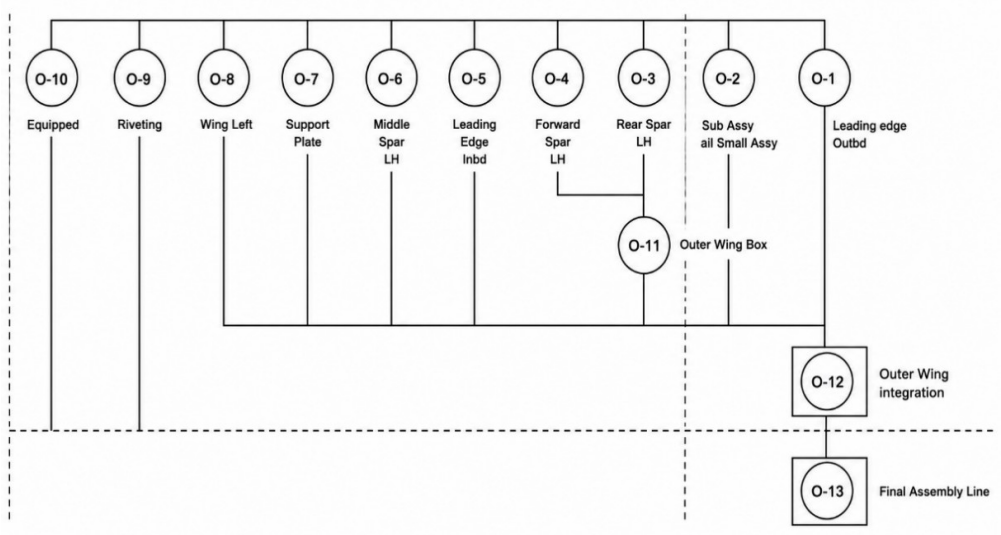


Fig. 3. Operation Processing Chart

Furthermore, As seen in Fig. 3 illustrates the sequential progression of the Outer Wing LH assembly from Week 1 through Week 13, revealing variations in workload distribution and process complexity across different stages. Early stages, such as spar assembly and leading-edge construction, involve numerous detailed operations that contribute significantly to overall cycle time. In contrast, later stages, such as Pruebas and Equipado, are shorter but essential for final verification and completion. The presence of multi-week tasks, such as the 30-day Outer Wing Box LH assembly, underscores the importance of identifying bottlenecks and synchronizing processes to prevent delays. Overall, the table provides a clear visual understanding of the production flow, supporting further analysis of cycle time, lead time, and opportunities for lean improvement within the assembly line.

3.2. Current State Value Stream Mapping

The initial assessment of the Outer Wing LH assembly process revealed a highly complex production flow consisting of twelve major assembly stations: Rear Spar LH, Forward Spar LH, Leading Edge (Outboard), Leading Edge (Inboard), Sub Assy Ribs & Small Assy, Outer Wing Box LH, Middle Spar LH, Support Flap, Winglet, Outer Wing Integration LH, Pruebas, and Equipado. Data were obtained through direct observation, time study, and interviews with assembly supervisors. Using these inputs, a Current State Value Stream Map (VSM) was constructed to visualize material flow, information flow, process time, and sources of inefficiency across the assembly line. The total calculated processing time across all stations reached 825 hours, equivalent to 118 working days, forming the baseline lead time for one complete Outer Wing LH unit.

A detailed classification in Table 6 of activities showed that only 93.96% of the total time contributed to value-added (VA) work, while 5.24% was categorized as non–value-added (NVA), primarily consisting of waiting, inspection delays, and part shortages. The remaining 0.79% was classified as necessary but non–value-added (NNVA), including transportation and sealant preparation activities. The Outer Wing Box LH station exhibited the highest cycle time (210 hours), making it the bottleneck of the entire assembly flow. The high cycle time at this station is mainly attributed to the complexity of structural assembly operations and the dependency on several upstream sub-assemblies. Since the Outer Wing Box integrates multiple components produced in previous processes, any delay occurring in upstream stations directly affects the start and completion of this stage. Furthermore, the manual nature of aircraft assembly operations and the extensive fitting and alignment requirements contribute to longer processing times.

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From a technical perspective, the Outer Wing Box LH assembly requires precise alignment, sealant application, dimensional verification, and integration of multiple structural components produced by preceding stations. These operations are highly dependent on manual workmanship and sequential assembly constraints, resulting in limited opportunities for task overlap and consequently increasing cycle time. In addition, the requirement for strict quality compliance in aerospace manufacturing further extends processing duration because each assembly stage must satisfy dimensional and structural requirements before subsequent activities can begin. The bottleneck at the Outer Wing Box LH station significantly affects the overall production flow. Since downstream activities such as Outer Wing Integration, Pruebas, and Equipado cannot proceed until this process is completed, any delay occurring at this station propagates throughout the entire assembly system. This condition increases work-in-progress accumulation, creates idle time at downstream stations, and ultimately prolongs the total lead time. Such flow interruptions reduce synchronization between processes and increase the risk of schedule instability.

The identified bottleneck also demonstrates an imbalance between cycle time and takt time requirements. With an initial total assembly lead time of 75 days, which exceeded the takt time target of 60 days, the existing production system was unable to accommodate future demand without causing order overlap. This indicates that the production pace imposed by the bottleneck station was slower than the customer demand rate, thereby preventing continuous flow and increasing the likelihood of delivery delays. From a lean manufacturing perspective, the presence of a bottleneck reflects the existence of unevenness (Mura) within the production system. Excessive workload concentration at the Outer Wing Box LH station disrupts flow continuity and limits the effectiveness of lean implementation. Therefore, balancing manpower allocation and introducing parallel processing become essential to redistribute workload and align cycle times with takt time. These improvements not only reduce lead time but also support the creation of a smoother and more stable production flow, which is a fundamental objective of lean manufacturing systems, particularly in high-mix and low-volume aerospace assembly environments.

The presence of this bottleneck has important implications for the overall production flow. A prolonged cycle time at the Outer Wing Box LH station may increase work-in-progress accumulation and create waiting conditions for downstream activities, thereby extending the overall lead time. In low-volume aerospace manufacturing environments, where process interdependencies are high, local delays can propagate throughout the system and reduce production stability. This finding is consistent with previous aerospace studies that identified bottleneck workstations as major contributors to lead-time growth and productivity losses. Damacharla (2022) reported that bottleneck processes and non-value-added activities significantly reduced productivity in aerospace assembly systems and highlighted the importance of workstation balancing and manpower optimization for improving operational performance.

Based on the execution of several activities carried out simultaneously, the total elapsed assembly lead time (critical-path) required for the NC-212 Outer Wing LH assembly process is 15 weeks, equivalent to 75 working days or 525 hours in Table 3 and Table 4. Two-time metrics are used in this study. The elapsed assembly lead time is 525 hours (75 working days), representing the critical-path duration from start to completion while accounting for parallel operations. In contrast, Table 4 reports the total work content (878 hours) as the sum of all recorded activity durations (VA+NNVA+NVA) used to quantify the VA/NNVA/NVA composition; therefore, it is not directly comparable to the elapsed lead time. The assembly sequence begins with the completion of the Forward Spar, Rear Spar, Leading Edge (Outboard), and Sub Assembly & Small Assembly, all of which start in the first week. While these three sub-assembly processes are underway, several other activities begin in parallel. The sequencing of each process is determined by the availability of manpower and the readiness of components required for assembly. The observed production pattern reflects the characteristics of high-mix, low-volume aerospace manufacturing, where synchronization between stations is more critical than maximizing the utilization of individual workstations.

However, this dependency also makes the production system highly vulnerable to delays in component availability and manpower allocation. Consequently, effective coordination between stations becomes essential to maintain process continuity. From a lean manufacturing perspective, the bottleneck identified in the Outer Wing Box LH station indicates that cycle time imbalance may hinder the achievement of takt-time requirements. If the bottleneck remains unresolved, future orders may overlap and increase the risk of delivery delays. This observation agrees with previous VSM studies, which demonstrated that cycle times exceeding the desired production pace can disrupt flow efficiency and reduce responsiveness to customer demand.

Table 2. Gantt Chart (Left-Hand (LH) Outer Wing Integration Activity)

No	Activity	Working days	Information
1	Outer Wing Integration LH	25	–
2	Outer Wing Box LH	30	+ sealant
3	Forward Spar LH	10	–
4	Rear Spar LH	10	–
5	Middle Spar LH	7	–
6	Pruebas	14	+ leak test
7	Equipado	10	–
8	Leading Edge (INBD) LH	20	–
9	Leading Edge (OUTBD) LH	15	–
10	Support Flap	10	–
11	Winglet	10	–
12	Sub Assy Ribs & Small Assy	15	–

Table 3. Gantt Chart of Manpower per Period

Activity	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12
Outer Wing Integration LH								8	8	8	8	6
Outer Wing Box LH		6	6	6	6	6	6	4				
Forward Spar LH	3	3										
Rear Spar LH	3	3										
Middle Spar LH			2	2								
Pruebas						2			2	4		
Equipado						2			2	4	4	
Leading Edge (INBD) LH	2	2	2	2	2	2	2					
Leading Edge (OUTBD) LH	2	2	2									
Support Flap			2	2								
Winglet			2	2								
Sub Assy Ribs & Small Assy	4	4	4	4	4							

Unlike many previous lean studies conducted in mass-production environments, the bottleneck observed in this study originated primarily from the complexity and interdependence of manual aircraft assembly operations rather than machine utilization issues. This result highlights the distinctive characteristics of aerospace manufacturing and reinforces the need for lean improvement strategies specifically tailored to low-volume, high-complexity production systems. Therefore, after identifying the assembly stages of the Outer Wing LH, the duration of each task, and the starting time of every activity, the overall process flow can be illustrated using the current-state Value Stream Mapping in Fig. 4.

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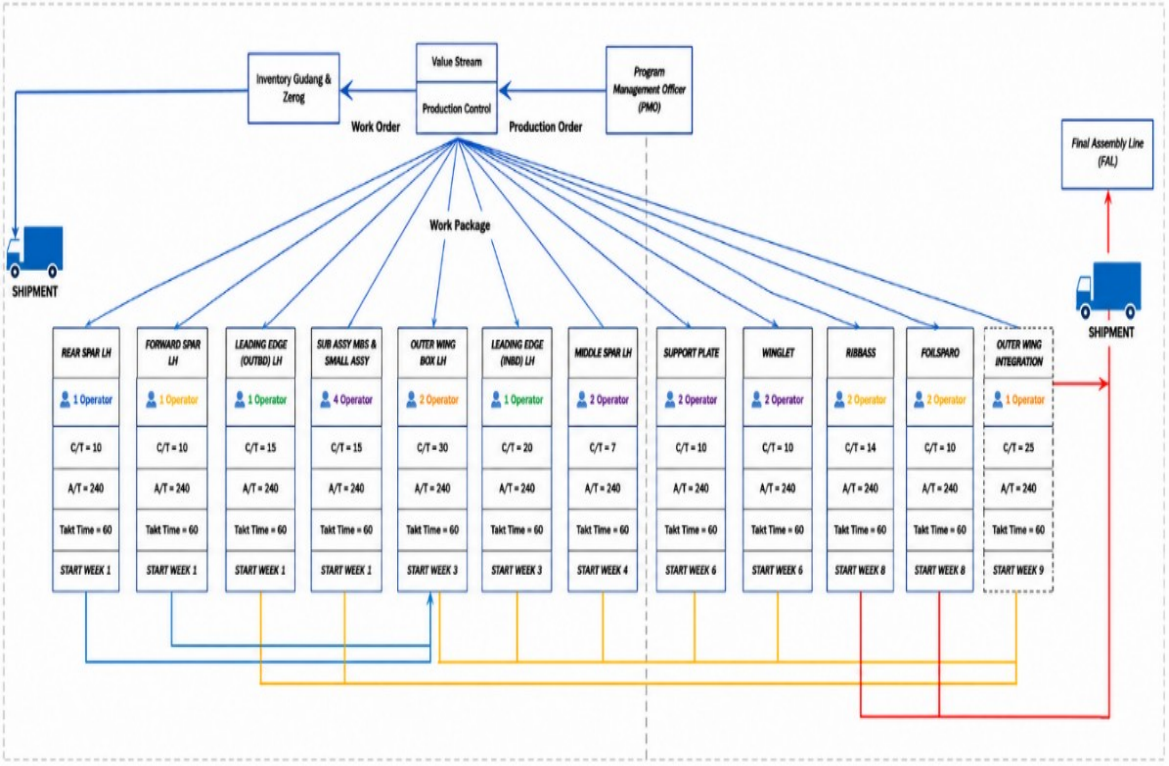


Fig. 4. Current State Value Stream Mapping

3.3. Process Classification and Waste Identification

The Current State Value Stream Mapping (VSM) of the NC-212 Outer Wing LH assembly process was developed based on direct observations and production data collected throughout the entire assembly sequence. The mapping covered twelve major processes, namely Rear Spar LH, Forward Spar LH, Leading Edge (Outboard) LH, Leading Edge (Inboard) LH, Sub Assembly Ribs & Small Assembly, Outer Wing Box LH, Middle Spar LH, Support Flap, Winglet, Outer Wing Integration LH, Pruebas, and Equipado.

The current state represents the initial condition of the system and describes the existing material and information flows within the value stream, including tasks, costs, process times, delays, and other related parameters (Dotoli et al., 2011). To construct the current-state map, direct observations were conducted throughout the production process, and relevant data such as cycle time, lead time, uptime, and other operational information were collected and visualized in a comprehensive mapping diagram.

Current-state mapping enables the identification and classification of activities into Value-Added (VA), Necessary but Non-Value-Added (NNVA), and Non-Value-Added (NVA) categories. VA activities directly contribute to product transformation, while NNVA activities, such as transportation and certain operational procedures, are necessary under current conditions but do not add value from the customer's perspective. NVA activities consist of delays or waiting times that do not contribute to product value and should be minimized or eliminated whenever possible.

The mapping results revealed that the NC-212 Outer Wing LH assembly process consists of operational activities, transportation, inspections, and delays distributed across several workstations. Table 4 presents the classification of activities identified during the assembly process. The results indicate that most activities were categorized as VA, suggesting that the majority of process time was devoted to productive operations. Nevertheless, several NNVA and NVA activities were identified, particularly those related to transportation, identification processes, and waiting caused by pending parts, indicating the existence of inefficiencies that may increase lead time and disrupt production flow in Table 4.

Table 4. Activity Classification

No.	Activity Name	Duration	Activity Classification
1	REAR SPAR LH		
	Setting the spar and fitting on jig (32 Hours)		VA
	Mixing of sealant (1 Hour)		NNVA
	Enlarge all previous diameter bonding F (40 Hours)	12 Days (90 Hours)	VA
	Transportation (1 Hour)		NNVA
	Painting (14 Hours)		VA
	Identification (1 Hour)		NVA
	Final inspection (1 Hour)		VA
2	FORWARD SPAR LH		
	Setting the fillets, profiles, webs and fitting (16 Hours)		VA
	Enlarge all previous diameter to definitive size (24 Hours)		VA
	Mixing sealant (1 Hour)	10 Days (74 Hours)	NNVA
	Install, fitting, bushing and fastening (16 Hours)		VA
	Transportation (1 Hour)		NNVA
	Painting (14 Hours)		VA
	Identification (1 Hour)		NVA
	Final identification (1 Hour)		VA
3	LEADING EDGE (OUTBD) LH		
	Setting position of ribs and skin jig (32 Hours)		VA
	Enlarge all previous drilling (48 Hours)		VA
	Transportation (1 Hour)		NNVA
	Painting (14 Hours)	15 Days (105.5 Hours)	VA
	Checking leading edge assembly (8 Hours)		VA
	Identification (1 Hour)		NVA
	Final inspection (1 Hour)		VA
	Transportation (0.5 Hours)		NNVA
4	SUB ASSY RIBS & SMALL ASSY	15 Days (105 Hours)	VA
	Pending part (5 Days / 35 Hours)		NVA
5	OUTER WING BOX LH	30 Days (210 Hours)	VA
6	LEADING EDGE (INBD) LH		
	Setting position of ribs and skin jig (32 Hours)		VA
	Enlarge all previous drilling (48 Hours)		VA
	Transportation (1 Hour)		NNVA
	Painting (14 Hours)		VA
	Checking leading edge assembly (8 Hours)	20 Days (137.5 Hours)	VA
	Equipado (32 Hours)		VA
	Identification (1 Hour)		NVA
	Final inspection (1 Hour)		VA
	Transportation (0.5 Hours)		NNVA
7	MIDDLE SPAR LH	7 Days (49 Hours)	VA
8	SUPPORT FLAP	10 Days (70 Hours)	VA
9	WING LET	10 Days (70 Hours)	VA
10	OUTER WING INTEGRATION LH	25 Days (175 Hours)	VA
	Preparation and transportation FAL (1 Day / 7 Hours)		NVA
11	PRUEBAS	14 Days (98 Hours)	VA
12	EQUIPADO	10 Days (70 Hours)	VA

As shown in Table 5, VA activities accounted for 825 hours (93.96%) of the total process time, while NVA and NNVA activities contributed 46 hours (5.24%) and 7 hours (0.79%), respectively. Although the proportion of non-value-added activities is relatively small, even minor delays can significantly affect lead time and delivery performance in aerospace manufacturing environments characterized by high product complexity and low production volume. Therefore, identifying and reducing sources of waste remains essential for improving production flow and supporting continuous improvement initiatives.

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Table 5. VA, NNVA, NVA Activities

Activity Type	Total Time (Hours)	Percentage
VA	825	93.96%
NNVA	7	0.79%
NVA	46	5.24%

3.4. Waste Identification

No overproduction was identified in the Outer Wing LH assembly process. This condition reflects the make-to-order production strategy implemented in the NC-212 program, where production activities are initiated only after customer requirements and component availability have been confirmed. Consequently, unnecessary production and excessive work-in-progress can be avoided.

Waiting waste was identified as one of the dominant non-value-added activities in the Outer Wing LH assembly process. Waiting mainly occurred because of pending part availability and repeated identification activities before assembly operations could proceed. This result suggests that material readiness rather than processing capability represents one of the major constraints within the current production system. Since aircraft assembly activities are highly interdependent, delays in one process may propagate to subsequent stations and increase the overall lead time.

The occurrence of waiting waste indicates that synchronization among upstream and downstream processes remains insufficient. Similar findings have been reported in previous aerospace manufacturing studies, which identified waiting activities as a major contributor to production inefficiencies and lead-time growth (Kundgol et al., 2021). However, unlike mass-production environments where waiting is frequently associated with machine downtime, the waiting waste observed in this study primarily originated from component dependencies and part availability constraints inherent in low-volume aircraft assembly systems.

Excessive transportation occurred when components had to be moved to specific work areas for painting and sealant application. Although these activities are operationally necessary, they do not directly add value to the product and increase handling time. Additional transportation activities may also increase the risk of component damage and disrupt production flow. Previous lean studies similarly reported transportation waste as a common source of inefficiency in assembly environments, emphasizing the importance of improving material handling and layout arrangements.

No significant inappropriate processing waste was identified because assembly activities were conducted according to process sheets and established standard procedures. This finding indicates that the existing process standardization is sufficiently effective in preventing unnecessary operations and maintaining process consistency. No unnecessary inventory was observed during the Outer Wing LH assembly process. Inventory levels were maintained according to production requirements, thereby preventing excessive stock accumulation. This condition is consistent with the characteristics of make-to-order aerospace manufacturing systems, which generally maintain lower inventory levels than conventional mass-production systems.

Unnecessary motion was identified in several activities involving mechanic movement between work areas. However, the observed movements did not significantly affect process performance because operators were still able to complete their tasks within the allocated cycle time. Therefore, motion waste was considered relatively minor compared with waiting and defect-related waste. Defects identified in the Outer Wing LH assembly process included buckling and skin deformation. Buckling generally occurred because of improper assembly methods, deviations from assembly sequences, or uneven fastening pressure, whereas skin deformation resulted from improper repeat-seat installation, thin material conditions, or incorrect positioning during assembly. The occurrence of these defects required rework activities before the assembly process could continue, thereby increasing lead time and reducing production efficiency. This finding suggests that product quality has a direct influence on flow performance within the assembly system.

Similar observations have been reported in previous aerospace studies, which emphasized that defects and rework are major contributors to productivity losses and schedule delays (Diaz et al., 2017). Due to the stringent quality requirements imposed on aircraft structures, even minor defects may significantly affect production reliability and delivery performance. Manpower waste occurred when some mechanics remained idle or when the number of assigned workers exceeded actual workload requirements. This condition indicates that manpower allocation has not yet been fully synchronized with takt-time requirements and workload distribution. Consequently, labor utilization becomes suboptimal and certain resources remain underutilized. This finding suggests that workforce balancing represents an important opportunity for improving production efficiency. Previous lean manufacturing studies demonstrated that manpower allocation based on takt time can significantly reduce idle time and improve operational performance (Ayough et al., 2020). Therefore, balancing workforce requirements with process demands is essential for achieving a smoother production flow.

3.5. Design of Future State Mapping and Continuous Improvement Strategy (Kaizen)

After identifying the conditions present in the Outer Wing LH assembly process of the NC-212 aircraft, improvements must be proposed based on the analysis of waste and non–value-added activities. The recommended improvements to reduce the identified waste are as follows:

3.5.1. Implementation of the Kaizen Method

The Kaizen approach was selected because it emphasizes gradual and sustainable improvements that can be implemented without major changes to the existing production system. This approach is particularly suitable for aerospace manufacturing environments characterized by low production volume, high process complexity, and strong interdependencies among assembly stages.

Through an analysis of the current-state VSM, the researcher identified several non–value-added activities that can be reduced as part of lean manufacturing implementation. Examples include reducing preparation time after assembly during the integration process before transferring components to the Final Assembly Line. With this improvement, once all components are assembled and inspected, they can be directly transported to the Final Assembly Line. Another improvement is ensuring consistent adherence to each process step based on the SOP and process sheet to minimize repeated identification activities across sub-processes, limiting identification to the final inspection stage. However, the reduction of identification steps must still ensure that product defects do not occur, as this could lead to rework.

Additional reductions can be made in transportation time across sub-processes, such as utilizing mechanical towing devices or existing handling tools to reduce preparation time. Continuous improvement may also include establishing safety stock for critical materials so that ongoing processes are not disrupted by part shortages or pending materials from inventory, thereby preventing bottlenecks.

3.5.2. Kaizen Steps and Continuous Improvement Strategy

To ensure that the proposed improvements align with Kaizen principles and produce measurable results, a structured set of Kaizen steps was formulated and implemented in designing the future-state mapping. The Kaizen strategy in this study consists of five major stages.

1) Identifying waste at the process and workstation level
2) Analyzing root causes using the 5W+1H and Five-Why techniques
3) Developing countermeasures focused on eliminating non–value-added activities
4) Standardizing improved work procedures
5) Continuously monitoring manpower performance and takt-time alignment to maintain stability. This structured Kaizen cycle provides a clear roadmap for sustainable enhancement of the outer wing assembly line.

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Step 1: Waste Identification Through Current-State Mapping

The first Kaizen step is the identification of waste within the current-state VSM, where waiting, transportation, defect, unnecessary motion, and manpower idle time were found to be the most dominant. The detailed breakdown of VA, NNVA, and NVA activities enabled precise localization of inefficiencies across 12 major assembly processes.

Step 2: Root Cause Analysis Using 5W+1H and Five-Why

After identifying waste, the root causes were examined using structured questioning. Delays were linked to late part availability and inconsistent identification steps; excessive transportation resulted from distance between work areas and manual handling; and defects were traced to procedural deviations and insufficient supervision. Manpower waste was shown to originate from unsynchronized scheduling and the absence of takt-time–based workload allocation Table 6.

Table 6. 5W+1H Waste Analysis

Type of Waste (What)	Source of Waste (Where)	Responsible Person (Who)	Time Occurrence (When)	Cause (Why)	Improvement Suggestion (How)
Waiting	Sub-assy ribs & small assy station	Sub-assy ribs & small assy operator	During the sub-assy ribs & small assy workstation process	Machining division delays the supply of parts	Scheduling part availability before processing and applying safety stock
Waiting (Identification delay)	Each process station	Operators in each process	During identification activities in each process	Some processes still lack standardization	Ensuring compliance with standards, work procedures, and supervision to eliminate identification delays
Excessive Transportation	Sealant workstation	Sealant workstation operator	Material movement from several processes to the sealant hangar	Transportation is still done manually	Provide material-handling tools to improve transportation efficiency
Defect (Buckling skin)	Leading edge workstation	Leading edge workstation operators	During leading edge workstation processes	Lack of worker supervision during procedure execution	Improve process compliance with SOP, method discipline, and strengthen supervisor oversight
Defect (Skin deformation)	Leading edge workstation	Leading edge workstation operators	During leading edge workstation processes	Thin material, inclined/incorrect assembly method	Adjust process sheet, provide worker training, handle skin assembly carefully, ensure strict supervision
Excess Manpower Waste	All workstations	Production supervisor	During NC-212 outer wing takt time production	No clear workload assignment based on takt time	Define each activity according to takt time data and adjust workload distribution

Step 3: Development of Targeted Kaizen Countermeasures

Based on the root causes, Kaizen countermeasures were formulated, including: First, establishing safety stock for critical components to prevent waiting caused by pending material. Second, eliminating repeated identification steps and shifting quality confirmation to final inspection, while reinforcing SOP adherence. Third, reducing transportation time by using mechanical towing devices, optimizing layout flow, and improving handling readiness. Fourth, standardizing assembly sequences to prevent buckling and deformation defects. Five, reallocating manpower based on takt-time calculations, allowing parallel processing and minimizing idle time. These countermeasures directly support the reduction of NNVA and NVA activities while increasing value-added efficiency.

The proposed countermeasures were directly linked to the root causes identified through the 5W+1H and Five-Why analyses. Waiting waste was addressed through safety stock implementation and part availability scheduling, whereas defect-related waste was mitigated through improved process discipline and enhanced supervision. Transportation waste was reduced by improving handling methods, while manpower waste was addressed through takt-time-based workforce allocation. This root-cause-to-countermeasure linkage ensures that each improvement action targets the actual source of inefficiency rather than merely treating operational symptoms in Table 7.

Table 7. Five-Whys Analysis

Problem	Why 1	Why 2	Why 3	Why 4
Why does waiting waste occur in the outer wing assembly?	Delay in the availability of several parts	The process is carried out before certain parts are ready	The machining division experiences delays in supplying parts	
Waiting due to identification process	Each process undergoes repeated quality control checks	Some processes are still not fully standardized		
Why does excessive transportation waste occur in the outer wing assembly?	Different locations for production and sealant application	Material movement requires additional time	The sealant application area is relatively far	Transportation is still done manually
Why does defect waste occur in the outer wing assembly?	Skin buckling defects occur	Incorrect assembly method without following the proper sequence	Lack of worker supervision during the procedure	
Skin deformation defects occur	The skin material is too thin	Repeat-seat installation is not performed evenly	Workers perform assembly at an incorrect angle	
Why does excess manpower waste occur?	Some mechanics are idle during several processes	Not all processes are executed continuously	No task assignment based on defined takt time	

These findings are consistent with previous lean manufacturing studies. Amrani & Ducq (2020) demonstrated that lean implementation in aerospace manufacturing should be adapted to sector-specific characteristics and that standardized work procedures are essential for maintaining process stability. Similarly, Sasidharan (2025) reported that the integration of VSM, standardized work, and continuous improvement significantly reduced cycle time and defects in aerospace component production. In addition, Fortuny-Santos et al. (2020) emphasized that workload balancing and manpower allocation are critical factors for improving flow efficiency in manual assembly environments. However, unlike many studies conducted in mass-production systems, the improvements proposed in this study were specifically designed for a high-mix, low-volume aerospace assembly environment characterized by strong process interdependencies and extensive manual operations.

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The proposed Kaizen countermeasures were developed based on the root causes identified through the 5W+1H and Five-Whys analyses. By addressing waiting, transportation, defect-related issues, and manpower imbalance, the future-state design is expected to reduce non–value-added activities and improve process flow. Consequently, the proportion of value-added activities increases, whereas non–value-added activities are eliminated, as presented in Table 8.

Table 8. VA, NNVA, and NVA Activities After Improvement

Activity	Total	Time (Hours)	Percentage
VA	29	825	99,16%
NNVA	8	7	0,84%
NVA	0	0	0 %

The increase in value-added activities from 93.96% to 99.16% demonstrates that the proposed future-state design successfully reduced non-value-added activities and improved process efficiency. Although the percentage reduction may appear relatively small, even minor improvements are significant in aerospace manufacturing because production systems are highly sensitive to delays and schedule disruptions. This result indicates that eliminating waiting and transportation waste can substantially improve production flow without requiring major investments or changes to the existing production infrastructure.

Step 4: Standardization of Improved Processes (Work Standardization)

Kaizen emphasizes creating stable and repeatable work systems. Therefore, all improved processes were documented into updated SOPs and process sheets, including updated inspection points, revised sequencing for sub-assembly tasks, and reallocated manpower charts. Standardization ensures that improvements are not temporary, but institutionalized within daily operations.

Step 5: Continuous Monitoring and Performance Evaluation

The final step involves monitoring cycle time, manpower performance, and takt-time conformance to sustain the benefits of the improvements. Worker performance analysis demonstrated an average efficiency increase to 96.16%, indicating that the Kaizen strategy successfully reduced idle time and improved labor utilization. The increase of value-added activities to 99.16% further validates the effectiveness of continuous improvement in optimizing assembly performance.

3.6. Proposed Solution by Manpower planning for each activity

Based on the initial process duration of 75 days required to assemble the Outer Wing LH, the improvement proposal shows that the assembly time can be reduced to 59 days. This reduction aligns with the takt time, which defines the maximum allowable time to meet aircraft production demand based on available working time, 60 days of takt time. If the process exceeds 60 days, as in the initial condition, bottlenecks will occur in subsequent product orders, preventing the fulfillment of future demand. One of the proposed improvements is determining activities that can be performed simultaneously by utilizing 12 workers. The numbers indicated in each process show how the same workers can continue to the next task once the previous activity is completed, thus reducing worker idle time and increasing overall productivity.

The future-state schedule begins on Day 1 with four parallel processes, namely Rear Spar LH, Forward Spar LH, Leading Edge (Outboard), and Sub Assy Ribs & Small Assy. The Rear Spar LH process requires 12 days and is performed by three workers, while the Forward Spar LH process requires 10 days and also involves three workers. The Leading Edge (Outboard) assembly has a cycle time of 15 days and is handled by two workers, whereas the Sub Assy Ribs & Small Assy process requires four workers and is completed within 15 days. After the completion of the Sub Assy Ribs & Small Assy process, the available workers are reassigned to subsequent operations. On Day 16, the

Support Flap and Wing Let processes are initiated, each requiring two workers and a cycle time of 10 days. The Outer Wing Box assembly starts earlier on Day 13 and represents the most critical operation in the assembly sequence. This process requires six workers, consisting of three workers transferred from the Rear Spar LH station and three workers from the Forward Spar LH station, and has a cycle time of 30 days.

Additional workforce reallocation is applied to maintain process continuity. The Middle Spar process starts on Day 16 with two workers previously assigned to the Leading Edge (Outboard) station and requires seven days for completion. Subsequently, the Leading Edge (Inboard) process starts on Day 23 and utilizes the same two workers reassigned from the Middle Spar station, resulting in a cycle time of 20 days. On Day 26, the Equipado and Pruebas processes are initiated. Equipado requires two workers transferred from the Support Flap station and is completed within 10 days, whereas Pruebas employs two workers previously assigned to the Wing Let station and requires 14 days. Finally, the Outer Wing Integration process starts on Day 43. Although the initial cycle time of this process was 25 days, the increased availability of workers from previous stations raises the workforce from eight to twelve mechanics, allowing the cycle time to be reduced to 17 days. This workforce synchronization enables the overall assembly process to be completed within the targeted production period.

The manpower reallocation strategy enabled several processes to be executed in parallel while minimizing worker idle time. Additional manpower assigned to the Outer Wing Integration station reduced its cycle time from 25 days to 17 days, thereby preventing the formation of a new bottleneck in the downstream assembly stages. As a result, the total assembly duration decreased from 75 days to 59 days, which is lower than the required takt time of 60 days. This indicates that the proposed workforce balancing strategy is capable of supporting future production demand and preventing order overlap. It should be noted that the proposed Kaizen improvements and future-state Value Stream Mapping presented in this study have not yet been implemented directly on the actual production line. The obtained performance improvements, including the reduction of total assembly duration from 75 days to 59 days and the increase in worker utilization, were derived from analytical evaluation and future-state scheduling based on observed process data and takt-time-based workforce allocation. Therefore, the proposed improvements should be regarded as a conceptual future-state design supported by simulation and quantitative analysis rather than as validated results from full-scale industrial implementation.

Consequently, one limitation of this study is the absence of real-world implementation and long-term performance validation. Factors such as operator adaptation, variability in material availability, and unforeseen operational constraints may influence the actual effectiveness of the proposed improvements. Future research should focus on pilot implementation and monitoring of key performance indicators to validate the practicality and sustainability of the proposed Kaizen strategy under actual production conditions.

Similar results have been reported in previous studies on line balancing and takt-time-based scheduling. Fortuny-Santos et al. (2020) showed that workforce balancing improves flow synchronization and reduces workload variability in manual assembly lines. Likewise, studies on aircraft assembly systems by Borsato et al. (2022) and subsequent aircraft line-balancing research demonstrated that integrating scheduling with workforce allocation significantly improves productivity and reduces lead time. However, unlike conventional manufacturing systems that mainly focus on machine utilization, the present study emphasizes workforce synchronization and takt-time alignment in a manual aircraft assembly environment.

3.7. Worker Performance

Based on the initial waste analysis, several workers experienced idle time during specific assembly stages. After implementing the proposed improvements, worker utilization increased significantly due to manpower balancing and synchronized task allocation. The first worker group (three workers) achieved 100% utilization, while the second group (three workers) reached 91.52%. The third group, consisting of four workers, achieved 94.91% utilization, whereas the fourth group

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(two workers) also reached 100% utilization. Based on the weighted average of all twelve workers, the overall worker performance after implementing the proposed improvements reached 96.16%. These results indicate that the proposed workforce scheduling strategy successfully reduced idle time and improved labor utilization across the assembly process. The increase in average worker utilization to 96.16% indicates that takt-time-based manpower balancing can effectively reduce idle time and improve resource efficiency. This finding is consistent with lean manufacturing principles emphasizing workload equalization and continuous flow. Previous studies by Aucasime-Gonzales et al. (2020) showed that lean improvement and resource optimization increased operational performance and efficiency. However, unlike conventional manufacturing systems that rely heavily on machine utilization, the present study demonstrates that workforce synchronization remains an effective strategy in labor-intensive aerospace assembly environments in Fig. 5 and Fig. 6.

$$\text{Average Performance} = \frac{(3 \times 10) + (3 \times 91.52) + (4 \times 94.91) + 2 \times 100}{12} = 91.16\%$$

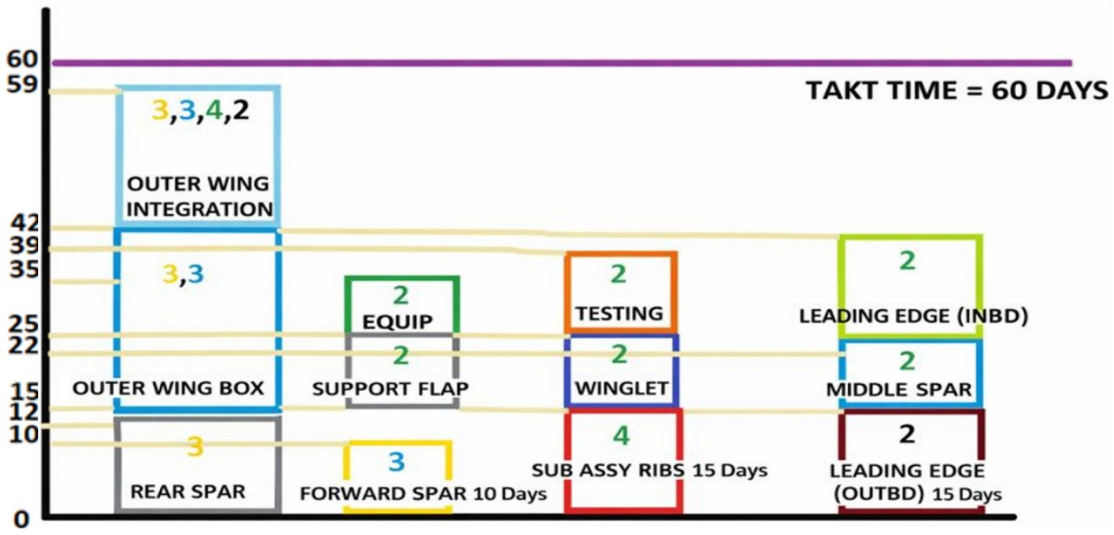


Fig. 5. Process Improvement Proposal

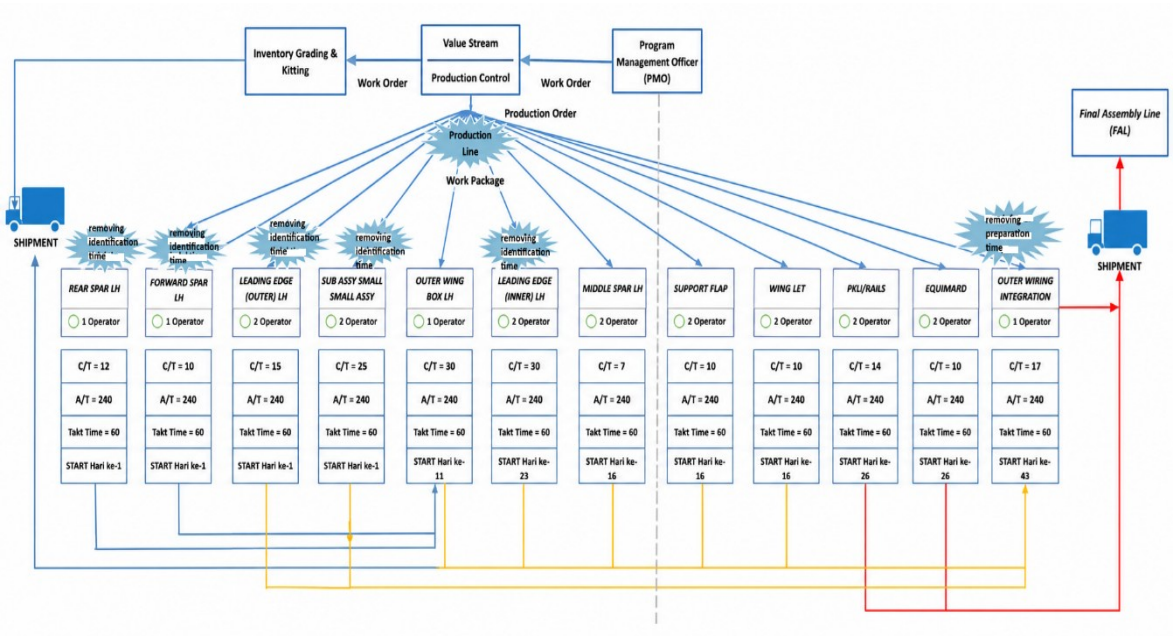


Fig. 6. Future State Value Stream Mapping

4. Conclusion

This study investigated the application of lean manufacturing to improve the efficiency of the NC-212 Outer Wing LH assembly process through Value Stream Mapping (VSM), root-cause analysis, and Kaizen-based improvements. The results showed that dominant wastes in the assembly system included waiting, excessive transportation, defects, and manpower imbalance, which negatively affected production flow and increased lead time. By implementing the proposed improvement strategies and takt-time-based workforce allocation, the total assembly lead time was reduced from 75 days to 59 days, while the proportion of value-added activities increased to 99.16%. This study contributes to the application of lean manufacturing in high-mix, low-volume aerospace production by demonstrating how VSM and takt-time-based manpower scheduling can be integrated to improve workflow synchronization and reduce inefficiencies in manual aircraft assembly. From a practical perspective, the proposed approach provides aerospace manufacturers with a structured framework for identifying waste, balancing manpower, and supporting continuous improvement initiatives without requiring major changes to the existing production system.

Despite these contributions, this study has several limitations. First, the analysis was limited to the Outer Wing LH assembly process of a single aircraft type (NC-212), which may restrict the generalizability of the findings to other aircraft structures or manufacturing environments. Second, the study was based on observations conducted within a limited period and production scope. Third, the proposed future-state improvements have not yet been validated through long-term implementation. Therefore, future research may extend the analysis to other aircraft components, evaluate the long-term effectiveness of the proposed improvements, and integrate simulation or optimization approaches to further enhance aerospace production performance.

Supplementary Materials: all materials available by request.

Author Contribution: Dwi Adi Purnama: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Visualization, writing – original draft, Writing – review & editing, and Project administration. Diyah Dwi Nugraheni: Methodology, Validation, Investigation, Resources, Data curation, and Writing – review & editing. All authors have read and approved the final version of the manuscript.

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