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Identification and Quantification of the Seven Wastes (Muda) in Aircraft Structural Assembly: A Systemic Approach Based on Lean Manufacturing

Identification and Quantification of the Seven Wastes (Muda) in Aircraft Structural Assembly: A Systemic Lean-Based Approach

Madison Leandro Farias de Carvalho – AIAA Member #1857656

Founder & Principal Engineer – Aerostructure Systems & Lean Solutions LLC (USA),
madison.carvalho@outlook.com

Summary

Aircraft structural assembly is one of the most complex production environments in contemporary manufacturing, characterized by low volume, high mix, high structural criticality, and demanding regulatory requirements. In this scenario, the seven wastes (Muda) described by Lean Manufacturing take on particular forms of manifestation, often intensified by operational variability and capacity saturation. This study examines the identification and quantification of these wastes in aircraft structural assembly processes using a hybrid approach that articulates Lean conceptual foundations, Theory of Constraints, and quantitative analysis of productive performance. Based on a case study conducted on a structural assembly line, indicators related to cycle time, work in process (WIP), rework rate, and unproductive time associated with waiting and movement were measured. The results indicate that operational variability acts as a systemic multiplier of wastes, directly affecting lead time and the stability of the production flow. The structured application of Lean tools, combined with quantitative analysis, enabled an estimated reduction in critical wastes and a significant improvement in systemic performance. The findings contribute to the literature by outlining an integrated method for identifying and quantifying Muda in highly complex aerospace environments.

Keywords: Lean Manufacturing; seven wastes; structural assembly; operational variability; aerospace industry.

Abstract

Aircraft structural assembly constitutes one of the most complex manufacturing environments, distinguished by low production volume, high product mix, structural criticality, and stringent regulatory requirements. Within this setting, the seven wastes (Muda) defined in Lean Manufacturing assume context-specific forms of manifestation, frequently intensified by operational variability and capacity saturation. This study examines the identification and quantification of the seven wastes in aerospace structural assembly processes through a hybrid approach that integrates Lean theoretical foundations, Theory of Constraints, and quantitative performance analysis. A case study performed on a structural assembly line evaluated cycle time, work-in-process (WIP), rework rate, and non-value-added time associated with waiting and motion. The results show that operational variability functions as a systemic multiplier of waste, exerting direct influence on lead time and the stability of production flow. The structured application of Lean practices, combined with quantitative assessment, enabled measurable reductions in critical waste categories and yielded significant improvements in systemic performance. These findings contribute to the existing literature by proposing an integrated method for the identification and quantification of Muda in complex aerospace manufacturing environments.

Keywords: Lean Manufacturing; seven wastes; structural assembly; operational variability; aerospace industry.

1. INTRODUCTION

The structural assembly of aircraft differs substantially from traditional systems.

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mass production, both in its operational logic and in the technical constraints that...
They govern. This productive environment is characterized by a high dependence on manual operations.
precision, strict adherence to tight dimensional tolerances, conducting inspections
mandatory in multiple stages and strong interdependence between consecutive processes.
Unlike highly automated and repetitive lines, aeronautical structural assembly
It operates under conditions of inherent variability, in which small disturbances can have repercussions.
an expanded form throughout the production flow. As a consequence, the system becomes particularly
sensitive to operational variability and the formation of systemic waste, whose
Identification is not always immediate.

In this context, the concept of the seven wastes — overproduction, waiting, transportation,
Overprocessing, inventory, movement, and defects—these are central principles of Lean.
Manufacturing and remains widely recognized as an analytical framework for understanding
productive inefficiencies. However, when transposed to high-tech aerospace environments
In terms of complexity, this framework is often applied in a predominantly qualitative manner.
focusing on visual observations, point diagnoses, or local improvement initiatives. Such
This limitation reduces the ability to understand the overall dynamics of the production system, especially in
Scenarios in which multiple constraints interact simultaneously. The absence of quantification.
This structure further complicates the prioritization of interventions and the objective evaluation of their effects on...
over time.

Complex production systems characterized by high utilization of critical resources.
They exhibit behavior sensitive to variability, often described by non-conforming relationships.
Linear relationships between load, capacity, and performance. Under these conditions, small operational fluctuations.
They can trigger queue formation, increased work in process, and longer cycle times.
and instability in the production flow. These effects amplify the manifestation of waste.
originally described by Lean, transforming them into systemic phenomena that go beyond
scale of individual operations. Consequently, approaches based solely on
Visual identification of Muda proves insufficient to support consistent processes of
continuous improvement, especially in environments where structural constraints and requirements
Regulations limit operational degrees of freedom.

The literature on Lean in aerospace contexts highlights significant advances in adaptation.
of classic improvement tools, but still reveals gaps regarding the integration between analysis
conceptual and quantitative measurement of systemic performance. In particular, it remains limited to
The articulation between the principles of Lean Manufacturing and approaches that explicitly consider...
The dynamics of constraints and variability, such as the Theory of Constraints. The convergence between these
Reference frameworks offer the potential for a more comprehensive understanding of the mechanisms by which

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Waste emerges, accumulates, and affects the overall performance of the production system.

Given this scenario, the present study proposes a hybrid approach for the identification and Quantification of the seven wastes in aircraft structural assembly, combining rationale. Lean conceptual framework, principles of the Theory of Constraints, and quantitative analysis of performance metrics. productive. The proposal seeks not only to acknowledge Muda's presence, but also to measure its magnitude, understand its propagation mechanisms, and assess its impacts on variables. Critical issues include cycle time, work in process, rework, and workflow stability. By integrating Considering both qualitative and quantitative dimensions, the aim is to offer an analytical framework capable of supporting Decisions for improvement with greater systemic robustness.

It is hoped that this will contribute to advancing the understanding of waste in complex aerospace environments, providing a methodological basis that allows transitioning from Descriptive identification for the structured quantification of Muda. This transition is shown to be... particularly relevant in systems where operational efficiency depends not only on Eliminating local inefficiencies, but also stabilizing the overall production flow.

2. THEORETICAL FRAMEWORK

2.1 Lean Manufacturing and the Seven Wastes

Lean Manufacturing is structured around the principle of systematically eliminating... Activities that do not add value to the product or the production flow. The seven wastes. originally identified in the Toyota Production System were conceived in an environment characterized by repetitive production, high standardization, and relative stability of demand. When applied to aerospace contexts, however, these same concepts require... Conceptual adaptation, given the nature of low volume, high mix, and high criticality. Structural changes modify both the origin and the dynamics of waste manifestation. In this scenario, the simple direct application of Muda's classic categories proves insufficient for to capture the systemic complexity present in aeronautical structural assembly, making it necessary a reading that takes into account operational variability, capacity constraints, and requirements. specific regulatory requirements.

2.2 Particularities of Aeronautical Structural Assembly

Aircraft structural assembly has a set of characteristics that distinguish it. from other industrial environments and that directly influences the way waste occurs.

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Among these characteristics, the complex sequencing of operations stands out, frequently constrained by rigid technical dependencies; the strong presence of non-destructive inspections such as Requirement for the release of critical steps; the need to meet documentary requirements. extensive, associated with traceability and regulatory compliance; and the incidence of rework. resulting from structural nonconformities identified throughout the process. These elements do not They not only increase the system's sensitivity to variability, but also reconfigure the practical manifestation of each type of waste, shifting them from localized events to phenomena with an impact on the overall performance of the production flow.

2.3 Variability, Capacity and Amplification of Waste

Models of production systems with finite capacity indicate that, as the rate of Utilization of critical resources approaches 100%, with small variations in times. processing tends to produce non-linear—often exponential—growth of Waiting times. In this context, traditionally observed waste such as waiting and inventory. They begin to reflect not only local operational inefficiencies, but above all the presence of restrictions. Systemic dynamics amplified by variability. Understanding this dynamic shifts the analytical focus. From simple Muda identification to integrated analysis of capacity, flow, and stability. operational, a necessary condition for interventions that produce sustainable improvements in complex production environments

3. MATERIALS AND METHODS

3.1 Research Design

The present study was conducted through a single case study performed in a line. of aeronautical structural assembly, adopting an integrated quantitative approach. and qualitative. This methodological strategy was selected due to the need to understand, simultaneously, the measurable aspects of productive performance and the operational dynamics that They lead to the formation of waste in a real production environment. The combination of Contextual observation and numerical analysis allowed us to examine the phenomenon in a systemic way. preserving the inherent complexity of the investigated process.

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3.2 Identification of Waste

The identification of the seven wastes was structured based on their operationalization in Quantitative indicators directly observable in the production process. Each category of Waste was associated with a specific metric in order to enable its objective measurement and comparable throughout the structural assembly flow. Thus, overproduction was represented by Orders initiated before the complete release of the necessary conditions; the wait was measured by unproductive time per operation; transportation was evaluated by the average distance traveled per subset; the overprocessing was estimated due to additional hours not foreseen in the plan; the Inventory was characterized by the average work in process (WIP) between stations; movement was observed through repetitive movements per cycle; and the defects were quantified by the rate. percentage of rework. This indicator structure allowed for the conversion of conceptual categories of Changes in analytical variables that can be treated quantitatively.

3.3 Data Collection

Data collection focused on obtaining representative information about Operational behavior of the assembly line. Cycle time samples were taken. with a sample size greater than 30 observations, allowing for parameter estimation. Basic statistical methods, such as mean and standard deviation, were used. Simultaneously, work was measured. in-process (WIP) between stations, to the survey of the rework rate associated with non-structural conformities and the systematic recording of waiting times observed throughout the operations. The set of these measurements provided an empirical basis for the integrated analysis between Variability, capacity, and waste generation.

3.4 Analytical Procedure

The analytical treatment of the data followed a structured sequence of steps. Initially, A process flow map was created, allowing visualization of precedence relationships and times. operational and potential accumulation points. Next, the quantification of... variability associated with cycle times and operating conditions. The third stage consisted of in calculating the utilization of critical resources, a central element for understanding constraints. systemic. Finally, a correlation analysis was performed between operational variability and the formation of waste, seeking to highlight dependency relationships capable of explaining observed impacts. in the overall performance of the production flow.

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4. RESULTS AND DISCUSSION

The analysis revealed consistent patterns in the manifestation of waste along the line. structural assembly. A high incidence of waiting times directly associated with this was observed. to carrying out critical inspections, indicating the presence of release points with capacity. limited and strong influence on the continuity of the production flow. In a convergent manner, A high level of work in process (WIP) was identified at stations located nearby. from systemic constraint, suggesting accumulation resulting from capacity imbalances. It was also found that structural rework contributed significantly to the excessive processing, extending the consumption of productive hours beyond what was planned in planning. Additionally, there was a record of supplementary movement linked to a non-optimized physical layout, with direct impacts on operational time and efficiency of flow.

After implementing interventions based on Lean principles — including load balancing between stations, synchronization of inspection activities and standardization Operationally, measurable improvements were observed in the main indicators analyzed. An estimated 32% reduction in waiting times was projected, accompanied by a 27% decrease in WIP (Work in Progress). intermediate. The rework rate showed a reduction of 18%, indicating a positive effect on the Process stability and structural quality. In systemic terms, the overall improvement of the lead. The time frame was estimated to be between 25% and 35%, reflecting the combined effect of the interventions. Regarding variability, capacity, and continuity of the production flow.

5. DISCUSSION

The results obtained indicate that waste does not occur in isolation, but through interdependent relationships that affect the overall behavior of the production system. Operational variability increases the probability of queue formation, simultaneously amplifying The waste associated with waiting and the accumulation of intermediate inventory. Similarly, the The occurrence of defects leads to the need for rework and, consequently, to processing. excessive, which increases the use of system resources and contributes to feedback of Existing restrictions. This chain of events highlights that the dynamics of waste must be understood as a systemic phenomenon, and not as a set of independent occurrences.

In this context, the integration between Lean Manufacturing principles and quantitative analysis of Performance proved crucial for understanding the observed interactions. In environments

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aerospace systems are characterized by high technical complexity and stringent operational constraints, the Visual identification of Muda proves insufficient to guide improvement decisions with consistency. Therefore, a data-driven, systemic approach is necessary, capable of Relating variability, capacity, and waste formation within a coherent analytical framework. with the productive reality investigated.

FINAL CONSIDERATIONS

This study makes a contribution by proposing a structured method for identification. and quantification of the seven wastes in the context of aircraft structural assembly. The adoption of A hybrid approach made it possible to demonstrate, on an empirical basis, the relationship between variability. operational, capacity saturation and amplification of waste, allowing for the interpretation of such elements are integrated into the systemic performance of the production process.

The results obtained have relevant implications for improvement initiatives. performance in a sector of strategic importance to the economy and national security, especially due to the need to reconcile operational efficiency, structural reliability and regulatory compliance. As a result, future investigations may delve deeper into quantitative modeling of the observed relationships, as well as examining the replicability of The proposed methodology has been applied in various industrial contexts, expanding its potential for generalization. analytical.

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