Analysis of the Impact of External Factors on Human Errors in a Typical Aero-Engine Plant

Artin Markousian

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By: Artin Markousian

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Signed by the final Examining Committee:

______________________________ Chair

Dr. Mingyuan Chen

______________________________ Examiner

Dr. Mingyuan Chen

______________________________ Examiner

Dr. Andrea Schiffauerova

______________________________ Supervisor

Dr. Masoumeh Kazemi Zanjani

Approved by ____

Dr. Martin D. Pugh

Chair of Department of Mechanical, Industrial, and Aerospace Engineering

December 6, 2021 ____

Dr. Mourad Debbabi

Dean of Gina Cody School of Engineering and Computer Science

Abstract

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Aero-engine assembly activities type and volume limit the manufacturers' ability to automate all processes; thus, the assembly of engines and many supporting processes heavily rely on the operators' skills. Human operators show significant variability in their performance, which is usually referred to as human errors. Such errors are identified as the Escape to perform an action within the safe operating limits and often lead to quality defects. With a particular focus on one of the engine families (Group A engines) of a typical aero-engine plant, the first objective of our analysis revolves around identifying the interruptions and distractions incurred during the engine assembly process that can potentially lead to quality defects induced by human errors. Based on the analysis of the quality reports, the group A engines produced in this facility have a higher percentage of quality defects as compared with the average quality defect rates of other engine groups within the company.

It is noteworthy that quality reports suffer from a lack of information regarding the relationship between reported quality defects and human errors. In other words, the data extracted from these reports cannot be directly used to identify sources of such errors. Therefore, two main data collection methods, namely observations through site visits and interviews, are alternatively used. Afterward, a combination of various Lean Manufacturing and quality engineering approaches, namely Value Stream Mapping (VSM), cost of quality escapes, cause-and-effect diagram, Escape Mode and Effect Analysis (FMEA), and Analytic Hierarchy Process (AHP) are explored to provide a prioritized list of external root causes that can potentially lead to human errors at the assembly facility.

The current Value Stream Map analysis results, along with our observations from the assembly facility and the conducted interviews, are presented as twenty-five sources of interruptions and distractions that could be the root causes of quality defects (due to human errors). The results are summarized in a fishbone diagram with six major categories; material, communication, manpower, methods, environment, and movement. Afterward, by using FMEA and AHP methods, those twenty-five sources of interruptions and distractions are prioritized. Results revealed that the leading root causes include: Reworks/QNs/Andons; insufficient root

cause analysis of frequent problems/breakdowns; frequent changes in production priorities; informal information flow and inaccuracy of transferred information; distractive people or activities in assembly area; slow and complicated procedure of technical support; lack of inspection or quality control between sub-assemblies; and inefficient order of executing assembly flow sequences.

The second goal of this study is to propose Lean manufacturing and quality engineering solutions in order to eliminate the root causes identified in the first objective. The proposed solutions rely on: *i*) improving the quality control system via enhancing the documentation methods for recording quality Escape; in addition to *ii*) developing a Split Mixed-Model VSM for the engine assembly facility. The first solution, in particular, aim to use statistical control tools and root cause analysis to reduce assembly Escapes caused by human errors. Implementing a Split Mixed-Model VSM, on the other hand, contributes to a smooth flow of products while systematically eliminating sources of interruptive and distractive issues during the assembly process. More precisely, it mainly targets the elimination of quality defects caused by stoppages due to shortage of components/sub-assemblies, late delivery of materials, delivered materials with quality defects, and insufficient assemblers or support teams. In other words, the proposed split mixed-model value stream is expected to favourably affect the quality and performance of the process in this plant. When developing this VSM, the order of doing assembly instructions is rearranged; the new *TAKT* time for each engine model in the Group A engine family is calculated, and a new layout for the assembly facility is accordingly provided.

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Introduction

Human operators show significant variability in performance when operating in complex manufacturing systems that are usually referred to as human factors. Such errors are identified as the Escape to perform an action within the safe operating limit and often lead to produce quality defects. Aviation safety depends on minimizing errors in all facets of the system. There has been significant improvement in the facilities and equipment's reliability and stability in the production and assembly systems. However, human error remains one of the most significant causes of quality defects in manufacturing systems. According to the literature, about 70% - 90% of quality defects in the assembly production systems are directly or indirectly due to human errors (Wang, 1997).

Rasmsussen (1982) associates human errors with both the mechanisms of human information processing malfunction, the task, situation factors (task, physical, and work time characteristics), operator effect and intentions, and ultimately the external factors causing the error. With a particular focus on one of the engine families ("Engine Group A") assembled in a typical aero-engine plant, the main objective of the first phase of this project is to identify external factors that can potentially cause human errors in the assembly center. In other words, the main focus of our analysis revolves around interruptions and distractions incurred during the engine assembly process that can potentially lead to quality defects induced by human errors. In general, distractions in a manufacturing process can be defined as any external factor, such as noises, unavailability of tools, parts, machine break down, etc., that could negatively influence the performance of the operators.

Engine assembly is the last step in the value stream of engine manufacturing and, hence, directly impacted by perturbations in the upstream entities, such as sub-assembly manufacturing units and external suppliers. Late delivery of parts, changes in engineering requirements, and production priorities are a few examples of such disruptions, among others. In other words, the engine assembly work environment is subject to an ever-changing cycle of slack time, pressure, lateness, delay, changing priorities, rework, and new requirements. While the operators are usually very well trained in this industry, they may miss a step, overlook an incorrectly installed part or make an error in their documentation every once in a while. The solutions to these events are often narrowly focused on the specific issues and overlook the underlying root causes of human errors.

Relying on the analysis of historical defect data supplemented with a detailed analysis of work environment, procedures, and delays as well as stoppages in the engine assembly center, our first objective is to provide a prioritized list of the root causes of the aforementioned distractions and disruptions that eventually lead to human errors. Our methodology mainly relies on Lean Manufacturing and Six Sigma, in particular Value Stream Mapping, Escape-Mode-and-Effect-Analysis (FMEA), and Analytical Hierarchy Process (AHP). Relevant data are collected via multiple site visits and semi-structured interviews conducted in the assembly facility along with all departments that exchange material and information with the assembly plant. Our second objective revolves around developing a split mixed-model value stream map along with the corresponding facility layout. This new production model aims to reduce disruptions and stoppages identified in the first contribution and ultimately reduce human errors caused by them.

The remainder of this report is organized as follows. In chapter 1, brief overviews of the quality defect statistics in this center are provided. Chapter 2 summarizes the main categories of human errors according to a brief survey of the literature and presents a literature review of Lean manufacturing approaches with a particular focus on mixed manufacturing models. Chapter 3 presents the results of our first contributions by laying stress on the analysis of quality defects associated with human errors in this site. A detailed description of the adopted methodology, the analysis of the collected data, the prioritized list of root causes, along with the list of our recommendations based on the root cause analysis are also presented in this section. Chapter 4 describes our efforts to improve the quality control system and documentation methods of quality Escape, whereas chapter 5 illustrates our steps to develop a new value stream (Split Mixed-model). Concluding remarks and future avenues for extending the current study are provided in chapter 6.

Chapter 1

A Typical Aero-engine Plant in terms of Quality Assurance

The aero-engine plant presented in this study produces multiple engine families with different models and variations of engines for applications such as business, commercial and regional aviation and helicopters. These engine families presented as “Group A” to “Group H.” A short description of these engine families is presented in Table 1. Among those engine families, the “Group A” engine family is selected for further analysis.

Engine family	Short description
Group A	A typical family can be a turboprop engine family. This family is presented in three main categories (A-1, A-2, and A-3).
Group B	A typical different engine family may be a variation of Group A to be used for different applications, such as in a different aerial vehicle type.
….	
Group H	Additional engine families may manufacture further variations of the main Groups A and B, for use in other applications and/or vehicles.

Table 1. Engine Families produced at a typical assembly facility

1.1. Quality Control in a Typical Aero-engine Plant

1.1.1. Quality Control during the Production Process

During the production process and before sending the engine to the customer, there are at least three quality inspections:

1. The in-process inspection: Performed by assemblers as part of the assembly instructions. Information is collected whenever a damaged part is involved.
2. The Engine test in test cells: In this case, data is generated when issues are detected.
3. The Visual Inspection of the engine:
   3.1. Inspection Checklist (ICL): Some specific visual cues are checked directly by the quality inspector.
   3.2. Final visual inspection: is done by an inspection robot, then validated by a quality inspector.

1.1.1.1. In-process Inspection

This inspection concerns different levels of verification embedded in the sequence of assembly operations. For each assembly operation, there is a set of instructions grouped in assembly instructions containing detailed steps of how the worker needs to proceed. The detailed steps of operations are displayed to assemblers on a screen in a workstation near the assembly station. The assembler must follow the entire sequence of steps described in the assembly instructions and displayed by the system on the screen. The work instructions system is designed in a way that validations are systematically required after finishing a sequence of steps. Some of the steps in the assembly instruction are related to the inspection or verification that must be done by the worker, or by a co-worker, in the case of witness inspection. In-process inspection issues are corrected during the assembly process.

In this way of conducting in-process quality inspection by assemblers, the assembler needs a witness-assembler to validate the quality of their work (witness inspection and check inspection).

1.1.1.1.1. Quality Notification

The QN is a process for detailed documentation of the condition of potentially non-conforming parts. The analysis will establish if the issue is out of the boundaries of acceptability of the product, and then the part can be accepted, or deemed for repairs, rework, or scrap. Quality notification can be opened by a request from the supplier (RFA in figure 1), or after receiving the part from suppliers (at the receiving department), or it can be opened in the assembly facility during the assembly process (Figure 1).

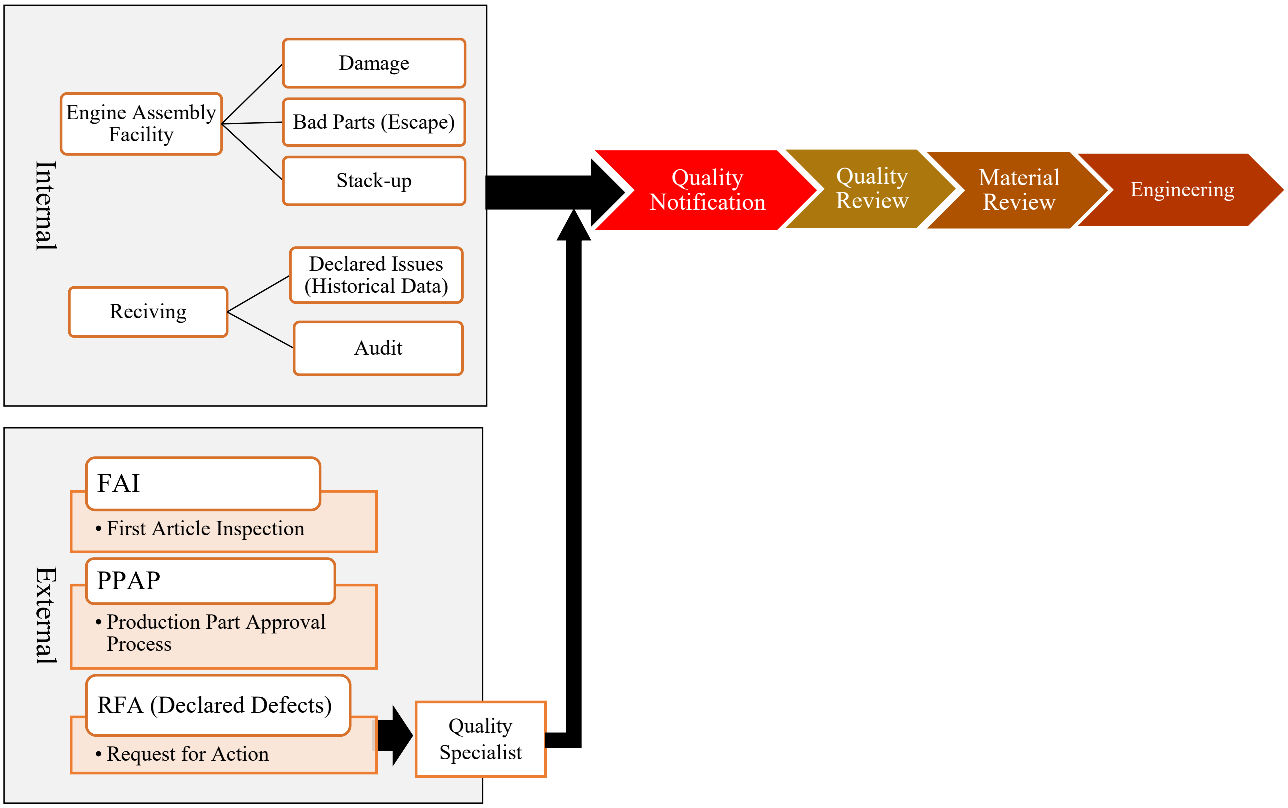

Figure 1. Quality Notification (QN) and its' following up process

During the assembly process, some parts could be detected as having quality issues, and then a process of verification is established. In other cases, some parts of the engine suffer damages generated by operations or manipulations conducted by the assemblers, generating some quality notifications (QN) as a result of manual assembly.

There is a follow-up process for parts damaged as a result of assembly operations.

The follow-up process involves complexity and processing time to follow-up, investigate, and close a QN request, as shown in figure 1. An open quality notification could arise in the system and stop the assembly process, causing interruptions and materials shortages that will consequently interrupt the production flow.

1.1.1.2. Engine Test Cells

Engines are tested once the assembly is completed. This is conducted in test cells, a specialized facility where engines can run safely during the test. Tests are conducted to evaluate the performance of the engine in a relationship with several parameters like vibration, combustible consumption, and performance in general. A certain amount of assembly quality issues can be detected during this process if there is an impact on the performance of the engine. If an engine does not pass the test, an analysis is done to find the root cause of the issue. Almost 10 % of engine retests can be associated with manual assembly. In the case of retests, the investigation process is conducted by the Assembly and Test Technical Support, and usually, quality specialists are involved, but the process is not the same as for the original equipment manufacturer intervention (OEMI) and visual inspection. Typical percentages of retested engines in a given year compared to the total delivered engines in the same period of time for a typical aerospace company may range from 4% to 20%.

1.1.1.3.Visual Inspection of the Engine

At the end of the assembly process, there is a computerized visual inspection system. This system is basically a robot that conducts visual inspection by taking pictures of the engine. Once this step is completed, these pictures are compared to a reference. The reference is called the golden engine, and there is a set of images in a database already taken from this golden engine or an engine considered not to have defects. Pictures taken by the visual inspection system are systematically compared with the reference. Each model of the engine has a golden engine in the database to compare with. According to the visual inspection system manufacturer, the system can validate the final assembly based on its capabilities to perform optical character recognition. This system looks for deviations in forms and colours and can detect quality issues mainly related to physical components in the exterior of the engine. Once the visual inspection system detects a deviation, a human validation is necessary to confirm the case because of false positives. False-positive represents all those occasions in which the visual inspection system triggers an alarm, but there was no quality issue. This is the result of the robot having high sensitivity.

The Inspection Checklist (ICL) is a human visual inspection conducted at the end of the assembly. This inspection is conducted in complement to the automated inspection since the visual inspection system has limits in the spectrum of visual issues that the system can detect. The ICL is constituted by physical manuals of inspection for each of the engine models. These manuals have a set of pictures with instructions for the quality specialist. Instructions indicate what specific parts to verify. In this case, quality issues are detected at the final inspection just before leaving production facilities. Thus, the visual inspection system & ICL could be considered the last barrier before the engine leaves the production facility. It has been found that for some aerospace companies, the final visual inspection can represent a majority of all quality issues detected at different levels of the barrier system. So, it comprises a significant source of data. For example, it has been found that the percentage can range from 0% to 80% of all issues detected for a given engine family over a given year.

1.1.2. The original equipment manufacturer intervention (OEMI)

Any quality issues detected once the engine has been already delivered to the client (aircraft manufacturer) must be raised as OEMI. It could be visual or operation-related, non-conformance on the engine or engine parts, or other events that need to be recorded for future reference, e.g., metal in the oil, low oil pressure, shipping damage to the box, etc. Not all quality issues detected once the engine is delivered (OEMI) are related to an in-process source, such as the damage during manipulation and transportation. When OEMI's are linked to the manufacturing process, they are considered as "Escapes". In other words, any raw material, parts, assemblies, engines, and IPPS (Integrated Power Plant System) that did not meet specified requirements and were or may have been released for further processing are considered as an Escape.

It has been found that for a typical aerospace company, the percentage of OEMIs from delivered engines for a given engine family can range from 0% to 10%.

1.2. Cost of Quality Escapes in a Typical Aerospace Assembly facility

The cost of quality escapes includes any cost that would not be expected if the quality were perfect. This includes the apparent costs of scrap and rework, as well as less obvious costs, such as the cost to replace defective material, expedite shipments for a replacement material, the staff and equipment to process the replacement order, etc. More specifically, quality costs are the total of the cost incurred by (a) investigating in the prevention of non-conformances to requirements; (b) appraising a product for conformance to requirements; (c) Escape to meet requirements. For most organizations, quality costs are hidden costs. Quality escapes impact companies in two ways: higher cost and lower customer satisfaction. Figure 2 illustrates the hidden cost concept.

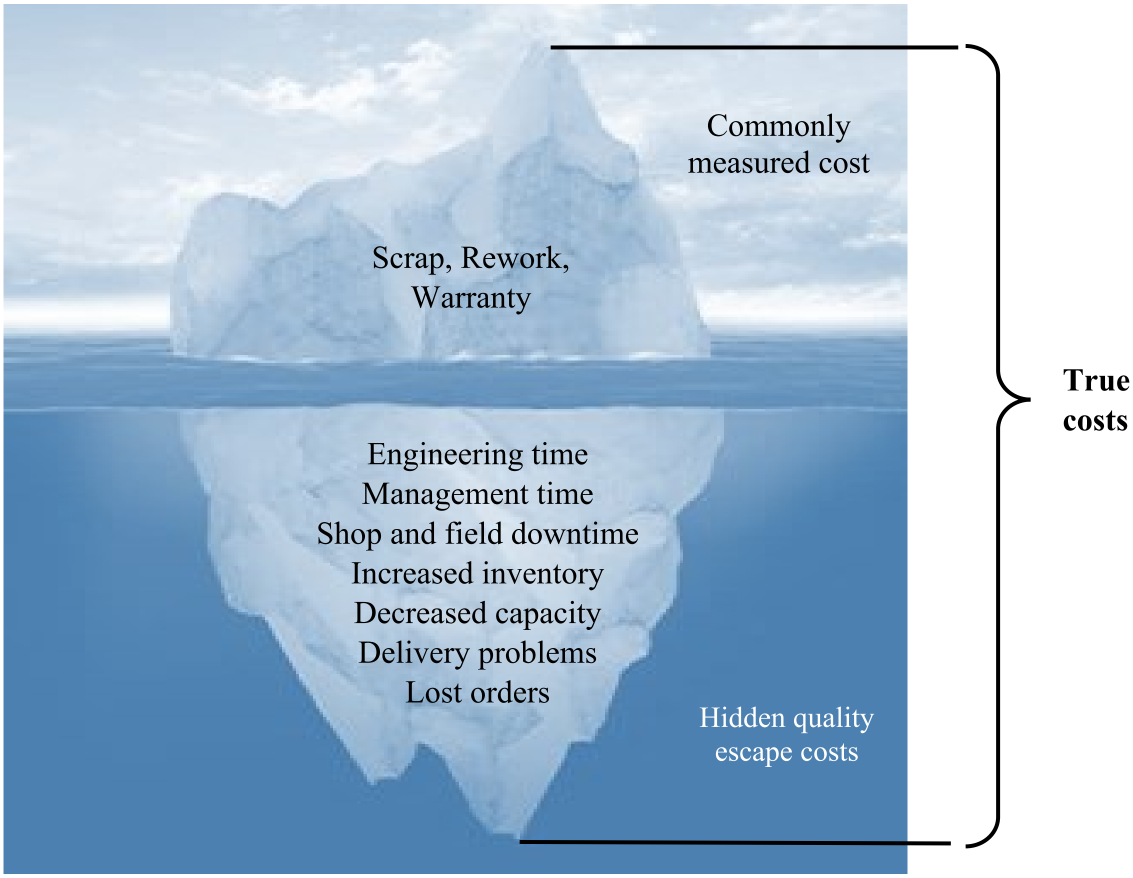

Figure 2.The hidden cost of quality and multiplier effect (Pyzdek, 2010)

As a general rule, quality costs increase as the detection point moves further down the production and distribution chain. The lowest cost is generally obtained when errors are prevented in the first place. Another advantage of early detection is that it provides more meaningful feedback to help root causes. The time lag between production and field Escape makes it very difficult to trace the occurrence back to the process state that produced it. While field Escape tracking is prospectively evaluating a “fix,” it is usually of little value in retrospectively evaluating a problem (Pyzdek, 2010).

The results reveal that the scrap, rework, and repair costs can surpass a given year’s total budget for SRR costs and negatively affect a company's net profit. Another source of the cost of quality escapes is the labourers’ hours used for doing the engines’ retests. During a given year, thousands of hours of labourers’ hours can be dedicated to engine retest activities. It is essential to mention that these analyses can include in large part the scrap, reworks, and warranty-related activities and do not include all the hidden Escape costs, such as engineering time, management time, and total downtime.

1.3. Human errors in a Typical Aero-engine Plant

Analysis was conducted on engines returned to the maintenance facility of a given Aero-engine company to categorize the causes of quality escapes. Based on these analyses, the most important causal factor that causes the highest number of quality escapes for a typical company can be “Human factors.” Human Factors can represent a majority of all quality escapes in a given year.

Moreover, these analyses provide a list of human factors that can cause quality defects in engines. The human factors can include; distractions, task execution, part setup, adjustment, communication, instructions interpretation, fatigue, training, and tool selection. It has been found that the most important causes of human errors can be related to interruptions and distractions during the assembly of the engines. For instance, these could be the result of stoppages on the assembly line or distracted assemblers.

These results revealed that up to 70 to 80% of quality defects in a given company could be related to human factors in a given year. It is important to note that our focus in the project is on external factors among all human factors that may cause quality escapes. This emphasizes the need for aero-engine manufacturing companies to focus on all sources of distractions and interruptions during engine assembly in assembly facilities.

Chapter 2

Literature Review

2.1. A review of Human Errors in Manufacturing

Human operators show significant variability in performance when operating in complex manufacturing systems that are usually referred to as human errors. Such errors are identified as the Escape to perform an action within the safe operating limit and often lead to produce quality defects. There is increasing evidence that human error is a major contributor to system risk: approximately 50%-80% of the incidents and accidents in safety-critical systems have been associated with human error.

Despite the recent technological advances in eliminating errors in the design and manufacturing of aircraft engines, at least some engine assembly centers around the world can still be heavily dependent on human interventions.

2.1.1. Understanding Human Escape

Two major approaches have been developed to address human error in accident and incident analyses: human reliability assessment (HRA) and Human error classifications (Gertman, 1993 and 2004). The HRA approach identifies all risks associated with human error that a system is exposed to, describes associations among these risks, quantifies risk likelihood, and expresses this information in a fault-tree presentation. In particular, human errors are identified as the Escape to perform an action, Escape to perform an action within the safe operating limits (i.e., time, accuracy, etc.), or performance of an irrelevant action that degrades system performance.

As opposed to the HRA approach, human error classification schemes are more qualitative and can be classified as behavioural, contextual, or conceptual in nature (Reason, 1990). Behavioural classifications describe human errors as easily observed surface features via partitioning them to characteristic dimensions (omission, commission, extraneous), immediate consequences (extent and nature of damage), observability of consequences (active/immediate vs. latent/delayed), degree of recoverability, and responsible party. Contextual classifications begin to address causality by associating human errors with characteristics of the environmental and task context. However, these classifications are correlational and cannot explain why similar environmental circumstances do not deterministically produce repeatable errors. Conceptual classification, on the contrary, attempts to establish causality in terms of more fundamental and predictable characteristics of human behaviour. Such classification methods usually begin with a model of human information processing and define error types based on the Escape modes of information processing stages. In other words, they address the error proneness of the information processing mechanisms of an individual operator.

Based on conceptual classification systems, there are two main types of human Escape:

- Human error: an unintentional action or decision.
- Violations: intentional Escapes (deliberately doing the wrong thing)

Different types of human Escape have been summarized in Figure 3. (Latorella, 2000).

However, to fully address the causes and effects of human error, a more holistic approach is required. Rasmsussen (1982) emphasis this needs to place errors in a rich context. His classification (table 2) considers not only the mechanisms of human information processing malfunction but also the task, situation factors (task, physical, and work time characteristics), operator effect and intentions, and ultimately the external expression of the error.

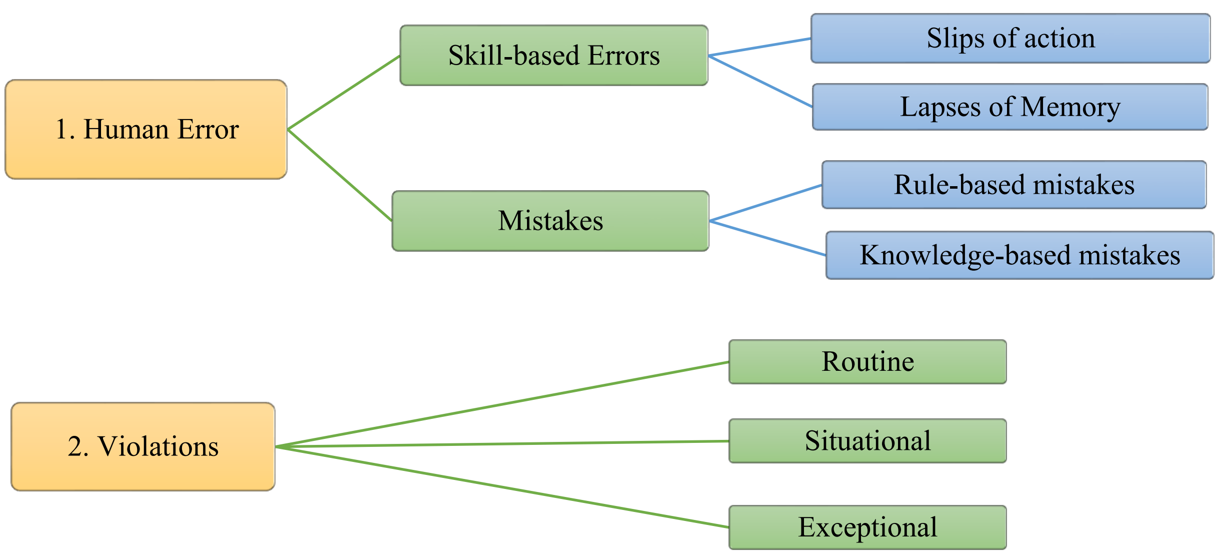

Figure 3. Different types of human Escape (Latorella, 2000)

Table 2. Some of the Multifaceted Human error taxonomy (adapted from Rasmussen (1982))

Factors Affecting Performance
Subjective Goals and Intentions
Equipment/procedure design, installation, inspection, etc.
Affective factors
Internal Human malfunction
Identification
Decision
Action
Causes of human malfunction
External events (Distraction, Interruption, etc.)
Commission of an erroneous act
Commission of an extraneous act
Mechanisms of human malfunction
Accidentally coincidental events (Sneak path)
Input information processing
Recall

2.2. A Literature Review on Lean Manufacturing Practices

This section provides a brief literature review on Lean manufacturing concept and implementation along with relevant research on mixed-model and split-line production systems.

2.2.1. Lean production

Reviewing the existing literature provides a starting point in defining lean production. In conducting our review, we began with the earliest publications related to Japanese manufacturing/ production systems, ending with lean production's most recent publications. Moreover, this review reveals that quality and quality management programs do not receive enough attention in lean research and implementation.

Lean production is generally described from two points of view, either from a philosophical perspective related to guiding principles and overarching goals (Womack, 1996; Spear, 1999) or from the practical perspective of a set of management practices, tools, or techniques that can be observed directly (Shah, 2003 & 2007).

Following some conceptual definitions of lean production from different literature are presented in 2 categories;

- **Toyota production system (TPS)**
- The basic idea in Toyota Production System(TPS) is to produce the kind of units needed, at the time needed and in the quantities needed such that unnecessary intermediate and finished product inventories can be eliminated. Three sub-goals to achieve the primary goal

of cost reduction (waste elimination) are quantity control, quality assurance, and respect for humanity. These are achieved through four main concepts: JIT, autonomation, flexible workforce, and capitalizing on worker suggestion and eight additional systems (Monden, 1983).

- Toyota Production System (TPS) includes standardization of work, uninterrupted workflows, direct links between suppliers and customers, and continuous improvement based on the scientific method (Spear, 1999).
- Lean production is an integrated system that accomplishes the production of goods or services with minimal buffering costs (Hopp, 2004).
- **Just in time (JIT)**
- JIT is based on eliminating waste by simplifying manufacturing processes, such as eliminating excess inventories and overly large lot sizes, which cause unnecessarily long customer cycle times (Flynn, 1995 a,b).
- JIT is composed of three overall components, namely, flow, quality and employee involvement (McLachlin, 1997)
- Kanban system, production smoothing and set up time reduction are critical components of any JIT system (Monden, 1981b).

Taj and Morosan (2011) describe lean manufacturing as a multi-dimensional approach that consists of production with a minimum amount of waste (JIT), continuous and uninterrupted flow (Cellular Layout), well-maintained equipment (Total Preventive Maintenance (TPM)), well-established quality system, and well-trained and empowered workforce (Human Resource Management (HRM)) that has a positive impact on operation/competitive performance (quality, cost, fast response, and flexibility).

2.2.2. Lean implementation

Shah and Ward (2003) developed lean manufacturing measures and operationalized them as bundles of practices related to JIT, TQM, TPM, and HRM. They limit their analysis to four bundles that are oriented internally to reflect a firm’s approach to managing its manufacturing operation. All practices related to production flow were combined to form the JIT bundle. The underlying rationale is that JIT is a manufacturing program with the primary goal of continuously reducing and ultimately eliminating all forms of waste (Sugimori, 1977). Two significant forms of waste are work-in-process (WIP) inventory and unnecessary delays in flow time. Both can be reduced by implementing practices related to production flow, such as lot size reduction, cycle time reduction, quick changeover techniques to reduce WIP inventory, implementing cellular layout, reengineering production processes, and bottleneck removal. Practices related to continuous improvement and sustainability of quality products and processes were combined to form the TQM bundle. It includes practices such as quality management programs, formal continuous improvement programs and process capability measurement capability. The TPM bundle includes practices primarily designed to maximize equipment effectiveness through planned predictive and preventive maintenance of the equipment and maintenance optimization techniques. More generally, emphasis on maintenance may also be reflected by the emphasis given to new process equipment or technology acquisition (Cua, 2001). The HRM bundle has significant theoretical and empirical support. The most commonly cited practices are job rotation, job design, job enlargement, formal training programs, cross-training programs, work teams, problem-solving groups, and employee involvement. In order to have a flexible cross-functional workforce, a job rotation program, job design, and formal cross-functional training programs have to be in place. Similarly, self-directed work teams are required, such that employees are organized in work teams and involved in problem-solving groups (Shah and Ward, 2003).

In another research, Shah and Ward (2007) identified 48 practices/tools to represent lean production's operational space. They distill these tools into ten factors. Together, these ten factors constitute the operational complement to lean production philosophy and characterize a lean system's ten distinct dimensions. They are composed of supplier feedback, JIT delivery by the supplier, supplier development, customer involvement, pull system, continuous flow, set up time reduction, total productive/ preventive maintenance, statistical process control, and employee involvement.

The main objective of lean production is to eliminate waste by reducing or minimizing variability related to supply, processing time, and demand. The ten underlying factors/dimensions of lean production jointly enable firms to address variability in the following manner. In order to facilitate continuous flow, products are grouped according to product families, and equipment is laid out accordingly; and in order to prevent frequent stop-and-go operations, the equipment undergoes frequent and regular preventive maintenance (TPM). Closely grouped machines and the similarity of products allow employees to identify problems while cross-trained, self-directed teams of workers are able to resolve problems more quickly and effectively (Employee involvement). Actively involved customers (Customer involvement) enable firms to predict customer demand accurately. Reduced set-up times and stricter quality assurance methods (SPC) allows firms to predict process output more precisely. To produce the kind of units needed, at the time needed, and in the quantities needed, firms use kanban and pull production systems, which require that suppliers deliver sufficient quantities of the right quality product at the right time. This JIT delivery by suppliers relies on providing suppliers with regular feedback on the quality and delivery performance (Supplier feedback) and providing training and development for further improvement (Supplier development).

A case study conducted by Sundar et al.(2014) revealed that the significant elements explored in earlier studies for the implementation of lean manufacturing incorporate the following concepts:

- *Value Stream Mapping (VSM)*, which entailed mapping of each and every activity including Value-Added (VA) and Non-Value-Added (NVA) tasks required to convert the raw material into the finished product by incorporating the information flow essential to link different activities.

- *Push and Pull system:* a Pull system relies on customer requirements, whereas a push system relies on a predetermined schedule.

- *Cellular manufacturing* relates to the facility grouping to produce the product with minimum process time, waiting time, and transportation by smoothening the process flow. Further fluctuating line flow is improved by the U-line concept and line balancing concept.

- *Kanban* is the material flow Control mechanism (MFC) that delivers the right quantity of parts at the right time. The stages of this Kanban implementation include the production stage and withdrawal stage.

-*One-piece flow* ensures a just-in-time production system to adopt a detailed schedule without interruption, backflow or scrap, relaxing the Takt time and decreasing the risk of machine failures and operator mistakes.

-*Single Minute Exchange of Dies (SMED)/One-Touch Exchange of Die (OTED)* is the systematic reduction of changeover time by converting possible internal setting time (carried out during machine stoppage) to external time (performed while the equipment is running).

- *Production Levelling* enhances production volume, mix, and efficiency by reducing waste, unevenness, and overburden of people or equipment. Levelling of parts leads to a successful implementation of the Every Part Every Interval (EPEI) concept.

- *Employee perceptions* include belief, commitment, work method and communication.

2.2.3. Mixed-model Production lines and Splitting the Assembly line

Today's manufacturers need to improve both productivity and flexibility to satisfy the customers' demands. The mixed model line is a method of resolving such conflicting requirements. It allows the production of different models of a common base product in a facultative production sequence (lot size one) on a single assembly line. The mixed model technique is applied where the product variability is high. Given its high level of flexibility, it can adequately respond to the variability as needed (Duggan, 2013). Recent researches revealed that splitting a mixed model line by buffers into shorter lines further enhances productivity and flexibility (Zhang et al., 2017).

The existing studies on mixed production lines mainly focus on two types of production systems, i.e., job shops and flow lines. In the job shops, most researchers are trying to generate an optimal scheduling strategy for minimizing set-up time or the makespan of production systems to cope with many product models. In the flow lines, most literature focuses on long to medium-term problems in assembly production system design with only 2-3 product models for large volume industries, such as the automotive and chemical industries (Brigges, 2013).

According to the part group, some automobile factories have segmented mixed-model production lines into shorter sub-lines, such as engine, trim, and powertrain. The effects of splitting a line into sub-lines have been reported from the standpoints of cost, worker motivation, productivity improvement, and autonomy based on risk spreading. There has been no mention of the possibility of shortening the line length by altering the product sequence or improvement of quality (Zhang et al., 2017).

Monden (2011) examined the effect of splitting the assembly line at a Toyota automobile plant into several functionally diversified autonomous lines. According to the author, the functionally diversified autonomous line, or, in short, the split-line, is a mini-assembly line that similar parts from the viewpoint of car structure are rigorously grouped and assembled. It is also stated that a split line has two main advantages, including worker morale enhancement and productivity improvement throughout the assembly plant. The use of split lines decreases the stop time for the entire assembly plant. Christoph (2016) described the layout of the Toyota Plant by focusing on the topology of split lines, the number of stations of each split line, and buffer stocks' location. However, there has been no report on resequencing in buffer stocks between two functionally diversified autonomous lines.

Boysen et al. (2009) mentioned that a vital decision problem in a split-line context is the sequencing problem, which decides on the sequence in which the models are launched down the line. They reviewed and discussed three major planning approaches in the literature on mixed-model assembly lines: mixed-model sequencing, car sequencing, and level scheduling. The mixed-model sequencing approach attempts to minimize sequence-dependent work overload by using detailed scheduling, which explicitly considers the line's operational characteristics, such as operation times and worker movements. The car-sequencing approach attempts to minimize sequence-dependent workload implicitly by formulating a set of sequencing rules. The level-scheduling approach attempts to find sequences that are in line with the just-in-time (JIT) philosophy. The prerequisite for this approach is a steady demand rate of material over time. Based on their reviews, most studies on resequencing in a mixed-model assembly line adopt the car-sequencing approach.

However, If multiple departments with diverging sequencing objectives are to be passed or unforeseen disruptions like machine breakdown or material shortages occur, resequencing of a given production sequence often becomes equally essential. Boysen et al. (2012) presented a research framework for resequencing in a mixed-model assembly line and reviewed and summarized research based on this framework. The authors propose two resequencing approaches, namely a reactive one and a proactive one. Reactive resequencing is triggered by unforeseen disruptions such as material shortages, rush orders, machine breakdowns, and workpiece or material defects. Proactive resequencing allows for individual model sequences to be specifically reshuffled according to specific line segments' needs. Proactive splitting involves resequencing models before and after the buffers. An important aspect, therefore, is locating buffers between sub-lines. Four different types of buffers are mentioned in Boysen et al. (2012). An *automated storage and retrieval system (AS/RS)* is a resequencing buffer consisting of multiple buffer places. Each place can individually and independently be accessed for storage and retrieval of workpieces so that a buffer content can be reshuffled into a facultative model sequence. A *mix bank buffer* (also referred to as parallel line buffer or selectivity bank) consists of multiple parallel lanes without assembly operations, each having a restricted capacity for storing workpieces. A buffer consisting of multiple *pull-off tables* is situated right next to the line. Another buffer type is, *insert buffer*, composed of an overlap area between two line segments with two conveyors passing each other in the opposite direction. Monden (2011) described the advantages of reactive splitting based upon Toyota's production practices.

A mixed-model production has been identified as the possible solution for aircraft production with the advent of flexible tooling in a few studies. Most notably, Brigges et al. (2013) propose a methodology for designing the mixed-model production system for an aircraft assembly line. Moreover, they present a new scheduling approach by using combined backward and forward scheduling methods. Their methodology consists of three main stages: work content analysis, capacity requirement analysis and scheduling. They validate these methods through a real-life industrial example. Their numerical experiments reveal that by implementing the proposed approach, the number of workstations can be reduced by 50%, and the cycle time for making a fuselage can be reduced by 38%.

To the best of our knowledge, less effort has been made in the literature on the application of the mixed-model production concept in the context of aircraft engine assembly lines that manufacture a large number of engine models that belong to several families. This motivated us to investigate further this concept as an efficient method to reduce disruptions in the assembly of aircraft engines and eventually reduce human errors that are caused by such disruptions.

Chapter 3

Investigating the root causes of quality defects associated with human errors in a Typical Aero-engine Plant

3.1. Methodology

In order to investigate the external root causes of human errors in a typical engine assembly facility, a combination of different Industrial Engineering tools is recommended. More specifically, a combination of various Lean manufacturing approaches, namely Value Stream Mapping (VSM), cost of quality escapes, cause-and-effect diagram, Escape Mode and Effect Analysis (FMEA), and Analytic hierarchy process (AHP), are explored to provide a prioritized list of external root causes that can potentially lead to human errors.

- VSM, also known as material and information flow mapping, is a variation of process mapping. It looks at how value flows into and through a process to the customer and how information flow facilitates the workflow. VSM incorporates all value-added and non-value added activities that are required to bring a design from concept to launch, a product from raw materials into the hand of the customer, and a customer order to delivery.

In this project, the current VSM is analyzed with the aid of various Lean concepts for further analysis of the wastes and their root causes. In other words, all process steps and work practices are carefully evaluated to identify potential areas for eliminating stoppages of any sort. The goal is to improve the smoothness and continuity of how an object of value proceeds to the customer. As a result of this practice, we can expect further improvements in the quality of the products via fewer quality defects caused by interruptions, wastes, and distractions, improved lead time, and on-time delivery. The root causes of wastes and defects are usually summarized as a cause and effect (fishbone) diagram. Afterward, the root causes are prioritized by the aid of FMEA and AHP techniques.

FMEA (Pyzdek, 2010) is an attempt to delineate all possible Escapes, their effects on the system, the likelihood of occurrence, and the probability of undetected Escape. One objective of FMEA is to direct the available resources toward the most promising opportunities. An extremely improbable Escape, even an Escape with severe consequences, may not be the best place to concentrate preventive efforts. In this study, we use FMEA to prioritize the external root causes of human errors (i.e., distractions and disruptions). To this end, we use the AHP method to assign severity weights to the aforementioned root causes. The Analytic Hierarchy Process (AHP) is a multi-criteria decision-making approach and was introduced by Saaty (1980 and 1994). It uses a multi-level hierarchical structure of objectives, criteria, sub-criteria, and alternatives. The pertinent data are derived by using a set of pairwise comparisons. These comparisons are used to obtain the weights of importance of the decision criteria and the relative performance measures of the alternatives in terms of each individual decision criterion (Moore, 2001). Afterward, the rating for each decision alternative (in our case, root causes) for each criterion (in our case, severity level) is calculated (Render, 1999).

3.2. Data Collection

Two main data collection methods are used in our project - namely, observations through site visits and interviews. Through conducting several site visits in addition to participating in production meetings, we were able to collect essential data regarding the sequences of the typical assembly process (from receiving the materials to delivering the engines); the interruptions and stoppages during the typical assembly process; information and material flow; and all the groups that support the assembly process. We used a semi-structured interview, where a portion of questions and the order of such questions were pre-determined. However, an interviewer had flexibility in directing the focus of the interview by being able to ask further questions that were not part of the original interview questionnaire. As a result, information surrounding new or unexpected issues was often uncovered. The interviews were conducted with the departments of various manufacturers that directly support typical engine assembly activities and have an influence on materials, production, and information flow. Figure 4 illustrates the relationship between the aforementioned departments and a typical engine assembly facility. Finally, a site visit and an interview with the quality department were conducted to find out typical customers' feedback. The main topics include; 1) how the department/unit supports assembly activities; and 2) how these departments can assist the assembly facility to prevent interruptions during the assembly process and consequently improve the flow of information and material.

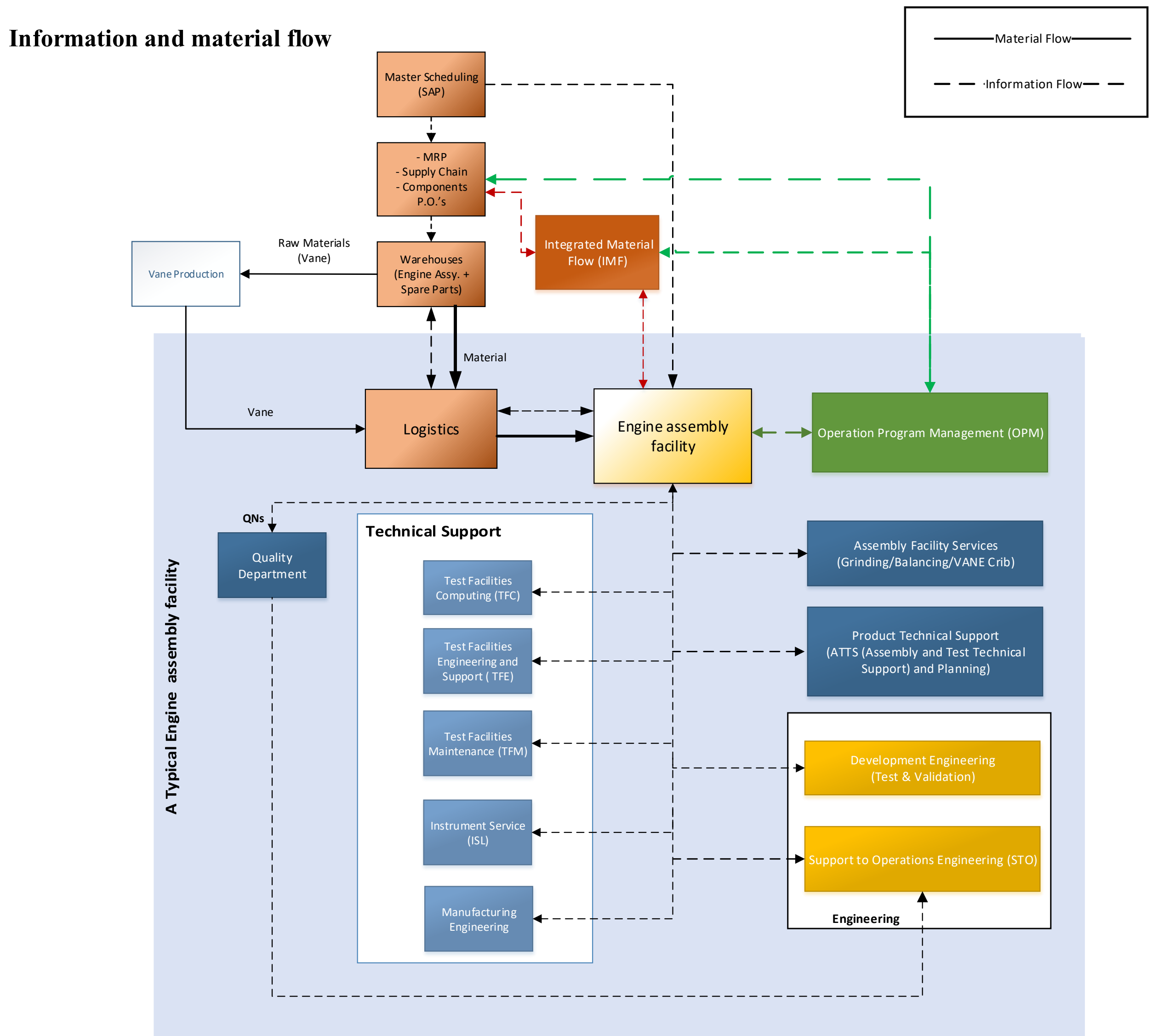

Figure 4. Information and materials flow between different departments and a typical engine assembly facility

3.3. Analysis of the External Causes of Human Errors

In this section, we first provide the current VSM along with a list of issues identified in terms of the flow of information and material flow. Afterward, we provide a summary of issues that can arise as were highlighted in the interviews. We finally provide a typical cause and effect diagram along with the list of prioritized root causes of external/internal disruptions/distractions identified by the aid of FMEA and AHP techniques.

3.3.1. Value Stream Map of the Engine Assembly Process of a typical Assembly Plant

The map is presented in Figure 5. Each box within this flowchart presents an assembly station and has a specific assembly instruction to follow. Further analysis of the VSM revealed the following issues that can cause disruptions in the assembly line and can potentially lead to human errors:

1. Any lateness of materials due to different problems, such as the delay from sub-assemblies, delays at solving a quality issue during the production process, and lack of enough resources to support the smooth production flow, adversely affects the production flow stopping the line and potentially causing quality defects.

a) The existence of an incomplete engine in the mainline assembly in case of delay from sub-assemblies is a crucial issue. This could increase the risk of quality defects as a result of:

- Damaging a part of an abandoned engine or accumulated inventory (WIP)
- Forgetting the spot where the routine procedure stopped during an assembly flow sequence, and making mistakes when operators resume the assembly process at a later time.
- Mixing the accumulated materials (WIP) for the incomplete engine with those of another engine.

b) Not following the order of assembly instructions, as a consequence of a shortage of materials, and in order to move forward the production process, could increase the risk of quality defects.

2. While investigating the Andons, it seems that a large portion of them can be caused by the late delivery of sub-assemblies. The late delivery of these parts has different causes, such as quality issues, overloaded departments, and the shortage of materials. The materials shortage dramatically affects the production flow on a large scale and is one of the most critical issues the company deals with. Finishing the production of all sub-assemblies, and having them prepared prior to mainline assembly, could be one solution to prevent the stoppages at the mainline stations and avoid accumulated WIP.
3. The high volume of shortages at sub-assemblies can cause the cycle times of these parts to be more extensive than expected in case of shortages. Therefore, calculating the exact

time for delivery of sub-assemblies to the mainline assembly is impossible. As a result, longer part wait time and the risk of stoppage during the assembly process can occur.

4. The VSM is not based on the innovative concepts of the Lean manufacturing framework.

- VSM follows a push production system.
- The critical path, bottlenecks, and the stations with more quality issues are not identified and consequently not analyzed.
- The VSM is not properly balanced in terms of daily workloads during a typical lead time.

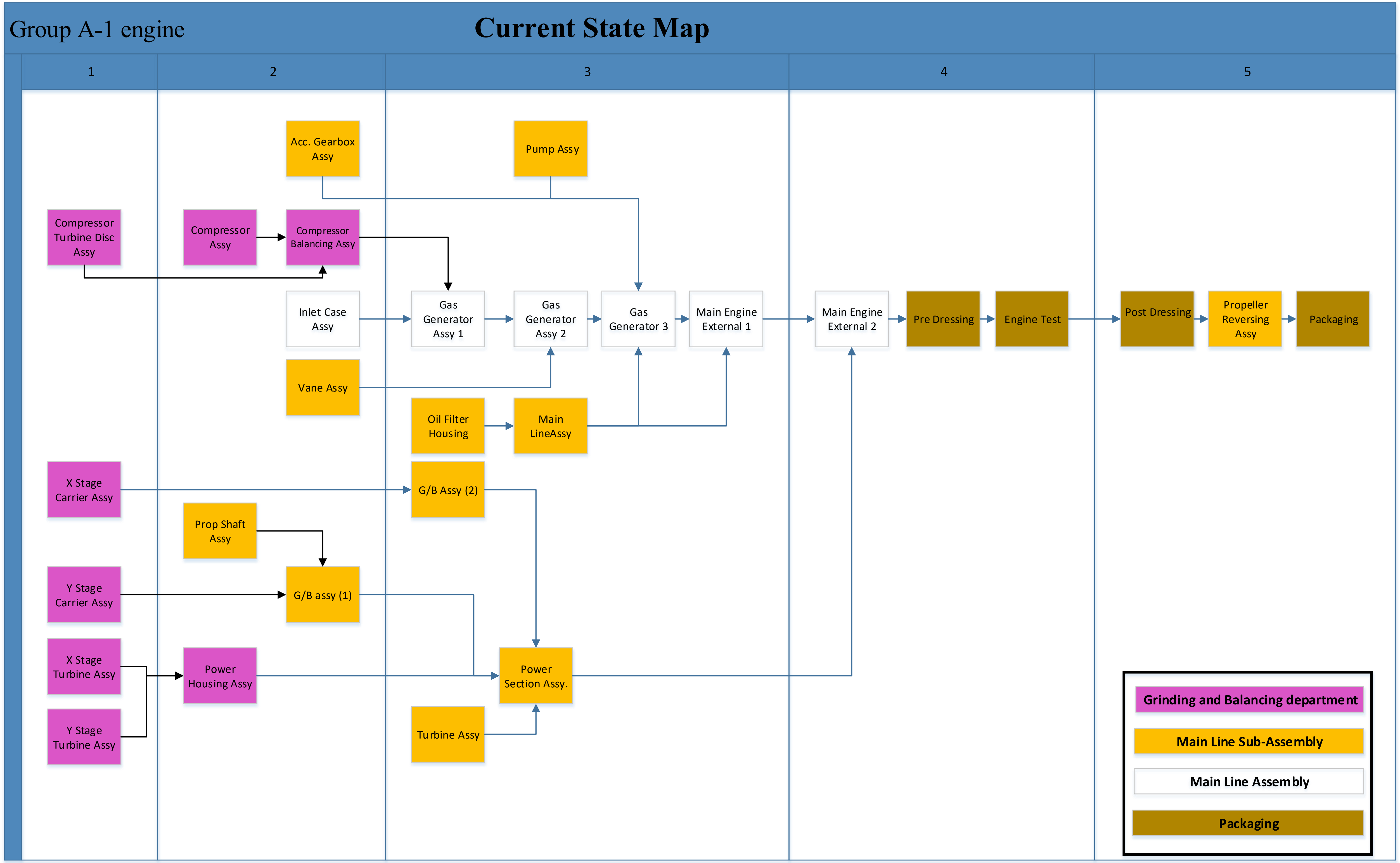

Figure 5. Current State Flowchart

3.3.2. Summary of the outcome of interviews

The following is a list of the essential issues which can interrupt the smooth flow of the information and materials and are brought up within the interviews:

1. Frequent changes in the production schedule without considering the availability of resources, such as materials, assemblers, tools, and facilities.
2. Lack of a frozen zone for the production schedule.
3. Inadequate training for using platforms for sharing all the production information.
4. Lack of updates in IT systems following the changes made on the schedule.
5. Not fully following the master schedule in all departments, especially the engine assembly facility.
6. Informal information flow and need to emphasize the responsibility of the Integrated Material Flow (IMF) department as a single source of the information, and the controller of the information flow.
7. Merging the IMF department with the supply chain department. This leads to adverse effects on IMF performance regarding the accuracy of transferred information to the typical engine assembly facility.
8. Insufficient efforts for establishing productive and efficient interaction between a typical aerospace company and the suppliers. In aerospace companies, the procedure of finding a backup supplier, as well as, replacing a supplier is complicated and expensive; therefore, it is vital for companies to keep a good cooperative relationship with their suppliers.
9. Insufficient root cause analysis for production problems, mistakes, or quality defects.
10. Need for improved and quick feedback for employee’s poor performance following quality defects as a result of human error.
11. Room for more frequent trainings for assemblers.

12. Room for improvement to the layout of the typical engine assembly facility. These can include improvements storage systems for WIP and sub-assemblies and the necessity of reducing extra movements during the process.
13. Room for improvement of information sharing and collaboration between departments.
14. Room for improvement of training of assemblers, group leaders, and shift leads to follow up and implement the quality aspects on the shop floor. This could help the quality department to improve the overall quality of products.
15. Room for improvement of a culture in which everyone feels responsible for the quality of the products.
16. Room for improvement of understanding of Lean manufacturing and Six Sigma.
17. Room for improvement in following the TAKT time and Pitch in order to control the progress of the assembly process.
18. Room for improvement in incorporating all costs when calculating the Cost of Quality escapes.

3.3.3. Cause and Effect Diagram

The results of the analysis of VSM, along with our observations from engine assembly facilities, and the conducted interviews, are presented as twenty-five possible sources of interruptions and distractions that could be root causes of at least some quality defects in a fishbone diagram as depicted in Figure 6.

3.3.4. Failure Mode and Effect Analysis

In order to prioritize the causes of disruptions, a combination of the FMEA and AHP methods is utilized. For developing the weights for the criteria, a pairwise comparison matrix from twenty-five failure modes (causes of quality defects) was prepared and filled by the interview participants. A sample of the FMEA Table is also provided in Appendix A. The results emphasize the variety of opinions of the employees from different departments. Consequently, a list of the causes of possible quality defects (due to human errors) along with their level of severity are presented in Appendix B. All these efforts are summarized in the following fishbone diagram (Figure 6). The results of the prioritization of the causes are presented in different colours. Accordingly, red colour factors, such as frequent changes in priority, reworks, QNs, etc., are identified as the most critical factors that might cause human errors in an assembly line.

In the next phases of this project, each cause from the fishbone diagram could be investigated in order to offer solutions to remove their effects on the quality of the products.

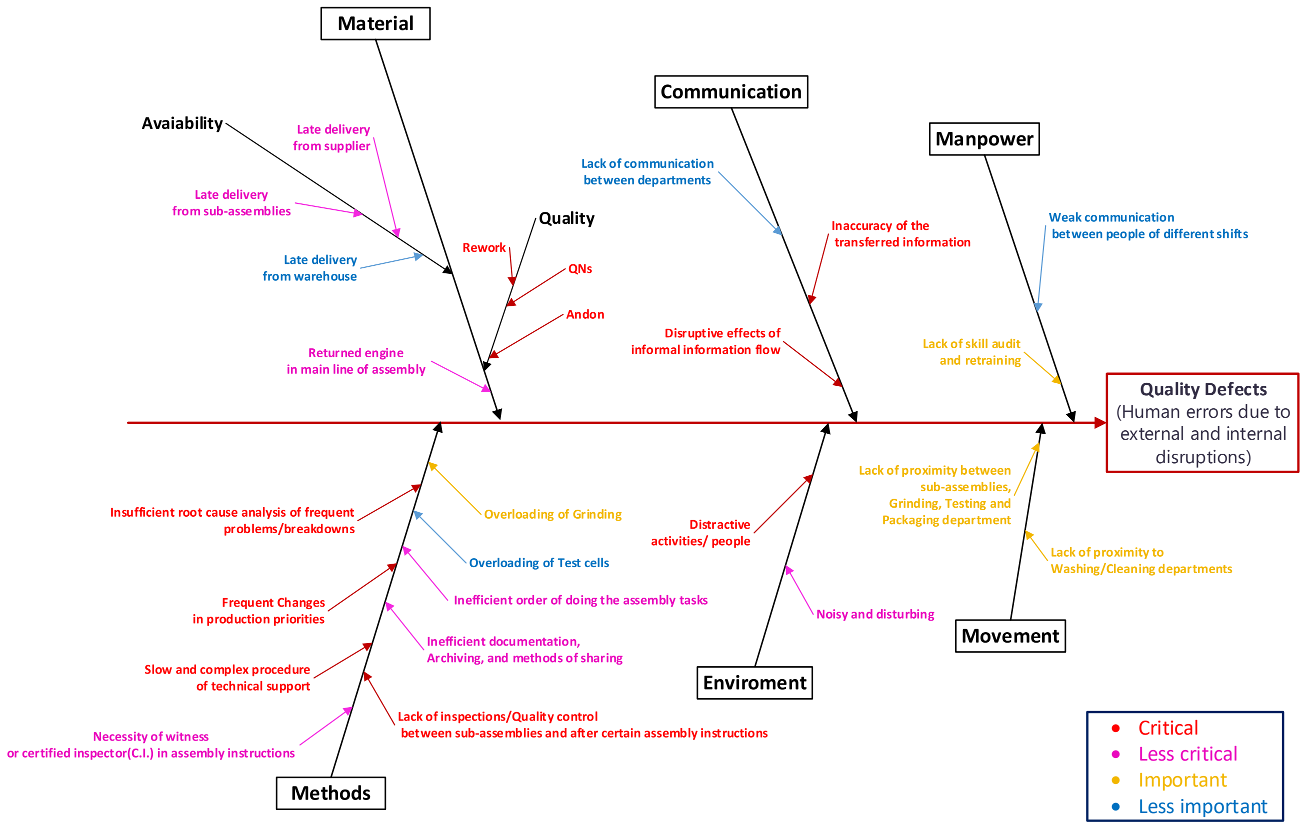

Figure 6.Cause and effect diagram of interruptions and distractions that causes quality defects

3.4. Recommendations

The following is a list of the most important recommendations for improving the system to achieve a fast, flexible flow of material and information while systematically reducing risks of issues that could adversely affect the quality and performance of operators in a typical assembly line. Reducing the risks of quality defects is attainable by reducing the interruptions during assembly, removing bottlenecks and wastes, and improving the flow of information and materials. As a result, it will improve the lead time and on-time delivery of the engines to the customers.

The recommendations are extracted by considering the root cause analysis conducted in the plant regarding the human error categories. They are presented on the priority of the orders of causes in the fishbone diagram.

Improvements Based on Lean Manufacturing Concepts

Reviewing and updating the value stream map

Two new Value Stream Maps are proposed; however, further investigation is required to take the aero-engine plant's particular requirements into consideration.

Considering the following factors in future investigations are necessary.

- Which stations have the most frequent quality issues in VSM (Quality Notifications, Andons, and Reworks)?
- Which stations have the most frequent shortages of materials?
- Which assembly instructions have higher complexity in the procedure and prove the risk of passing parts with an unveiled quality defect to the next station?
- Which path is the critical path?
- Which station or department is the bottleneck?
- Which methods must be implemented in order to reduce the risk of quality defects as a result of switching from one engine model to another?

Addressing the aforementioned issues can reduce the quality defects caused by:

- Inefficient order of doing the assembly instructions
- Stoppages due to quality issues, such as Quality Notifications, Andons, and reworks
- Stoppages due to shortage of materials from sub-assemblies or supplier
- Overloading the bottleneck (Grinding)
- Poor methods of assuring the inspections as well as quality controls have been done between sub-assemblies and certain assembly instructions

Nowadays, the stoppages in the assembly flow can be solved by moving on to the next available activity within an assembly flow sequence and leaving the assembly of the delayed part for later. In the most extreme cases of shortages, putting aside the incomplete engine and starting a new engine assembly process is the preferred solution. However, these methods increase the risk of human errors because instructions can become unclear, and steps may be forgotten. Based on the investigations performed in the plant, this factor has the highest impact on human errors.

First Option for Future Value Stream Map (option A)

The first scenario is an attempt to separate the sub-assemblies from the mainline assembly by doing all the sub-assemblies in advance before starting the mainline assembly. At the end of the sub-assemblies, all their products can be appropriately stored in the supermarkets before moving to the mainline. This Value Stream Map and its flowchart (presented in Appendix C) prevent the stoppage of flow on the mainline assembly due to late deliveries from sub-assemblies. The following justifications are provided for option A:

1. Value-adding time (VAT) of the sub-assemblies is much longer and hence more sensitive to time management as compared with the mainline assemblies. The current total work content of all stations in mainline assembly is almost 6 consecutive hours. On the other hand, the total work content of all the sub-assembly stations is almost 22 hours. However, if some of the sub-assemblies are perfectly produced in parallel, without any necessary gap time for unexpected situations, it is possible to achieve a lead time of 8 hours. Although, the necessity of adding a gap time between sub-assembly stations increases the lead time of 8 hours.
2. Higher ratio of quality defects at sub-assemblies, and consequently, prolonged cycle times for those stations.
3. More complexity of the work procedure and involvement of groups from different departments in each sub-assembly activity. Some assembly instructions' in sub-assemblies include various activities, such as grinding, washing, and balancing, in addition to their assembly activities. This could cause additional movements and wait-time in the queue and consequently more job interruptions during those assembly flow sequences.

Due to these reasons, it is possible to conclude that Option A value stream map is highly advantageous. However, there are still some notable disadvantages. For example, this method does not completely follow the lean manufacturing concepts and usually requires larger supermarkets to put all of their sub-assemblies products. There is also the possibility of having more idle time for the employees.

A Solution Towards Disadvantages of the Option A VSM

A solution to the disadvantages of option A would be to create mixed model value streams for the engine assembly process(Duggan, 2013). The aero-engine plant of this research has the ability to produce different engine families. Four engine families among them have a higher production quantity. Even though it would not be possible to mix all the mainline assemblies of different families at the beginning of implementing this solution, it is still possible to start with creating a mixed model value stream in all of their sub-assemblies. Implementing this model can be straightforward because of the similarity of work content and tools used in sub-assemblies' instructions for these families. This also provides the opportunity to have more cross-trained assemblers.

The benefits of using a mixed model include:

1. The possibility of assigning more employees to work on engines that are at the risk of late delivery.
2. It can solve the issue of excessive idle time for the employees. Implementing the mixed model production system makes it possible to assign an employee to work on different engine families instead of restricting them to one family.
3. The efforts can be directed towards the assembly of the engines with more available parts without considering their family.

Although this method is one of the best options for the company, more proficiency in managing the resources and better acquaintance with the lean manufacturing and six sigma concepts are necessary for managing the whole system. Furthermore, training of assemblers must be thorough in order to avoid increasing the quality defects.

Further investigation of plant resources and cooperation of all departments is necessary to create an efficient mixed-model value stream.

Second Option for Future Value Stream Map (Option B)

A second possible scenario focuses on the Group A engine family in order to make an ideal value stream map that considers the critical path and all lean concepts (Appendix D).

All the stations of this VSM will complete their assembly instructions in the shortest time and as much as possible in parallel. Moreover, this VSM is attainable by minimizing the wastes; optimizing the flow of materials; eliminating or reducing the effects of interruptive or distractive activities through the assembly process such as materials shortage or materials with quality defects; removing bottlenecks; improving information flow in a process; improving the whole system (different Kaizens are necessary). By implementing this VSM, it would be possible to reduce the production lead time by one day when lowering quality Escapes. Focusing on continuous improvement based on Lean techniques and tools is the dominant factor for these achievements.

Improving the layout of the Engine Assembly work area

After choosing the best VSM from the abovementioned options, designing an efficient layout for the shop floor is necessary based on movement and time studies. The goal is to:

- Reduce the movements of materials and employees during the assembly process, especially between different departments;
- Improve the flow of materials;
- Support the idea of separating the sub-assemblies from mainline assembly processes and processing them in advance;
- Shortening the mainline assembly as much as possible;
- Support the creation of the Mixed Model Value Stream Map.

To this end, the following critical aspects need to be considered during the layout improvements:

- Implementing well-designed supermarkets;
- Separating production area from and non-production ones;
- Separating the rework and returned engines areas;
- Implementing a new tooling storage system, especially for the mixed model value stream.

The aforementioned points can reduce the quality defects caused by:

- Distracting activities and personnel;
- Damaging of materials/WIP during movements and storage;
- Noisy and disturbing environment;
- Mixing the parts from different engine models;
- Poorly installed parts;
- The returned engine in mainline assembly.

Implementing Performance Indicator, Pitch and *TAKT* time

By using these three parameters, it is possible to:

- Evaluate the assemblers' activities and improve their performance;
- Provide a fast reaction to the slow procedure;
- Improve on-time delivery of products and the lead time;

- Retrain and support assemblers if it is necessary.

Improving the Assembly Instructions

The main goals of improving assembly instruction’s include:

- Having more flexible assembly instructions in order to provide the opportunity of working two assemblers in a station during cases of emergency (especially for external 1 and external 2 stations) during the hockey stick phenomenon;
- Reducing the total work content of each assembly instruction to under the TAKT time;
- Removing extra movements;
- Having more clear work instruction.

These improvements can reduce the quality defects caused by:

- The necessity of witness or certified inspector within assembly instructions;
- Lack of methods for assuring the accuracy of inspections done by assemblers during an assembly instruction;
- Extra pressure on assemblers.

Reviewing organizational chart and working procedure of each department

The following points have to be the main targets of this improvement:

- Encourage teamwork culture without damaging the independence of departments;
- Provide departments with the resources they need to work together;
- Clarifying roles and setting expectations of each department;
- Change the harmful norms from the system;

The abovementioned items provide faster support for the engine assembly facility and reduce its complexity. As a result, it could be possible to minimize the stoppages at the assembly line.

Considering a frozen zone in the production schedule

Preventing frequent changes of the production priority in the frozen zone will reduce the problems caused by:

- Accumulation of WIP on the mainline assembly and installing wrong parts on engines
- Interrupting the production flow by not considering resources available for that change

Improvements that focus on Information Flow and the Communication

Improving the Information Flow

The dominant role of the IMF department in the control of information has to be emphasized during this process. Among some of the expected benefits, we may mention:

- Provide an independent IMF department;
- Provide easy access for all departments to the necessary information;
- Involve IMF in decision-making processes of engine assembly facility, especially in the cases related to material availability;
- Eliminating the sources of informal information flow;
- Increase the accuracy of the transferred information and document all the information in a shared platform.

Establishing and developing a shared information platform

The idea is to create a shared platform to be used for exchanging information, knowledge, experience, and data between different departments.

In order to improve communication and cooperation between departments, it is necessary to:

- Do a root cause analysis in the company in order to find out the reasons that employees refuse, or are uninterested, in using a shared platform for the exchange of information;
- Improve the training methods for existing information-sharing systems, like PLM;
- Provide new platforms in the spots which are necessary;
- Improve the cooperating mentality between employees of different departments;
- Share the best practice between departments.

Using IT systems routinely and keeping them updated

For this reason, it is essential to:

- Do a root cause analysis in the company in order to find out the reasons why employees refuse or are uninterested in using the IT systems
- Improve the training methods for using the IT systems
- Enforce obligatory use of IT systems in all departments and continuously update them for small changes of information

Improving the methods of audit, documentation of the quality defects, and root cause analysis

Here the following items are essential to consider:

- Improving an audit system to ensure that assemblers follow the procedures according to assembly instructions;
- Improve the classification methods of human errors;
- Mention the type of human error by the detail in all quality reports;
- Provide an archive of solutions to eliminate possible human errors;
- Highlight the most critical and repetitive problems and find remedies for them.

Using the Supplier Relationship Management (SRM) system

The goal is to:

- Facilitate the supply chain management
- Strengthen the ties between the company and the suppliers by developing cooperation mechanisms among them
- Assure the high quality and timeliness of delivered materials;

Improvements based on Benchmarking Best Practices in the Industry

A similar aero-engine plant has been selected for benchmarking. There have been some site visits and a few interviews conducted with three of the departments in this plant.

The benchmarking benefits include (Pyzdek, 2010):

- Creating a culture that values continuous improvement;
- Enhancing creativity by devaluing the not-invented-here syndrome;
- Increasing sensitivity to changes in the external environment;
- Shifting the corporate mindset from relative complacency to a strong sense of urgency for ongoing improvement;
- Focusing resources through performance targets set with employee input;
- Prioritizing the areas that need improvement;
- Sharing the best practice between benchmarking partners.

Chapter 4

Improving Quality Control system and documentation methods of quality Escapes

After investigating typical company quality reports, room for improvement of information regarding the relationship between reported quality defects and human errors is revealed. Therefore, one of our proposed solutions to reduce the risk of human errors relies on the use of statistical control tools and efficient quality defects investigation, documentation, and root cause analysis. More precisely, we proposed to develop a statistical tool to:

- Evaluate the escapes that are frequently occurring and assess them by category,
- Improve the data collection platform for QN, ESCAPE, and OEMI and provide a uniform framework for quality defects investigation and their documentation methods,
- Visualize cause and effect of quality defects and identify the root causes,
- Emphasize the role of external human factors as a contributing factor to each quality defect,
- Provide a baseline for further root-cause analysis and consequently easier and faster decision-making.

In order to achieve the above-mentioned goals, existing quality control methods and the investigation procedures of quality defects are evaluated, and the most frequent quality issues are discovered. Moreover, interviews with quality specialists helped us to perceive better their quality control system and the effect of human errors on quality defects during engine assembly.

As a result, a new quality control checklist in the Microsoft Excel software is developed. This tool is expected to facilitate and unify the company's quality department data collection and analysis methods. It also provides a platform to find and eliminate quality defects caused by external human factors. As a result, achieving the ultimate goal of satisfying and exceeding customers' needs will be more feasible.

To design this Excel tool, Pivot tables, histograms, and Pie charts are established to present the results of assembly non-conformities or defects and identify Escape causes and their contributing factors. Besides, they will show the most frequent human errors that cause most of the quality defects. These charts are designed to be updated automatically after adding quality reports in the Excel sheets. Afterwards, the assessment of results could be performed in an Ishikawa diagram (fishbone diagram) to identify proper solutions for eliminating the causes of quality defects and sources of human errors.

This Excel tool is constructed in a disciplined way to move forward, step by step, by completing each sheet. It includes eight main worksheets:

- General Information,
- Escape Event,
- OEMI Event,
- Quality Notification Event,
- Assembly System Escape,
- Contributing Factors,
- Escape Causes Pivot Table,
- And Contributing Factors Pivot Table.

Moreover, to make it user-friendly, reduce the documentation's mistakes, and automatically extract the final report from information within all sheets, visual basic for an applications programming language (VBA) is used in developing this tool.

A pop-up user form appears on the screen by opening the 'Quality Checklist' excel (Figure 7). The first item in this form is 'Reference Number.' The value inserted in this box will be the quality report worksheet name. This worksheet will be created automatically and added at the end of the worksheets in this tool. All the provided information in the first six sheets will be extracted and saved automatically in that new sheet and used for future investigations.

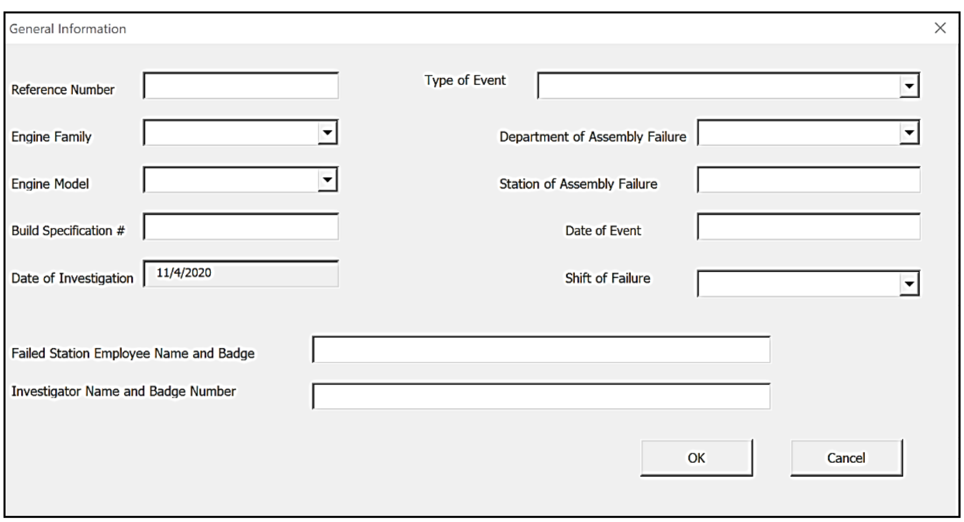

Figure 7.'Quality Checklist' excel pop-up user form

Users can choose appropriate options from drop-down menus for some information such as Engine Family, Engine Model, Department of Assembly Escape, Type of Event, or write in the appropriate place. Another essential item in this form is the 'Type of Event' that categorizes the quality inspection or quality report type and can be chosen from its' drop-down list (Table 3).

Table 3. Type of Events In the quality checklist excel

Type of Event
The Original Equipment Manufacturer Intervention (OEMI)
Computerized Visual Inspection System
Visual inspection by the quality inspector
Quality Notification (QN)
Damage
Escape
Stack-up
Audit
Declared Issue
Request for action (ENOVIA)
Engine Test Cell
ECATES
Rework

A factor that would reduce the quality defects caused by human errors is establishing performance indicators for operators. Therefore, we propose to record the name and other identifying information of assemblers who were involved in the occurrence of a given quality defect in the designed quality checklist. This will provide the opportunity to allow thorough investigation through interviews with the assembler of the event root causes.

- After entering the required information in this sheet, the user should press the OK button on the user form. By clicking on the next button at the bottom of the generated table at the 'General Information' sheet, the user is transferred to the next sheet, and the new excel sheet will be created with the name of the reference number to summarize all the provided information automatically. Afterward, the quality analyst will open one of the following three worksheets based on the type of quality report that he/she intends to provide.
- ESCAPE Event
- OEMI Event

- Quality Notification (QN) Event.

The following worksheet that the analyst will move to is the 'Assembly system Escape' worksheet. This page presents six main assembly system Escapes that cause the quality defect (quality event). Each category has some sub-categories in order to provide more detailed information on the report. These six main categories and some of their sub-categories are as follows;

1. Installation Escape
    - Equipment/part not installed
    - Wrong equipment/part installed
    - Improper location
    - Damaged on improper installation for engine test
2. Material Handling / Movement
    a) Damaged parts/final products
    b) Inappropriate storage of parts/finished products
3. Fault Isolation / Test/ Inspection Escape
    - Did not detect the fault
    - Not found by operational/functional test
    - Not found by task inspection
    - Not found by visual inspection
    - Not found by the visual inspection system
4. Assembly Control Escape
    - Scheduled task omitted/late/incorrect
    - Incorrectly deferred/controlled defect
    - Technical log oversight in assembly control
    - Modification control
5. Foreign object damage / debris
    - Tooling/equipment left in engine
    - Debris falling into open systems
6. Equipment damage
    - Wrong selection of tools/equipment
    - Tools/equipment used improperly

The following worksheet is ‘Contributing Factors.’ By filling out this sheet, the quality specialist provides more details on the quality issues that occurred in the line. This page includes ten primary categories and several sub-categories for each one to choose from. These details can help quality investigators to distinguish human causes and categories them correctly. These ten primary Escape contributing factors and some of their sub-categories are as follows:

1. Information
    - The update process is too long/ complicated
    - Unavailable/inaccessible/ unupdated information
    - Incorrect Information
    - Inadequate information
2. Organizational Factors/ Departments Support
    - Quality escapes of support from technical organizations/ departments (e.g., engineering, planning, manufacturing, quality control)
    - Overloaded departments
    - Not enough staff
    - Complicated work process/ procedure
    - Work process/ procedure not followed
3. Equipment / Tools
    - Unavailable
    - Inappropriate for the task
    - No instructions
    - Too complicated
4. Engine Design / Configuration /Parts / Consumables
    - Complex
    - Inaccessible
    - Engine configuration variability
    - Parts unavailable
    - Parts incorrectly labelled
    - Easy to install incorrectly

5. Communication
    - Between departments
    - Between assemblers
    - Between shifts
6. Environment / Facilities
    - Improper layout/ configurations
    - High noise levels
    - Not well-separated work environments
    - Ergonomy of work station
    - Work instruction system
7. Leadership / Supervision
    - Planning/organization of tasks
    - Prioritization of work
    - Deligation/assignment of task
8. Job / Task
    - Installation Instructions not followed
    - Installation instructions interpretation
    - Repetitive/monotonous
    - Complex/confusing
9. Individual Factors
    - Physical health (including hearing and sight)
    - Fatigue
    - Time pressure
    - Complacency
10. Knowledge / Skills
    - Technical skills
    - Task knowledge
    - Task planning
    - Teamwork skils

The last two Excel sheets from the designed quality checklist summarize Escape causes and their contributing factors from each quality report in pivot tables and pie charts. These could give a visual perception of the most critical human errors and their contributing factors.

A sample of the pie charts and pivot tables are presented below. The information presented in these charts are not corresponding to reality and only are for demonstration.

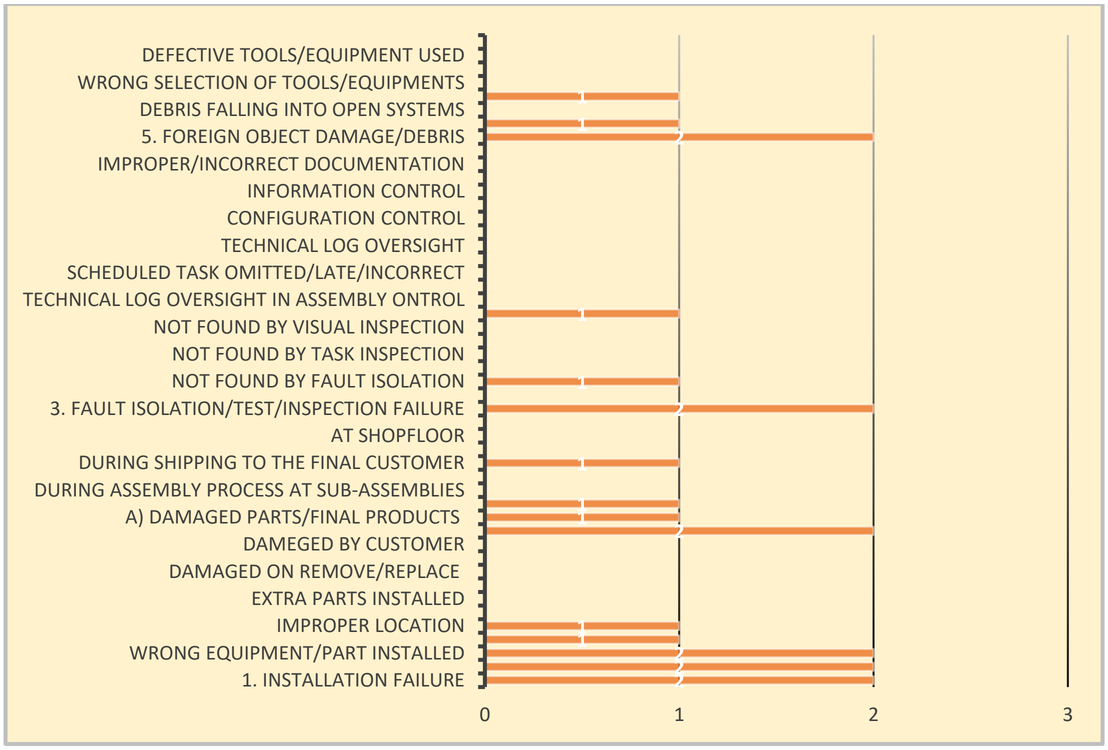

Chart 1. Causes of Engine Assembly Escape

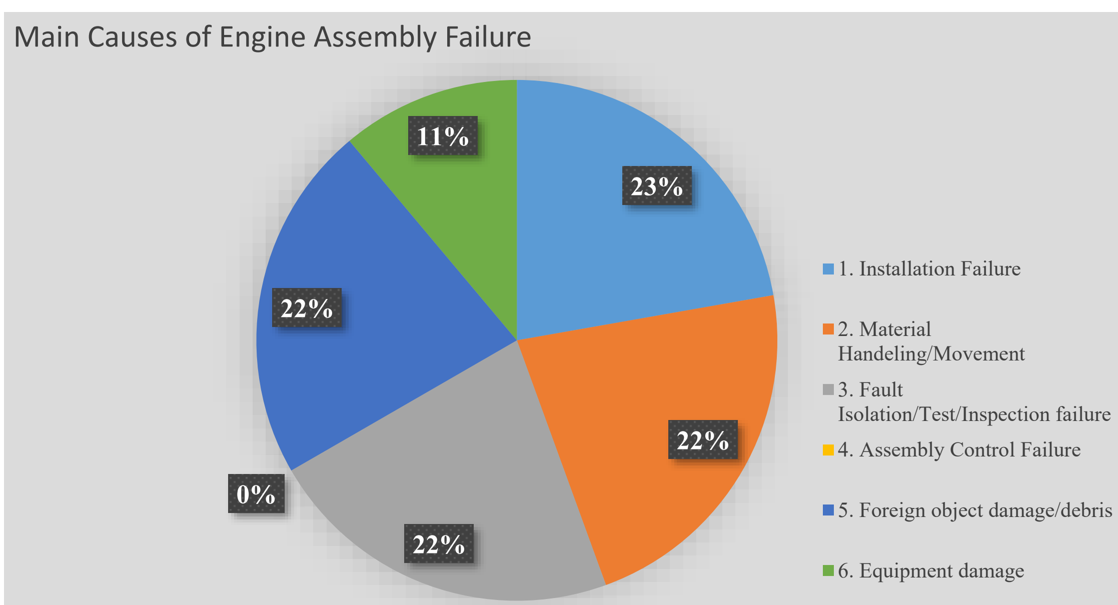

Chart 2. Main Causes of Engine Assembly Escape

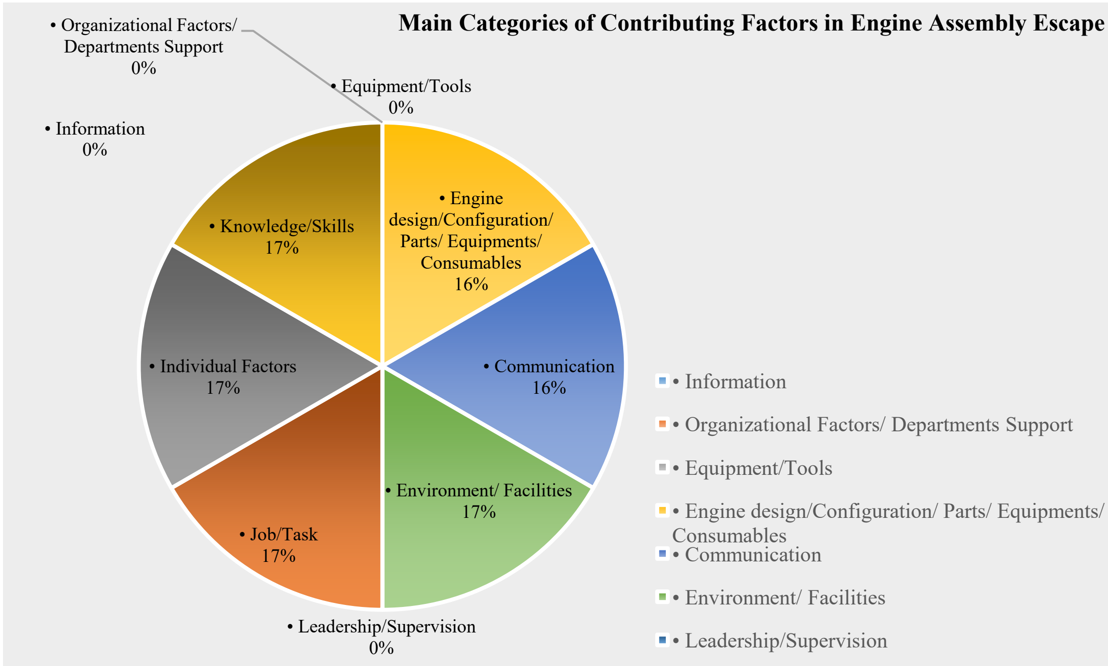

Chart 3. Main Contributing Factors in Engine Assembly Escape

In summary, quality specialists could extract the root causes of wastes and quality defects within the reports and pivot tables and summarize them in a cause and effect (fishbone) diagram. Afterward, the root causes could be prioritized with FMEA (Failure Modes and Effects Analysis) and AHP (Analytical Hierarchy Process) techniques. Finally, the top priority issues must be improved by the quality improvement team. A complete overview of the 'Quality Checklist' developed in Excel is presented in Appendix E.

Chapter 5

Lean manufacturing solutions for reducing human errors in A Typical Aero-engine Plant

The second improvement idea to reduce human errors in the assembly line relies on the use of Lean Manufacturing tools and methods. More precisely, a split mixed-model assembly line is proposed in order to reduce assembly Escapes caused by human errors. This idea is motivated by the fact that interruptions and distractions during the assembly process are one of the primary sources of human errors. More investigations revealed that such interruptions are caused by several factors, such as stoppages on the assembly line due to the shortage of materials or receiving materials with quality defects along with the lack of resources, such as the assemblers or support teams. Establishing a split mixed-model assembly line is expected to:

- Reduce quality escapes caused by interruptions, wastes, and distractions by providing the opportunity of resequencing the orders in case of material shortages and provide a faster response possibility to unforeseen stoppages or interruptions.
- Provide the opportunity to reschedule the production sequence based on the availability of materials, i.e., assembling engine families with more available components first,
- Provide the opportunity to have more cross-trained assemblers and support teams,
- Reduce the risk of late delivery and improve the lead time.

Shorter mixed-model assembly lines and assigned supermarkets between the departments will ease the orders resequencing process and provide a faster response to shortages. The goal of reactive resequencing of orders is to eliminate any stoppage or interruption triggered by unforeseen perturbations such as shortages of materials or support teams, rush orders, and workpiece or material defects in the following assembly department.

In order to design a value stream for the above-mentioned mixed-model assembly line, we first extracted the current value stream map, all process steps and work practices, Value-adding time (VAT) and sensitivity to time management, the ratio of quality defects and consequently prolonged cycle times and delays in the whole process. We further evaluated the complexity of work procedures and the involvement of different groups and departments in each station. Afterwards, in order to create the new split mixed-model value stream map, the following steps are followed:

- Establishing the daily and weekly demand for each engine family,
- Creating groups of the products based on the demand,
- Calculating the *TAKT* time for each engine group and department,
- Designing departments that constitute the split mixed-model assembly line and creating the sections for groups of products inside each department,
- Studying the assembly flow charts and breaking down each department's operations,
- Calculating the total work content for each department,
- Calculating the number of cross-trained assemblers required for each department,
- Calculating the cycle time of each assembler,
- Establishing the work stations in each department based on the similarity of work content and tools used in assembly instructions
- Establishing the assemblers' balance charts by equally splitting the assembly instructions among the assemblers in each station of each department,
- Assigning the supermarkets and calculating their capacity,
- Offering a new layout for the engine assembly facility.

5.1. Lean Implementation Steps

Developing the new value stream map (VSM)

In the new VSM (option A discussed in chapter 3), the engine assembly line is divided into four departments;

1. Balancing and grinding department;
2. Sub-assemblies department;
3. Mainline assembly department;
4. Engine Test and Packaging department.

In between each department, except the last two, supermarkets are considered to store parts and components. These supermarkets provide buffers for the resequencing of the initial sequence of ordered engines. It is worth mentioning that the balancing and grinding department is almost already working based on a mixed-model value stream. A team with a supervisor is cross-trained in this department and can independently work on a variety of processes corresponding to different engine families.

In the design of the new VSM, the main focus is on sub-assemblies. All engine families' sub-assemblies are thus thoroughly evaluated. The objective is to separate all sub-assemblies from the mainline assembly and do them in advance. By considering the demand, the similarity of work content of assembly instructions and the tools used in the sub-assembly department, this department is divided into three individual sections:

1. Group A and Group E engine families sub-assembly section,
2. Group C and Group D engine families sub-assembly section,
3. Group F, Group G, and Group H engine families sub-assembly section.

Although the sub-assembly department is separated into three sections, each engine family's assembly instructions could be done individually and in parallel. A cross-trained team with a supervisor will be allocated to work in all of the above-mentioned sections. Establishing a mixed model value stream in the sub-assembly department and having cross-trained assemblers would help the supervisor allocate resources based on the demand and rush orders. Furthermore, it allows resequencing the sub-assembly order and prioritizes the sub-assembly of engines with more available parts. Also, cross-trained employees can step in for absent employees without disrupting the flow, quality, and quantity of work (Monden, 1983, p.3).

The next department in this VSM is the mainline assembly. In this department, each engine family will be assembled in an independent assembly line. However, based on the similarity between some engine designs, it is possible to train cross-trained assemblers to work on different models from different families. From mainline assembly, produced engines are moved to the test and packaging department.

Establish the daily demand and group the products based on the demand

The numbers presented in all calculations are not corresponding to the actual values. They are rather fictitious values obtained from multiplying real values by a factor.

The weekly demand for each engine family is calculated as follows:

$$Average\ Demand\ per\ week = \frac{Total\ demand\ per\ year}{Number\ of\ weeks\ per\ year}$$

Based on the rate of demands for each engine model, engines are categorized into four groups;

1. Group A and Group B engine families;
2. Group C and Group D engine families;

3. Group E engine family;
4. Group F, Group G, and Group H engine families.

Calculating the Supermarkets' Capacity

Within the different strengths of splitting a mixed-model assembly line, the possibility of resequencing the orders is one of the most desirable aspects. Reactive resequencing is triggered by unforeseen disruptions, such as material shortages, rush orders, workpiece or material defects. Using this method will reduce stoppages during the assembly process and, as a result, reduce the possibility of human errors. To this end, planning buffers within a mixed-model line and positioning them at the right location are critical.

In the new VSM, supermarkets are assigned between departments to provide the buffers for resequencing. Moreover, the capacity of each supermarket is calculated based on the demand rate for each engine model. Our target is to store the subassemblies associated with one engine featured with higher demands or less stability in receiving their components (higher risk of delay in providing the materials) in supermarkets while producing the rest of the engines based on the actual order. For high-demand engines, the equivalent of one engine sub-assemblies will be kept in the supermarkets of the balancing and grinding department and sub-assembly department.

Calculating available production time and *Takt* time

The total available time per week is 139 hours. Table 4 presents different shifts per day and the working hours per shift. By considering 75 percent utilization, it could be possible to have 104 hours of productive working hours per week.

Table 4. Available time for production

	Shift 1 (Day)	Shift 2 (Evening)	Shift 3 (Night)	Shift 4 (Weekend)
Shift start	6.5	14.5	0	6
Shift end	15	24.5	7	16
Lunch (hrs)	0.5	0.5	0.5	0.5
Hrs / shift	8	9.5	6.5	9.5
shifts / week	5	4	5	3
Available hrs / week	40	38	32.5	28.5
Total Available time (hrs) / week	139 (Hrs)			
Utilization	75%			
Total Available time (hrs) / week	104.25 (Hrs)			

Takt time refers to the frequency of a part or component that must be produced to meet customers' demands. *Takt* time depends on production demand; if the demand increases, the *Takt* time decreases, and vice versa, which means the output interval increases or decreases. *Takt* time is calculated as the available production time divided by demand.

$$Takt\ Time = \frac{Available\ Production\ Time}{Demand}$$

The available production time per week is obtained from table 4. The demand of each engine family is calculated by adding the average quantity of customers' orders per week (weekly demand) to the number of engines kept as a buffer stock in each supermarket.

Restructuring the Working Sequence of the Assembly Process

The following steps are involved in preparing a detailed split mixed-model VSM:

- Evaluating the work elements of assembly flow charts by breaking down each department's operations followed by restructuring those,
- Developing the work stations in each department based on the similarity of work content and tools used in assembly instructions,
- Determining the number of cross-trained assemblers necessary for each station,
- And finally, distributing the job equally between those assemblers.

These steps are implemented for stations and departments of all engine families manufactured in this typical aero-engine facility.

Calculating the number of Assemblers for each station

Assembly instructions tasks for each station of grinding and balancing, sub-assemblies, and mainline assemblies departments are evaluated, and the total work contents (total actual build time) are calculated. The total work content is the total work time to do one assembly instruction. By using the Total Work Content (TWC) of all assembly instructions and *TAKT* time, the number of assemblers in each station is estimated.

$$Number\ of\ assemblers = \frac{TWC}{Takt\ Time}$$

Work Distribution between Assemblers

In distributing the work elements between operators, the lean option is followed. This approach redistributes work to load every operator but one fully. The operator with less work content can do reworks or extra workloads imposed on the station. In the end, the assemblers' balance charts for each station are prepared.

Order scheduling in a split mixed-model production line

From the list of orders, the schedule starts ahead with one engine assembly process moving upstream in VSM, from mainline assembly to the balancing department. For instance, from three engine models in a row for production, A, B, and C, model A is being assembled in the mainline assembly department; model B is in the sub-assembly department; and Model C components are being produced in the grinding and balancing departments. Afterwards, the delivery date is calculated from starting the assembly process in the mainline assembly department. Furthermore, in each department, the production of the engine with the most available parts is prioritized; whereas, and the assembly process of the engine with missing pieces and components is skipped.

Under the proposed split mixed-model VSM, each department's products can be stored in supermarkets, and they can only be released after assuring the availability of materials in the downstream department.

5.2. The split mixed-model VSM for the Group A engine family

The steps and calculations mentioned in section 5.1 can be applied to any given engine family of any aero-engine manufacturer. Herein next for illustration, these are applied to Group A of a typical aero-engine manufacturer. The numbers presented in all calculations are not corresponding to the actual values. They are rather fictitious values presented for demonstration purposes only.

Average Demand per Week

In the first step, the 2021 and 2022 demand and the most popular engine models of the Group A family are presented in table 5.

Table 5. Group A engine family yearly demand

Engine	Percent from the total Demand for 2021	Percent from total Demand for 2022
Group A-1	45%	46%
Group A-2/A-3	27%	33%
Group B	27%	21%

The average demand per week for Group A and B engine families is considered 46 engines per week. The demand quantities are fictitious and are not represent reality. Afterwards, three engines (1 from each category) were added as a safety stock in the supermarket. More precisely, we propose to keep assembled parts and components corresponding to 3 engines in a row on the production list in the supermarkets of balancing and grinding and the sub-assemblies departments. Therefore, by adding this number to the demand per week, the Group A and B engine families' demand will be 49 engines per week. The plan is to produce 23 subs for Group A-1, 13 subs for Group A-2/A3 and 13 subs for Group B per week. It respectively represents almost 45, 27, and 27 percent of this engine family's total demand, as presented in table 17.

- Group A-1 demand per week = (45%*49 (Fictitious Total Demand)) ≈ 23 engines subs
- Group A-2/A-3 demand per week = (27%*49) ≈ 13 engines subs
- Group B demand per week = (27%*49) ≈ 13 engines subs

***Takt* Time**

By having the average demand and available production time per week, each station's takt time and cycle time can be calculated.

$$Takt\ time\ for\ Group\ A\ engines\ family\ (All\ models\ included) = \frac{139}{49} = 2.8\ (hrs)$$

The *TAKT* time will increase by separating Group A-1/A-2/A-3 engines production from Group B. The average weekly demand for Group A-1/A-2/A-3 engines is 36 engines, and for Group B is 13 engines per week.

$$Takt\ time\ for\ \text{Group A} - 1/\ A - 2/\text{A} - 3\ \ engines = \frac{139}{36} = 3.9\ (hrs)$$

$$Takt\ time\ for\ Group\ B\ engines = \frac{139}{13} = 10.7\ (hrs)$$

Almost 75 percent of the above-mentioned *Takt* times are considered as the effective available time (cycle time) for each station and used to estimate the number of assemblers, distribute jobs between assemblers and create the assemblers' balance chart. The following sections detail the calculations and information for the Group A family departments and their stations.

5.2.1. Group A Engine family Departments in the new VSM

Balancing and grinding department

The balancing and grinding department for the Group A engine family is divided into two sections, station 1 and station 2. Assembly instruction tasks are distributed between these two stations and rearranged and prioritized based on the order of completion. The *Takt* time and effective available time were used as the guidelines to this end. In the following tables, the distribution of each engine model's assembly tasks between stations is presented.

Table 6. Balancing and grinding stations Assembly Tasks distributions for Group A-1 engines

Group A-1 Balancing station 1 Date Box
Group A-1 Balancing station 1 assy. tasks
• Compressor turbine disc Assy
• Compressor Assy
• X stage Turbine Assy
• Y stage Turbine Assy
• Y Stage Carrier Assy
Total Work Content (TWC) = Sum of the above activities' Cycle time
Number of assemblers = 2
Takt time = 2.8 (hrs)
Work stations (Tables) = 1,2, and 3
Yield = almost 80%

Group A-1 Balancing station 2 Data Box
Group A-1 Balancing station 2 assy. tasks
• Compressor Balancing Assy
• X stage Carrier Assy
• Power Housing Assy
Total Work Content (TWC) = Sum of the above activities' Cycle time
Number of assemblers = 2
Takt time = 2.8 (hrs)
Work stations (Tables) = 1,2, and 3

Afterwards, based on each station's total work content, the *TAKT* time and effective available time, the number of operators is estimated, and the assembly instructions (Tasks) are distributed between operators of each station.

For example, the number of assemblers and the cycle time for each assembler in station 1 of the Group A-1 engines are calculated as follows.

$$Number\ of\ assemblers = \frac{TWC}{Takt} \approx 2$$

$$Assembler's\ Cycle\ Time = \frac{TWC}{Number\ of\ assemblers} = 2.3\ (Hrs)$$

Based on the Lean manufacturing principles, the assembler's cycle time must be smaller than the *TAKT* time. For complex processes like the engine assembly, 75 to 85 percent of *TAKT* time is considered as the assembler's cycle time, representing the assembler's efficiency. The number of operators and their cycle time is calculated in the same fashion for all departments.

After estimating the number of operators for each station, the assembly instructions (Tasks) are distributed within assemblers. The order of completion of assembly instructions and TAKT time are taken into consideration for task distribution. The results are presented in the following tables and assemblers' balance charts.

Table 7. Balancing and grinding stations Assembly Tasks distributions between operators, Group A-1 engines

Station 1 assy. tasks Dist. - Group A-1	**Ops 1** Activities	**Ops 2** Activities
Compressor turbine disc Assy	*	
Compressor Assy	*	
X stage Turbine Assy		*
Y stage Turbine Assy		*
X Stage Carrier Assy		*

Station 2 assy. tasks Dist. - Group A-1	**Ops 1** Activities	**Ops 2** Activities
Compressor Balancing Assy	*	
Power Housing Assy	*	
Y stage Carrier Assy		*

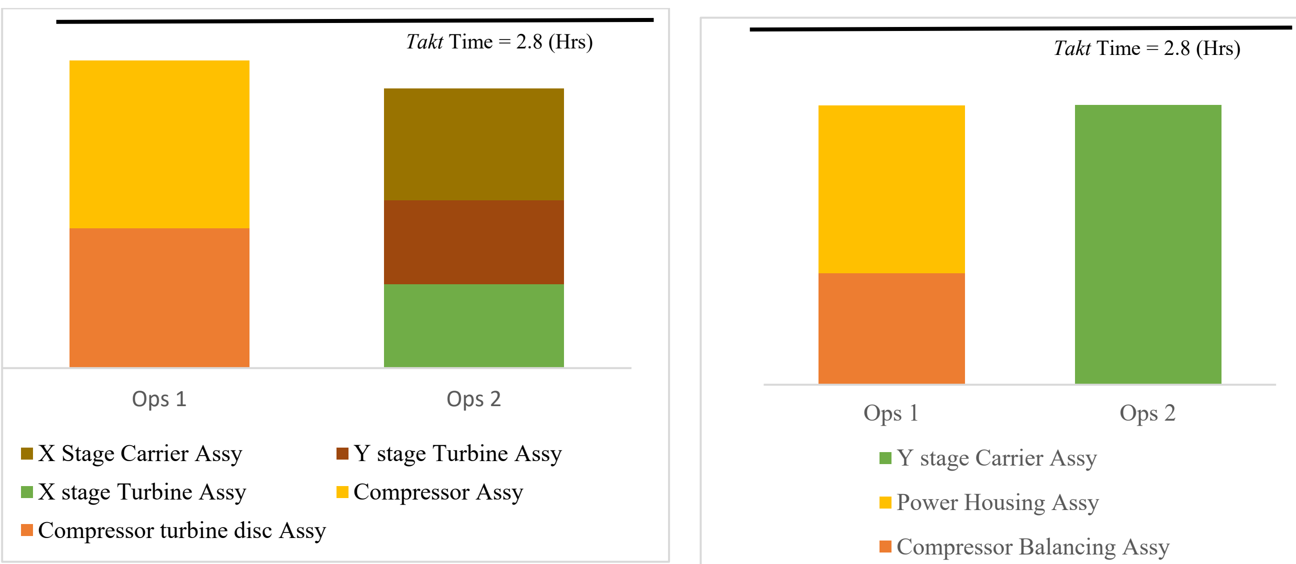

Chart 4. Balancing and grinding stations operators' Balance charts, Group A-1 engines

Table 8. Balancing and grinding stations assembly Tasks distributions between operators, Group A-2/A-3 engines

Station 1 assy. tasks Dist. – Group A-2	**Ops 1 Activities**	**Ops 2 Activities**
Compressor turbine disc Assy	*	
Disk Balancing Assy	*	
X stage Turbine Assy	*	
Y stage Turbine Assy		*
Power Rotor Assy		*

Station 2 assy. tasks Dist. – Group A-2	**Ops 1 Activities**	**Ops 2 Activities**
Compressor Assy	*	
Compress. Bal. Assy	*	
Power Housing Assy		*

Station 1 assy. tasks Dist. – Group B	**Ops 1 Activities**	**Ops 2 Activities**
Compressor turbine disc Assy	*	
X Turbine Assy		*

Station 2 assy. tasks Dist. – Group B	**Ops 1 Activities**	**Ops 2 Activities**
Power Housing Assy	*	
Compressor Rotor Bal. Assy		*

Station 1 assy. tasks Dist. – Group A-3	**Ops 1 Activities**	**Ops 2 Activities**
Compressor turbine disc Assy	*	
Compress. Rotor Assy	*	
X stage Turbine Assy		*
Y stage Turbine Assy		*

Station 2 assy. tasks Dist. – Group A-3	**Ops 1 Activities**	**Ops 2 Activities**
Compressor Bal. Assy	*	
Disk Bal. Assy	*	
Power Housing Assy		*
Power Shaft Assy		*

Sub-assemblies department

The sub-assemblies department for the Group A engine family are divided into three stations, and the assembly instructions for each station are assigned for each engine model, as summarized in the following tables and charts. As mentioned earlier, based on each station's total work content, the *TAKT* time and effective available time are calculated, followed by estimating the number of operators and the assembly tasks distributed between operators of each station. The following tables and the operators' balance charts present the assembly tasks distributions between operators.

Station 1 is shared among all Group A and B engine models. Therefore, this station's considered demand per week is 49 engines, and consequently, the *TAKT* time is 2.8 hours. Stations 2 and 3 in sub-assemblies are designed to work in parallel. Station 2 is dedicated to Group A engines and the considered demand quantity per week for these engines is 36; thus, the *TAKT* time is 3.9 hours in this station. Station 3 is dedicated to Group B engines. Their average demand considered 13 engines per week, and the *TAKT* time is 10.7 hours. The goal of using *TAKT* time is to control each department's production pace and fulfill the demand. Based on the calculations, the number of assemblers for stations 1, 2, and 3 is estimated as 2, 2, and 3, respectively. More details are provided in the following tables.

Table 9. Sub-assemblies stations and their assembly tasks for the Group A and Group engine family

SUB-assembly Station 1 (Share for All Group A and Group B engine Families)	
Group A-1/A-2 / A-3 Data Box	**Group B Data Box**
Assembly Tasks	**Assembly Tasks**
• Vane Assy	• VANE ASSY
• Turbine Ssy	• Turbine Assy
• Pump Assy	• PUMP ASSY
• Oil Filter Housing	• ACCESSORY GB ASSY
• Acc. Gearbox Assy	TWC = Sum of the above activities' cycle time
• Electric control	
Total Work Content (TWC) = Sum of the above activities' cycle time	
Takt time = 2.8 (Hrs)	
Number of assemblers = 2	
Workstations (Tables) = 1 & 2	
Yield = almost 85%	

SUB-assembly Station 2 (For Group A-1/A-2/A-3)	
Group A-1 Data Box	**Group A-2/A-3 Data Box**
Group A-1 Assembly Tasks	**Group A-2 Assembly Tasks**
• Gearbox Assy (1)	• Main Line Assy
• Gearbox Assy (2)	• Power Section Assy
• Power Section Assy	• RGB Assy
• Main Line Assy	• Bleed Valve Assy
• Shaft Assy	TWC = Sum of the above activities' cycle time
Total Work Content = Sum of the above activities' cycle time	
Takt time = 3.9 (Hrs)	
Number of assemblers = 2	
Workstations (Tables) = 3 & 4	

SUB-assembly Station 3 (For Group B) Data Box
Group B Assembly Tasks
• Exhaust Assy
• Clutch Gear Assy (1)
• Clutch Gear Assy(2)
• Cover Assy (1)
• Valve Assy
• Acc. Gearbox Assy
• Cover Assy (2)
• Output Gear Assy
• Output Housing Assy
• Valve Assy
• RGB Externals
• Main Line Assy
• Reduction Gearbox Assy
• Input & Housing Assy
• Diaphragm Assy
TWC = Sum of the above activities' cycle time
Takt time = 10.7 (Hrs)
Number of assemblers = 2
Workstations (Tables) = 5, 6 , & 7

Table 10. Sub-assembly station 1 Assembly Tasks' distribution between ASM

Station 1 Assy Tasks Dist. - Group A-1/A-2/A-3	Ops 1 Activities	Ops 2 Activities
Pump Assy	*	
Acc. Gearbox Assy	*	
Vane Assy		*
Turbine Assy		*
Oil Filter Housing		*
Engine control Assy		*

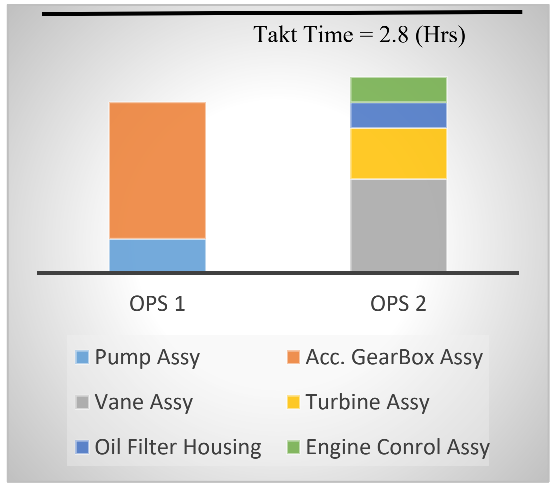

Chart 5. Sub-assy. station 1 assemblers' Balance chart

Table 11. Sub-assembly station 2 Assembly Tasks' distribution between ASM

Station 2 Assy Tasks Dist. – Group A-1/A-2/A-3	Ops 1 Activities	Ops 2 Activities
Gearbox Assy (1)	*	
Power Section Assy	*	
Gearbox Assy (2)		*
Main Line Assy		*
Prop Assy		*
Bleed Valve Assy		*
Prop Reversing Assy		*

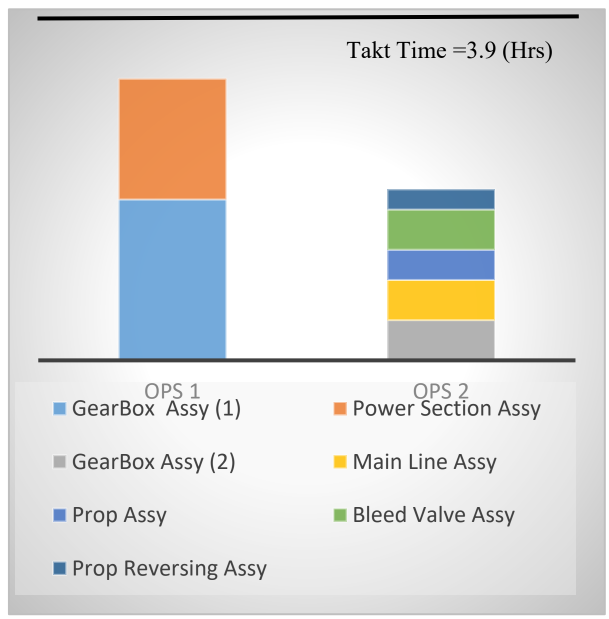

Chart 6. Sub-assy. station 2 assemblers' Balance chart

Table 12. Sub-assembly station 3 assembly tasks' distribution between ASM

Station 3 Assy Tasks Dist. - Group B	Ops 1 Activities	Ops 2 Activities	Ops 3 Activities
Exhaust Assy	*		
Housing Assy	*		
Valve Assy	*		
Reduction Gearbox Assy	*		
Diaphragm Assy		*	
Valve Housing Assy		*	
Acc. Gearbox Assy		*	
Clutch Gear Assy (1)			*
Clutch Gear Assy(2)			*
Cover Assy (1)			*
Cover Assy (2)			*
Output Gear Assy			*
Output Housing Assy			*
Main Line Assy			*
RGB Externals			*

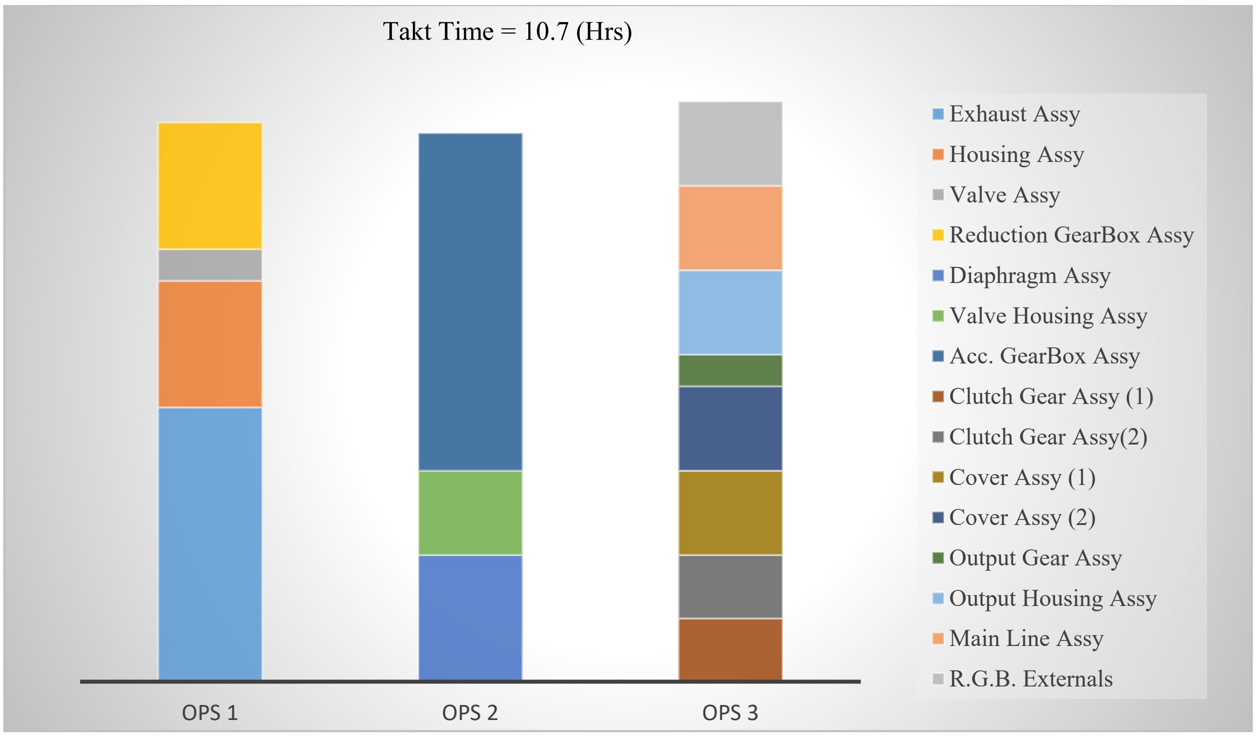

Chart 7. Sub-assy. station 3 assemblers' Balance chart

Mainline assembly department

The mainline assembly department is composed of two lines, one line for the Group A-1/A-2/A-3 engines assembly and the other for the Group B engines. These lines will perform in parallel. The Group A-1/A-2/A-3 engines mainline assembly has three stations. One assembler works in each station and the *TAKT* time is 3.9 hours. The Group B engine's mainline assembly has only one station with one assembler. The *TAKT* time in this mainline is 10.7 hours. More details are provided in the following tables and charts.

It is essential to mention that, in the proposed VSM, the engines' pre-dressing process that is performed before sending the engines to the test cell takes place in the mainline assembly department. It could be considered a final inspection on the mainline assembly before sending the engine for the test. This consideration could reduce human errors.

Table 13. Mainline assembly stations and their assembly tasks for the Group A-1/A-2/A-3 engines

Group A-1/A-2/A-3 Main Line Assembly

Main Assy 1 Data Box
Assembly Tasks
• Inlet Case Assy
• Gas Generator Assy 1
• Gas Generator Assy 2
Takt time = 3.9 (Hrs)
Number of operators = 1
Yield = almost 60%

Main Assy 2 Data Box
Assembly Tasks
• Gas Gen. Assy 3
• Main Engine External 1
Takt time = 3.9 (Hrs)
Number of assemblers = 1
Yield = almost 60%

Main Assy 3 Data Box
Assembly Tasks
• Main Engine External 2
• Main Engine External 3 / Rework
• Pre-Dressing
Takt time = 3.9 (Hrs)
Number of assemblers = 1
Yield = almost 60%

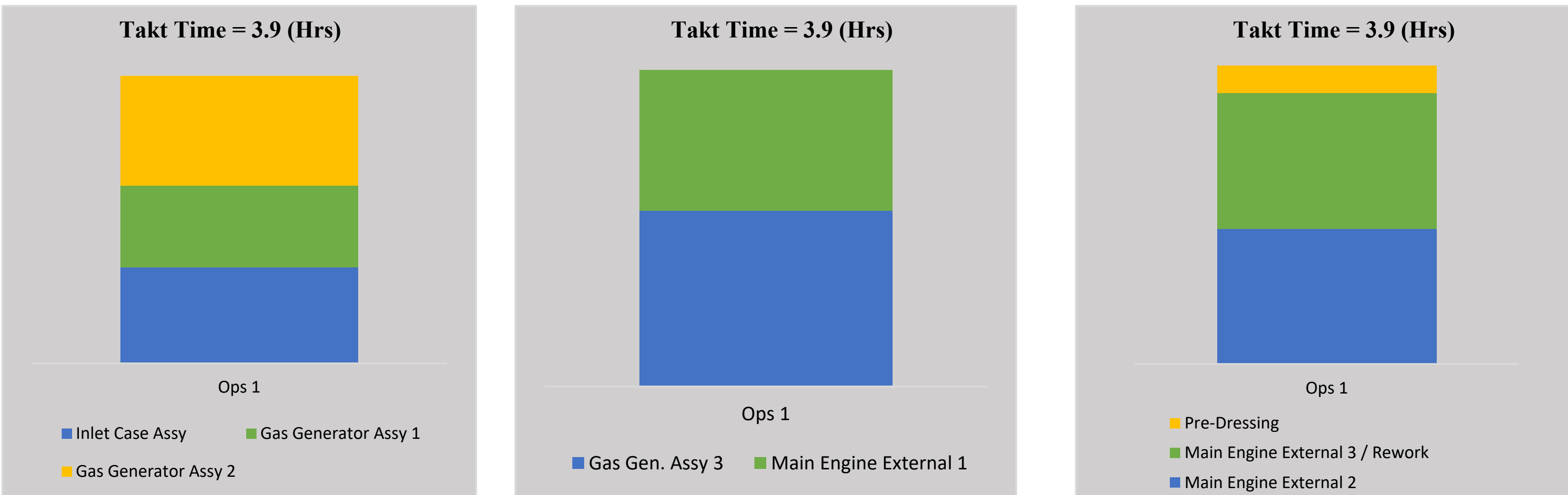

Chart 8. Mainline assy. station's assemblers' Balance chart for the Group A-1/A-2 engines

Table 14. Mainline assy station's Data Box for the Group B engines

Group A-3 Data Box
Assembly Tasks
• Gas Generator Assy
• Power Section
• Engine Complete
• Pre-Dressing
Takt time = 10.7 (Hrs)
Number of assemblers = 1
Yield = 67%

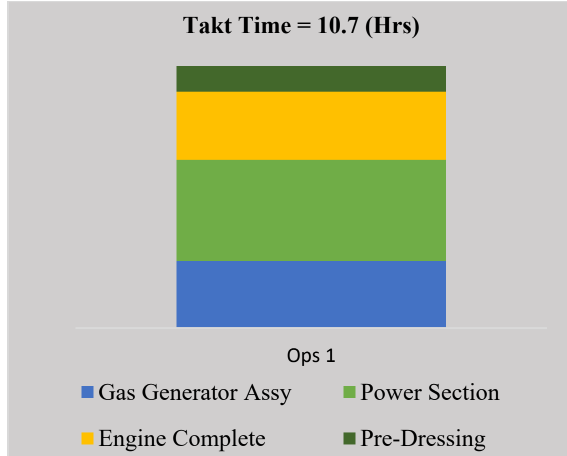

Chart 9. Group B engines mainline-assy. assemblers' Balance chart

Engine Test and Packaging Department

Although this section of the engine assembly process is not within the scope of this research, some upgrades and changes could improve the quality and the lead time. Some of them are mentioned below, though enormous expenses and more efforts would be necessary.

1. Installing another visual inspection system in order to increase the capacity of the final visual inspection;
2. Include the pre-dressing process in the mainline assembly department processes,
3. Improve the test cells and test methods of the engines and consequently reduce the engine test time.

The following tables illustrate the assembly tasks, TAKT times, the number of operators, and total work contents in this department for the Group A-1/A-2/A-3 and the Group B engines.

Table 15. Group A-3 engine family Test and Packaging stations and their assembly tasks

Group A-1/A-2/A-3 Test and Packaging

Test Data Box
Engine Test
Takt time = 3.9 (Hrs)
Number of assemblers = 1
Yield = 70%

Packaging Data Box
Tasks
• Post-Dressing
• Packaging
Takt time = 3.9 (Hrs)
Number of assemblers = 1
Yield = 75%

Group B Test and Packaging

Test Data Box
Engine Test
Takt time = 10.7 (Hrs)
Number of assemblers = 1

Packaging Data Box
Tasks
• Post-Dressing
• Packaging
Takt time = 10.7 (Hrs)
Number of assemblers = 1

Split Mixed-Model VSM for Group A-1/A-2/A-3 and the Group B families assembling in the aero-engine facility and their data boxes are presented in appendix F.

5.3. Presenting an ideal Layout for the new VSM

This section presents a new layout for the engine assembly facility that corresponds to the split mixed-model VSM described in the previous section. The main objective of the layout is to ensure a smooth flow of work, material, people, and information through the system. Effective layouts also:

- Minimize assemblers movements during assembly process;
- Utilize space efficiently;
- Utilize labour efficiently;
- Eliminate bottlenecks;
- Facilitate communication and interaction between workers and between workers and their supervisors;
- Eliminate wasted or redundant movement;
- Facilitate the entry, exit, and placement of material, products, and people;

- Incorporate safety and security measures;
- Promote product and service quality;
- Provide a visual control of operations or activities;
- Provide flexibility to adapt to changing conditions,

In addition to the above-mentioned criteria, in order to reduce the transformation expenses, minimal remodelling is considered in the preparation process of this layout. Due to this fact, the Balancing and Grinding and Engine Test and Packaging departments will remain where they currently are. As presented in the following figure, the sub-assemblies department is transformed substantially by being separated from the mainline assembly department and being located between grinding and balancing and the mainline assembly departments. The sub-assembly department is also divided into three stations:

1. Group A, B, E engines' family subs,
2. Group C, D engines' family subs,
3. Group F, G, H engines' family subs.

Furthermore, in each station, supermarkets are located to store the assembled products. Parts trucks will be used to transfer the materials in between departments. The number and sizes of supermarkets and workstations (tables) are calculated based on the demand of each section and the information provided in section 5.3 and summarized in (Table 16).

Table 16. Considered information for designing the layout of the sub-assembly department

Engine's Family	Ave. Demand per week	Number of Tables (Workstations)	Supermarket's Capacity
Group A, B, E engines	85 Engines	9	8
Group C, D engines	76 Engines	6	3
Group F, G, H engines	32 Engines	6	3

* Note: Numbers of this table are fictional and do not represent reality.

The mainline assembly department will stay more or less the same, corresponding to each engine family. The main change would be locating the supermarkets in each mainline assembly for storing the assembled products transferred from sub-assemblies to this department.

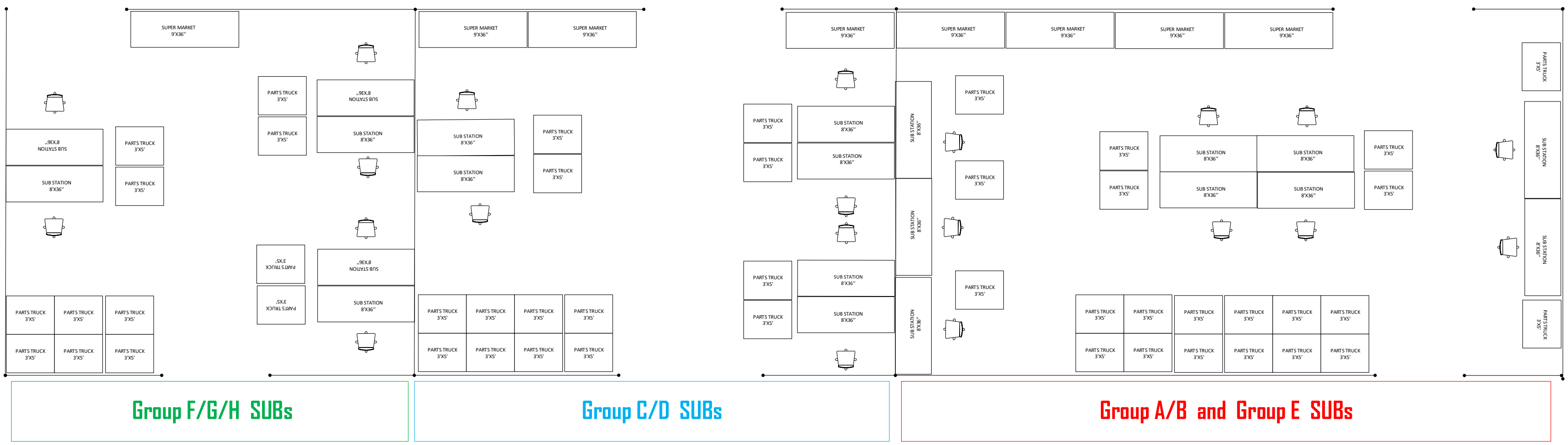

Figure 8.Sub-assembly department configuration in the new layout

Chapter 6

Conclusion and Future Research

6.1. Concluding Remarks

Manual assembly operations are sensitive to human errors that can negatively impact the quality of final products. Despite significant improvement in the facilities and equipment's reliability and stability in the production and assembly systems, human error remains one of the most important causes of quality defects in manufacturing systems. In this study, we implemented a suite of Lean manufacturing and quality engineering techniques to investigate and eventually eliminate external causes of human errors in a typical aero-engine facility. To the best of our knowledge, our study appears to be the first in the literature that applies the above-mentioned approaches for investigating human errors in manufacturing environments. In particular, the enhanced quality reporting tool that links quality defects with human errors in addition to the implementation of a Split Mixed-model assembly process are original ideas. The latter, for instance, aims to eliminate line stoppages, that deemed as one of the major external factors for the relatively high rate of human errors in this plant in the diagnostic phase of this study. The proposed split mixed-model that is specifically designed for the Group A engine family aims to achieve a smooth flow of products while systematically eliminating sources of interruptive and distractive issues during the assembly process, such as; shortages of components, late delivery of materials, delivered materials with quality defects, and insufficient assemblers or support teams. It is also expected to improve the quality and performance of the assembly line. Moreover, splitting a line into sub-lines provides the opportunity for resequencing the order arrangements between departments. We also proposed to install buffers (supermarkets) between sub-lines for the purpose of reactive resequencing and ultimately reducing the stoppages during the assembly process and improving the assembly lead-time.

6.2. Future steps

According to the analysis conducted in the diagnostic phase of this study, summarized in chapter 3, and the analysis conducted in chapters 4 and 5, the following areas are identified to extend the current study in order to eliminate external factors that cause human errors in a typical Aerospace engine assembly facility. Their ultimate goal is to enhance information and material flow, and consequently, reduce human errors due to interruptions and distractions.

- Execution of the presented Split mixed-model VSM:

  With regard to the details and information provided in chapter 5, this step incorporates: establishing the new departments and configuring their workstations; emplacing the supermarkets; and providing the necessary tools and instruments for each station.
- Implementation of the new layout:

  This implementation eases the flow of materials and assists in achieving the predetermined goals of Split Mixed-model VSM.
- Improving the information flow and communication between departments:

  In order to facilitate the assembly process and reduce the stoppages during the process, evaluating, updating and improving the existing shared information platform and the training methods for using these platforms are vital.
- Evaluating organizational chart and working procedure of each department:

  The goal is to support the new VSM performance via:
  - Analyzing the quality control data and assess the new checklist competency; and
  - Developing tasks and roles for the supporting departments while establishing new methods for encouraging teamwork.
- Improving the usage of IT systems:

  The idea is to conduct a root cause analysis to determine the reasons for not using IT systems in different departments and providing solutions to eliminate them.
- Establishing the Supplier Relationship Management (SRM) system:

  This would require the evaluation and categorization of suppliers, followed by discovering the cooperation opportunities with each one in order to moderate the side effects of late delivery of materials or delivered materials with quality defects and improve the lead-time.

Glossary

Andon: Andon is a system designed to alert operators and managers of problems in real-time to take corrective measures immediately.

Cycle Time: the time between the completion of two jobs/products.

ICL: Inspection checklist.

OEMI: The original equipment manufacturer intervention.

Pitch: The amount of time needed in a production area to make one unit of the engine.

QN: Quality Notification.

TAKT time: the speed with which the product needs to be created to satisfy the customer's needs.

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Appendixes

Appendix A

A sample of one of the AHP results done by a participant

	Late delivery of materials from supplier	Late delivery of materials from sub-assemblies	Late delivery of materials from warehouse	Reworks	QNs	Andons	Returned engine in main line of assy	Lack of communication between departments	Inaccurancy of the transfered information	Disruptive effects of Informal information flow	Necessity of witness or certified inspector in AFS	Lack of inspection or quality control between sub-assemblies and after certain AFSs	Slow and complex procedure of technical support	Inefficient documentation and archiving	Frequent changes in production priorities	Inefficient sequences of the AFSs	Insufficient root cause analysis of frequent problems/ breakdowns	Overloading of Grinding	Overloading of Test cells	Noisy and disturbing environment	Distractive people or activities in assembly area	Lack of proximity between sub-assemblies, Grinding, Testing, and Packaging departments	Lack of proximity to Washing/ cleaning departments	Lack of skill audit and retraining	Weak communication between people of different shifts	25 Root	Priority Vector
Late delivery of materials from supplier	1	1	4	0.333333333	0.33333	0.33333	5	3	0.5	0.2	1	1	0.5	8	0.2	5	0.2	3	6	0.3333	0.33333	3	3	3	3	1.14	0.034887416
Late delivery of materials from sub-assemblies	1	1	4	0.333333333	0.33333	0.33333	5	3	0.5	0.2	1	1	0.5	8	0.2	5	0.2	3	6	0.3333	0.33333	3	3	3	3	1.14	0.034887416
Late delivery of materials from warehouse	0.25	0.25	1	0.142857143	0.14286	0.14286	1	1	0.14286	0.11111	0.25	0.25	0.2	2	0.2	2	0.14286	1	2	0.2	0.2	1	0.5	1	1	0.41	0.012388576
Reworks	3	3	7	1	1	1	7	5	1	0.33333	3	3	2	5	0.25	3	0.5	3	5	0.3333	0.2	3	3	3	1	1.71	0.052159101
QNs	3	3	7	1	1	1	7	5	1	0.33333	3	3	2	5	0.25	3	0.5	3	5	0.3333	0.2	3	3	3	1	1.71	0.052159101
Andons	3	3	7	1	1	1	7	5	1	0.33333	3	3	2	5	0.25	3	0.5	3	5	0.3333	0.2	3	3	3	1	1.71	0.052159101
Returned engine in main line of assy	0.2	0.2	1	0.142857143	0.14286	0.14286	1	1	0.14286	0.11111	0.25	0.25	0.2	2	0.2	2	0.14286	1	2	0.2	0.2	1	0.5	1	1	0.40	0.012169384
Lack of communication between departments	0.333333333	0.33333	1	0.2	0.2	0.2	1	1	0.14286	0.11111	0.25	0.25	0.2	2	0.2	2	0.14286	1	2	0.2	0.2	1	0.5	1	1	0.43	0.013199329
Inaccurancy of the transfered information	2	2	7	1	1	1	7	7	1	0.33333	3	3	2	5	0.25	3	0.5	3	5	0.3333	0.2	3	3	3	1	1.68	0.051178543
disruptive effects of Informal information flow	5	5	9	3	3	3	9	9	3	1	3	3	2	5	0.25	3	0.5	3	5	0.3333	0.2	3	3	3	1	2.32	0.070704117
Necessity of witness or certified inspector	1	1	4	0.333333333	0.33333	0.33333	4	4	0.33333	0.33333	1	1	0.5	8	0.2	5	0.2	3	6	0.3333	0.33333	3	3	3	3	1.15	0.035125317
Lack of inspection or quality control between sub-assemblies	1	1	4	0.333333333	0.33333	0.33333	4	4	0.33333	0.33333	1	1	0.5	8	0.2	5	0.2	3	6	0.3333	0.33333	3	3	3	3	1.15	0.035125317
Slow and complex procedure of technical support	2	2	5	0.5	0.5	0.5	5	5	0.5	0.5	2	2	1	5	0.25	3	0.5	3	5	0.3333	0.2	3	3	3	1	1.38	0.042102017
Inefficient documentation and archiving	0.125	0.125	0.5	0.2	0.2	0.2	0.5	0.5	0.2	0.2	0.125	0.125	0.2	1	0.11111	0.5	0.16667	0.33333	1	0.1667	0.16667	0.333333	0.33333	0.33333	0.33333	0.26	0.007886948
Frequent changes in production priorities	5	5	5	4	4	4	5	5	4	4	5	5	4	9	1	3	0.5	3	5	0.3333	0.2	3	3	3	1	2.77	0.084521462
Inefficient sequences	0.2	0.2	0.5	0.333333333	0.33333	0.33333	0.5	0.5	0.33333	0.33333	0.2	0.2	0.33333	2	0.33333	1	0.14286	1	2	0.2	0.2	1	0.5	1	1	0.44	0.013337058
Insufficient root cause analysis of frequent problems/ breakdowns	5	5	7	2	2	2	7	7	2	2	5	5	2	6	2	7	1	3	5	0.3333	0.2	3	3	3	1	2.63	0.080170204
Overloading of Grinding	0.333333333	0.33333	1	0.333333333	0.33333	0.33333	1	1	0.33333	0.33333	0.33333	0.333333	0.33333	3	0.33333	1	0.33333	1	2	0.2	0.2	1	0.5	1	1	0.54	0.016536445
Overloading of Test cells	0.166666667	0.16667	0.5	0.2	0.2	0.2	0.5	0.5	0.2	0.2	0.16667	0.166667	0.2	1	0.2	0.5	0.2	0.5	1	0.1667	0.16667	0.333333	0.33333	0.33333	0.33333	0.28	0.008656075
Noisy and disturbing environment	3	3	5	3	3	3	5	5	3	3	3	3	3	6	3	5	3	5	6	1	0.2	3	3	3	1	2.89	0.088034551
Distractive people or activities in assembly area	3	3	5	5	5	5	5	5	5	5	3	3	5	6	5	5	5	5	6	5	1	3	3	3	1	3.87	0.117913181
Lack of proximity between sub-assemblies, Grinding, Testing, and Packaging departments	0.333333333	0.33333	1	0.333333333	0.33333	0.33333	1	1	0.33333	0.33333	0.33333	0.333333	0.33333	3	0.33333	1	0.33333	1	3	0.3333	0.33333	1	0.5	1	1	0.57	0.017507886
Lack of proximity to Washing/ cleaning departments	0.333333333	0.33333	2	0.333333333	0.33333	0.33333	2	2	0.33333	0.33333	0.33333	0.333333	0.33333	3	0.33333	2	0.33333	2	3	0.3333	0.33333	2	1	1	1	0.70	0.021257985
Lack of skill audit and retraining	0.333333333	0.33333	1	0.333333333	0.33333	0.33333	1	1	0.33333	0.33333	0.33333	0.333333	0.33333	3	0.33333	1	0.33333	1	3	0.3333	0.33333	1	1	1	1	0.59	0.018000099
Weak communication between people of different shifts	0.333333333	0.33333	1	1	1	1	1	1	1	1	0.33333	0.333333	1	3	1	1	1	1	3	1	1	1	1	1	1	0.92	0.027933374
SUM	40.94166667	40.9417	90.5	26.38571429	26.3857	26.3857	92.5	82.5	26.6619	21.3	39.9083	39.90833	30.6667	114	16.8778	72	16.5714	56.8333	100	13.333	7.46667	52.66667	48.6667	51.6667	31.6667	32.79	1
SUM*PV	1.4283489	1.43	1.12	1.376255	1.38	1.38	1.125668	1.09	1.36	1.51	1.4	1.402	1.29	0.9	1.43	0.96	1.33	0.94	0.87	1.17	0.88	0.922	1.03	0.93	0.88	29.53	

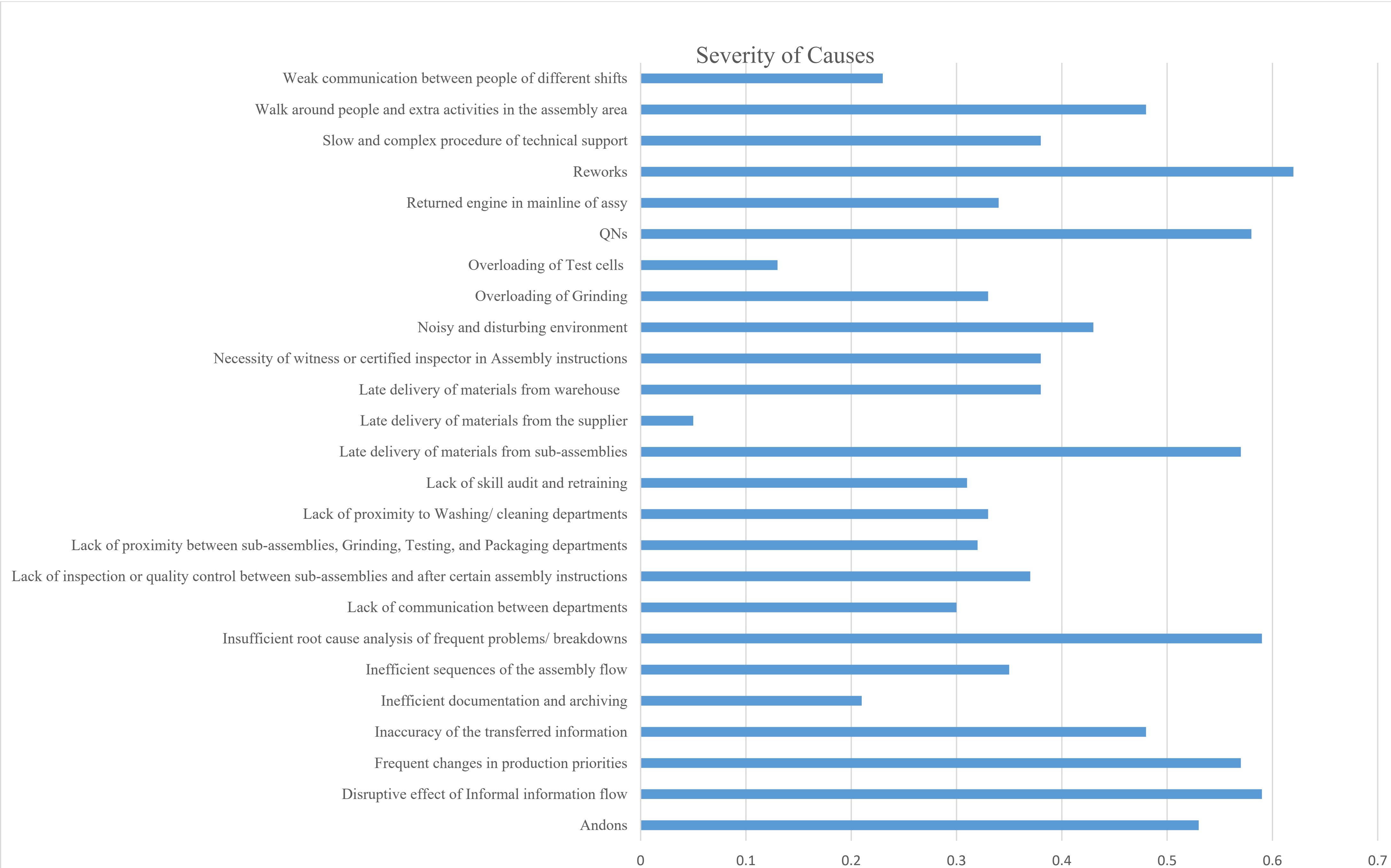
Lambda-max	29.53	
CI (Consistency Index)	0.1471567	
RI (Random Index for n= 25)	1.6624	
CR (Consistency Ratio)	0.08852	Because CR is smaller than 0.10 the pair-wise comparisons are relatively consistent.

A sample of one of the participants FMEA results

Potential Causes	Severity	Occurrence	Detection	RPN
Late delivery of materials from the supplier	9	8	1	72
Late delivery of materials from sub-assemblies	9	8	1	72
Late delivery of materials from warehouse	9	4	1	36
Reworks	9	9	1	81
QNs	9	9	1	81
Andons	9	9	1	81
Returned engine in mainline of assy	6	9	1	54
Lack of communication between departments	9	5	1	45
Inaccuracy of the transferred information	9	9	1	81
Informal information flow	9	9	1	81
Necessity of witness or certified inspector in Assembly instructions	8	7	1	56
Lack of inspection or quality control between sub-assemblies and after certain assembly instructions	9	8	1	72
Slow and complex procedure of technical support	7	8	1	56
Inefficient documentation and archiving	5	8	1	40
Frequent changes in production priorities	6	8	1	48
Inefficient sequences of the assembly flow	8	9	1	72
Insufficient root cause analysis of frequent problems/ breakdowns	7	9	1	63
Overloading of Grinding	8	9	1	72
Overloading of Test cells	6	5	1	30
Noisy and disturbing environment	7	7	1	49
Walk around people and extra activities in the assembly area	8	9	1	72
Lack of proximity between sub-assemblies, Grinding, Testing, and Packaging departments	5	8	1	40
Lack of proximity to Washing/ cleaning departments	8	8	1	64
Lack of skill audit and retraining	8	8	1	64
Weak communication between people of different shifts	8	6	1	48

Appendix B

Pareto chart presenting an average of severity for causes (extracted from different AHP results)

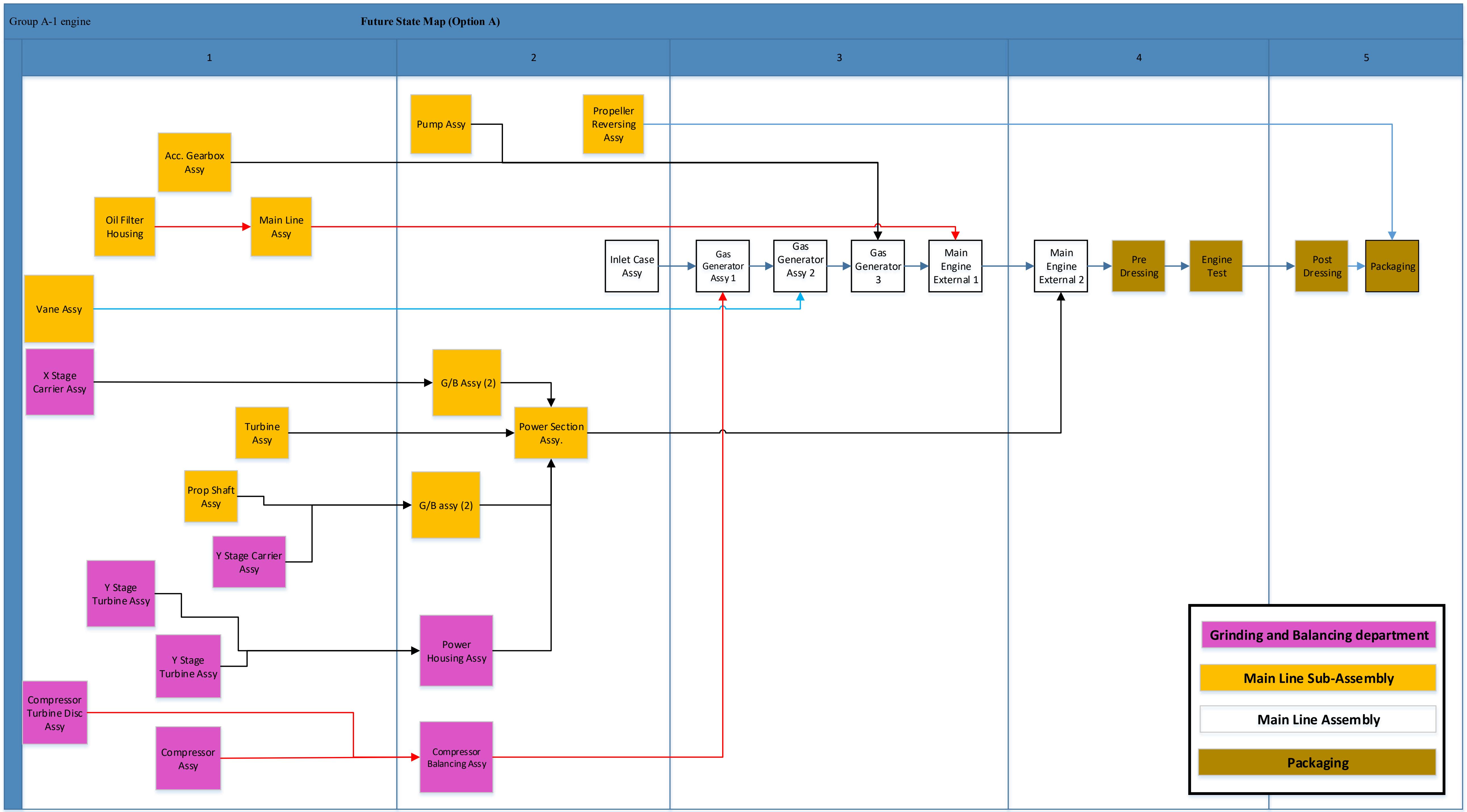


Priority of causes of quality defects (extracted from the combination of FMEA and AHP methods)

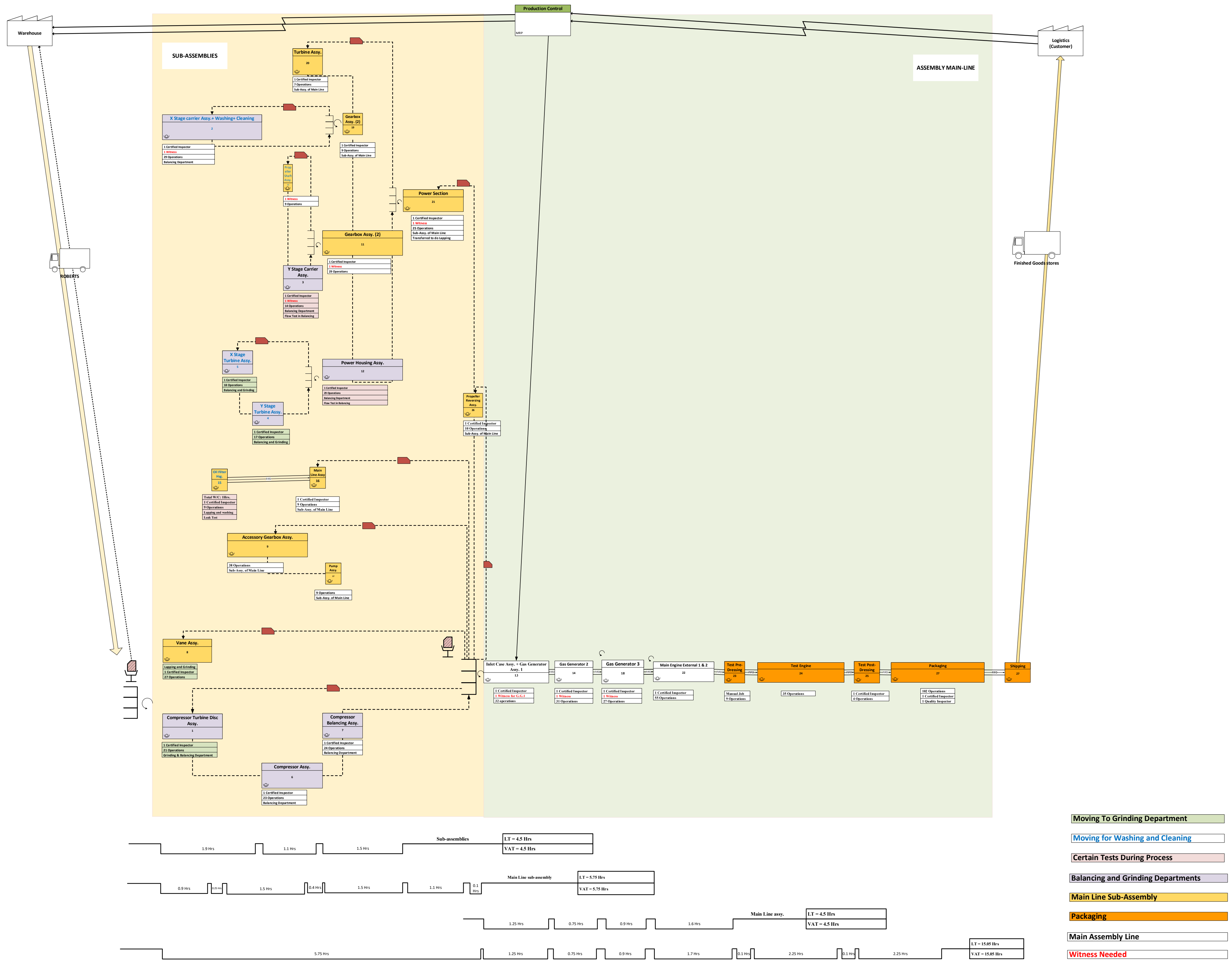
1	Reworks QNs Andons
2	Insufficient root cause analysis of frequent problems/ breakdowns
3	Frequent changes in production priorities
4	Disruptive effects of informal information flow Inaccuracy of the transferred information
5	Distractive people or activities in the assembly area
6	Slow and complex procedure of technical support
7	Lack of inspection or quality control between sub-assemblies and after certain assembly instructions
8	Necessity of witness or certified inspector in assembly instructions
9	Returned engine in mainline of assembly
10	Noisy and disturbing environment
11	Late delivery of materials from the supplier Late delivery of materials from sub-assemblies
12	Inefficient order of doing the assembly tasks
13	Inefficient documentation and archiving
14	Lack of proximity to Washing/ cleaning departments Lack of proximity between sub-assemblies, Grinding, Testing, and Packaging departments
15	Lack of skill audit and retraining
16	Overloading of Grinding
17	Late delivery of materials from warehouse
18	Lack of communication between departments
19	Weak communication between people of different shifts
20	Overloading of Test cells

Appendix C

a) First Option for Future production flowchart (option A)

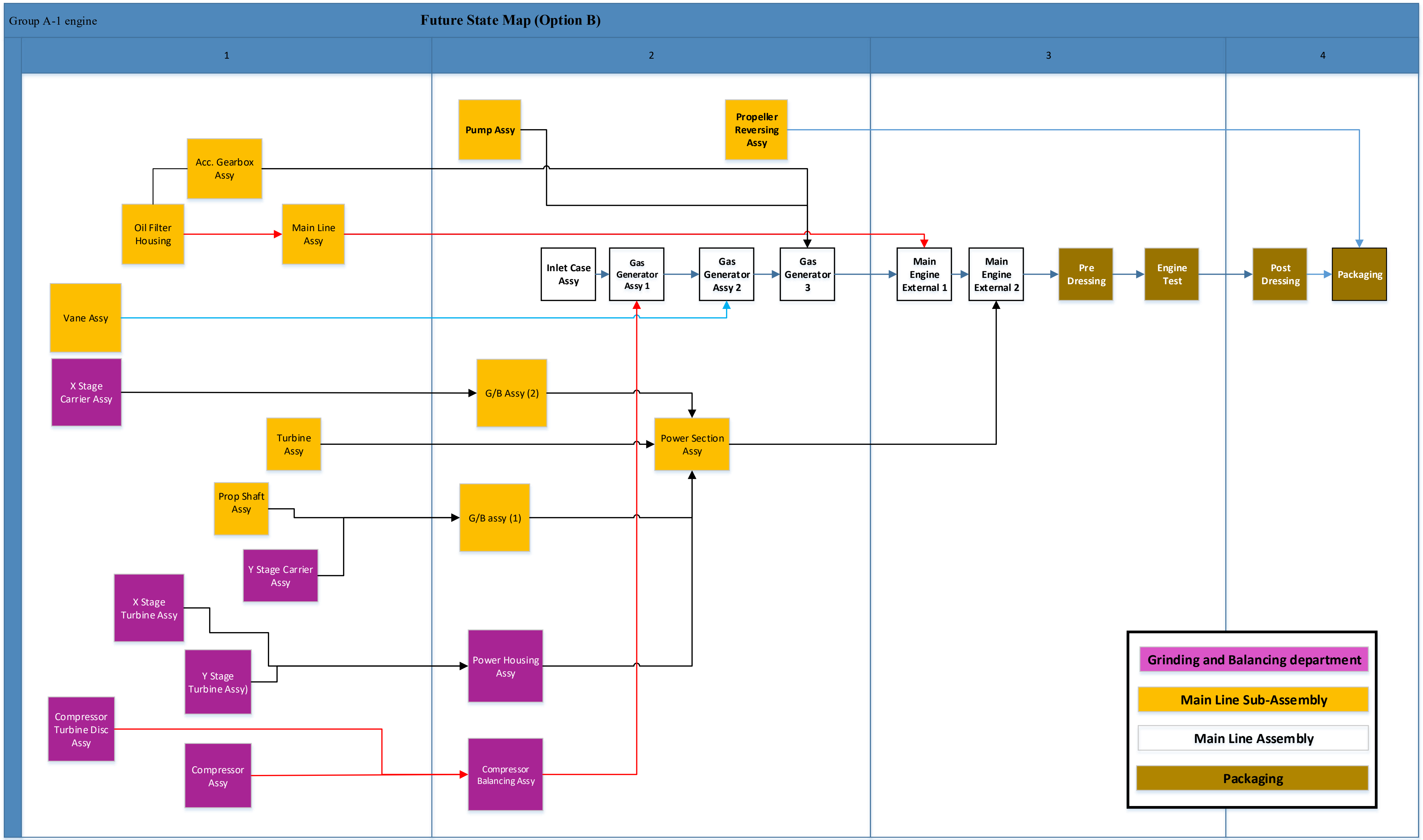


b) First Option for Future Value Stream Map (option A)

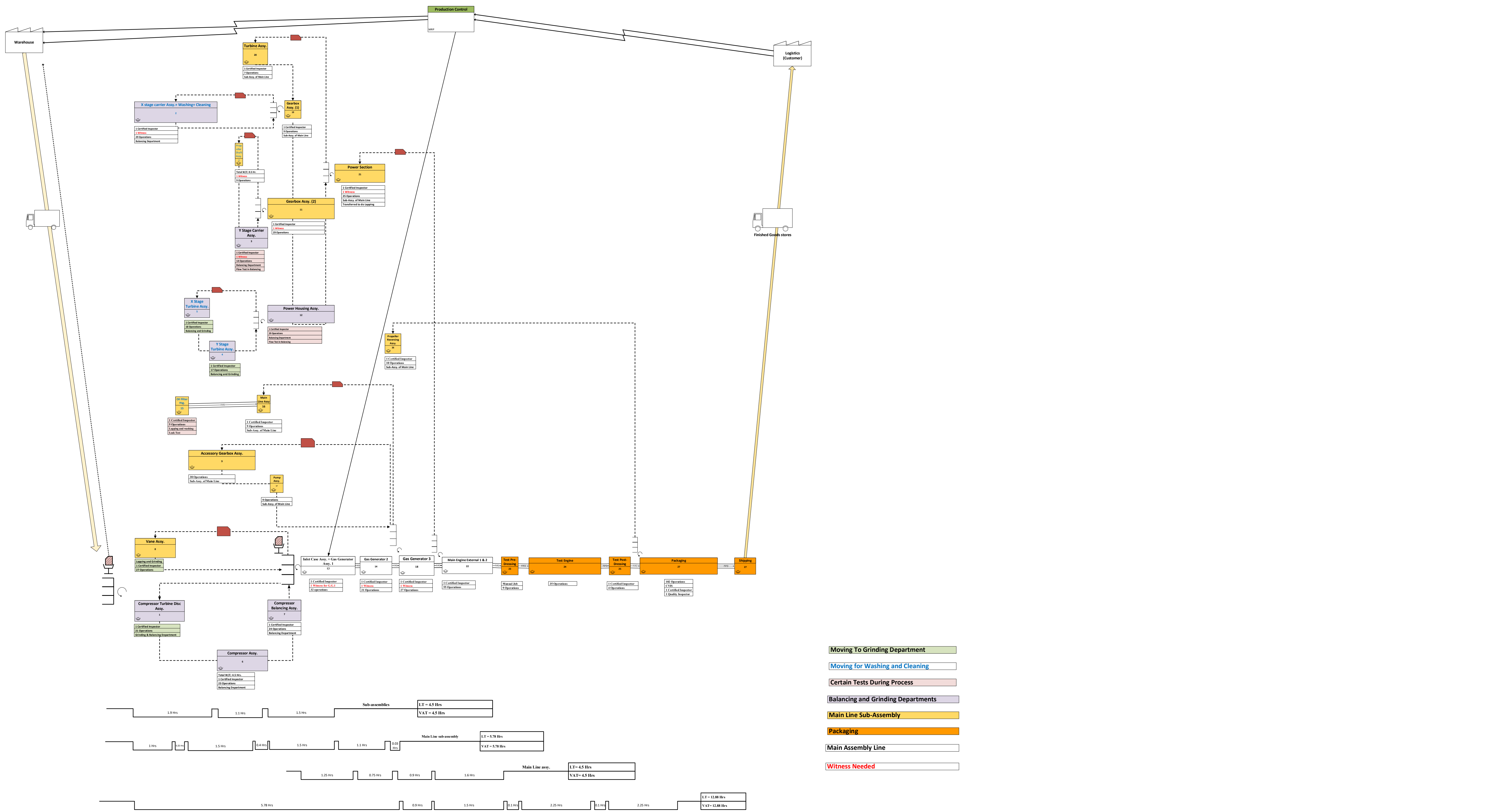


Appendix D

a) Second Option for Future production flowchart (Option B)

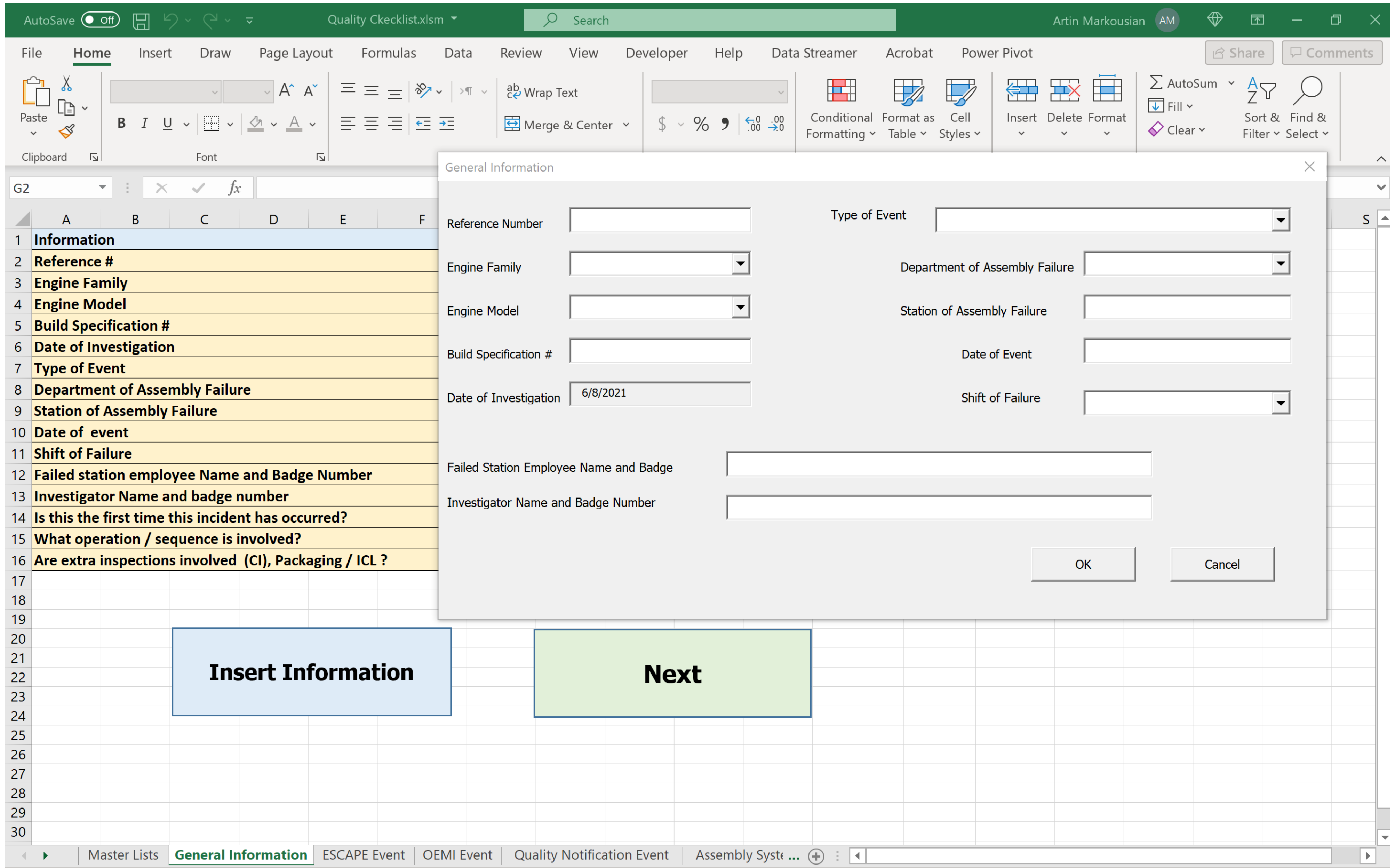


b) Second Option for Future Value Stream Map (option B)

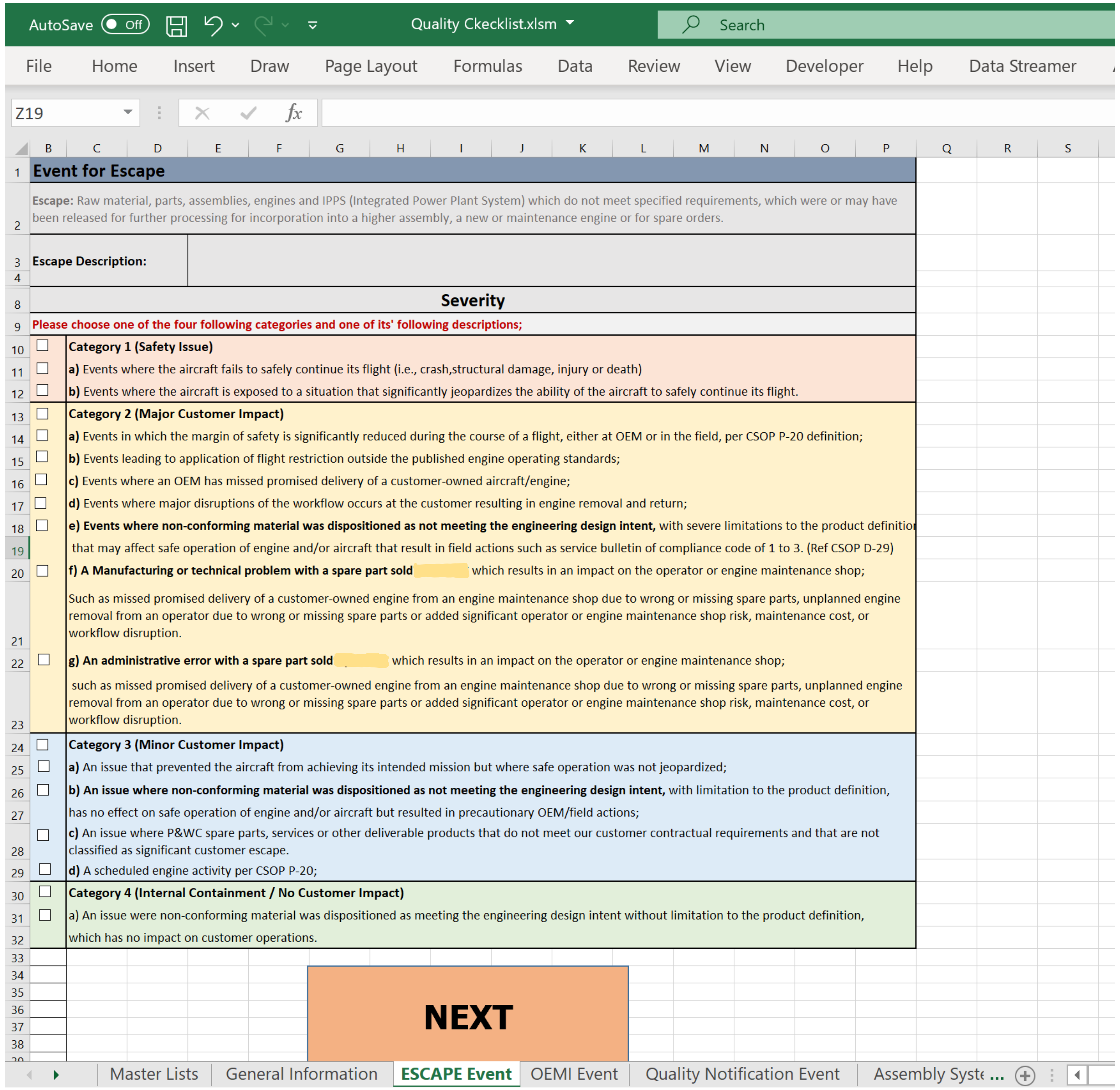


Appendix E

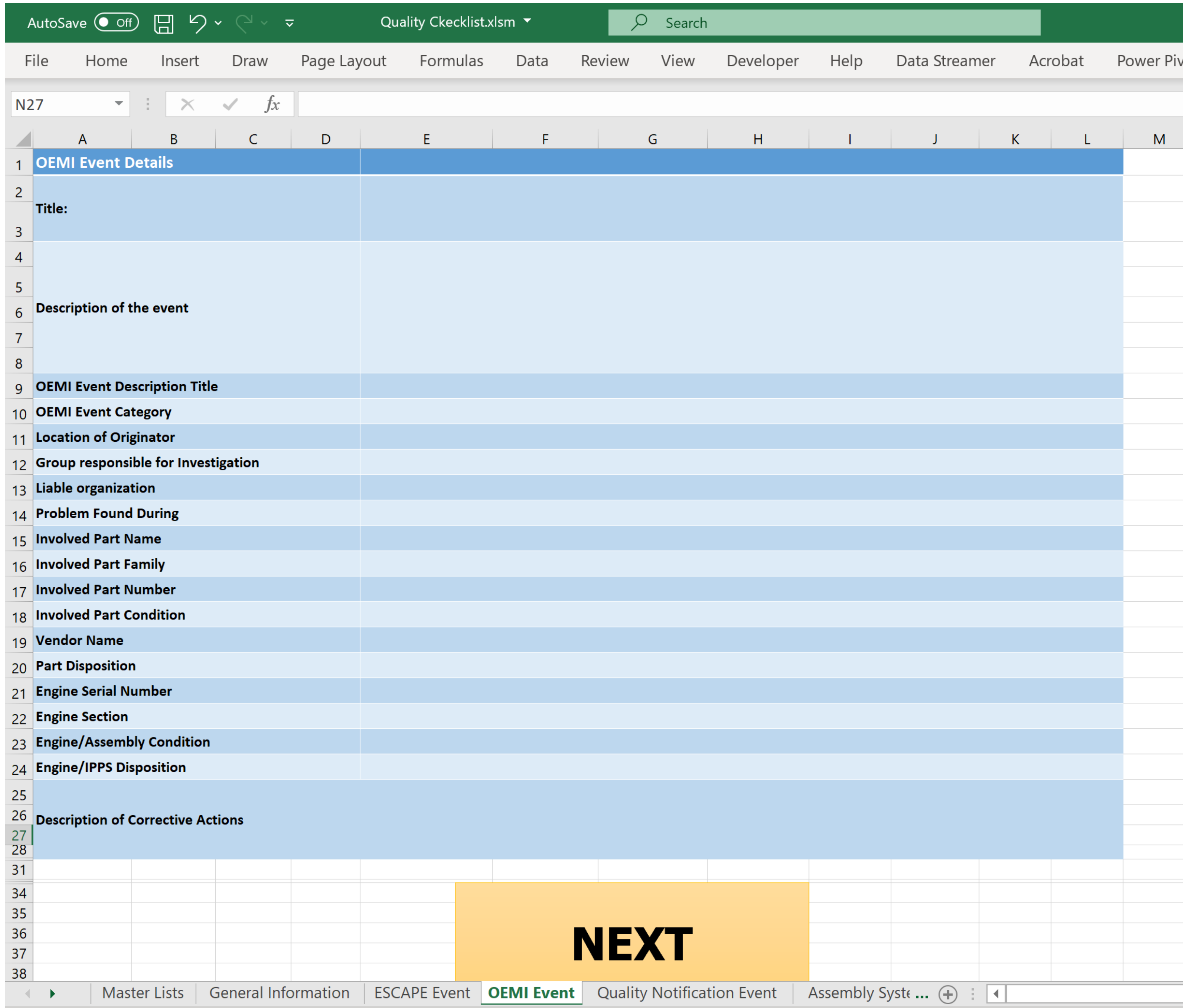
First Page of designed Quality Checklist – Pop-up window shows up to insert information. After pushing on the "Ok" button, information transfers to the first page of the excel ("General Information").



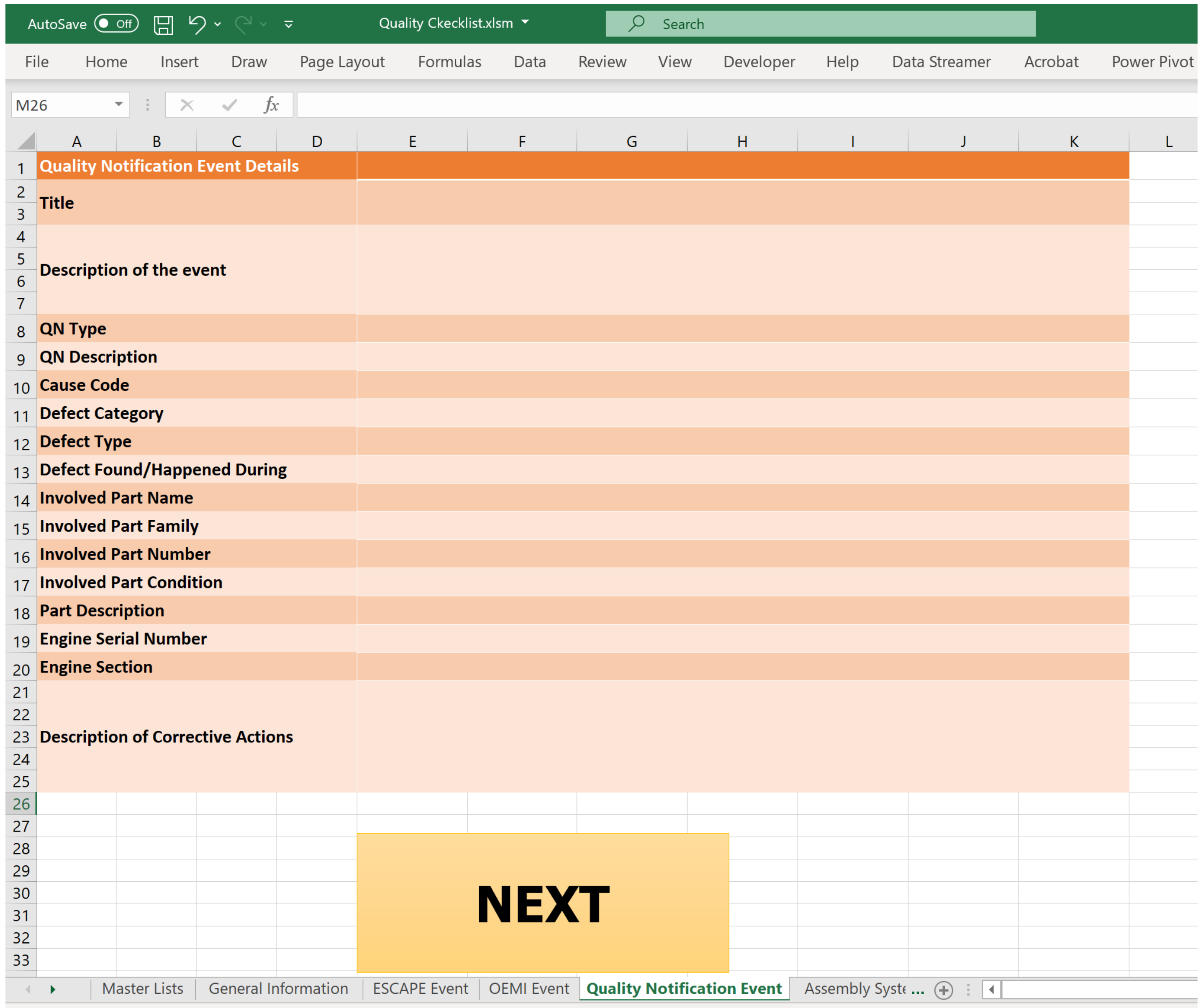
- **Based on the type of event to document, quality specialists choose to insert the information in one of the following three pages.**
  - Escape Event,
  - OEMI Event,
  - Quality Notification (QN) Event.



- **OEMI Event**


AutoSave Off
Quality Ckecklist.xlsm
Search
File Home Insert Draw Page Layout Formulas Data Review View Developer Help Data Streamer Acrobat Power Piv
N27
OEMI Event Details
Title:
Description of the event
OEMI Event Description Title
OEMI Event Category
Location of Originator
Group responsible for Investigation
Liable organization
Problem Found During
Involved Part Name
Involved Part Family
Involved Part Number
Involved Part Condition
Vendor Name
Part Disposition
Engine Serial Number
Engine Section
Engine/Assembly Condition
Engine/IPPS Disposition
Description of Corrective Actions
NEXT
Master Lists
General Information
ESCAPE Event
OEMI Event
Quality Notification Event
Assembly Syste ...

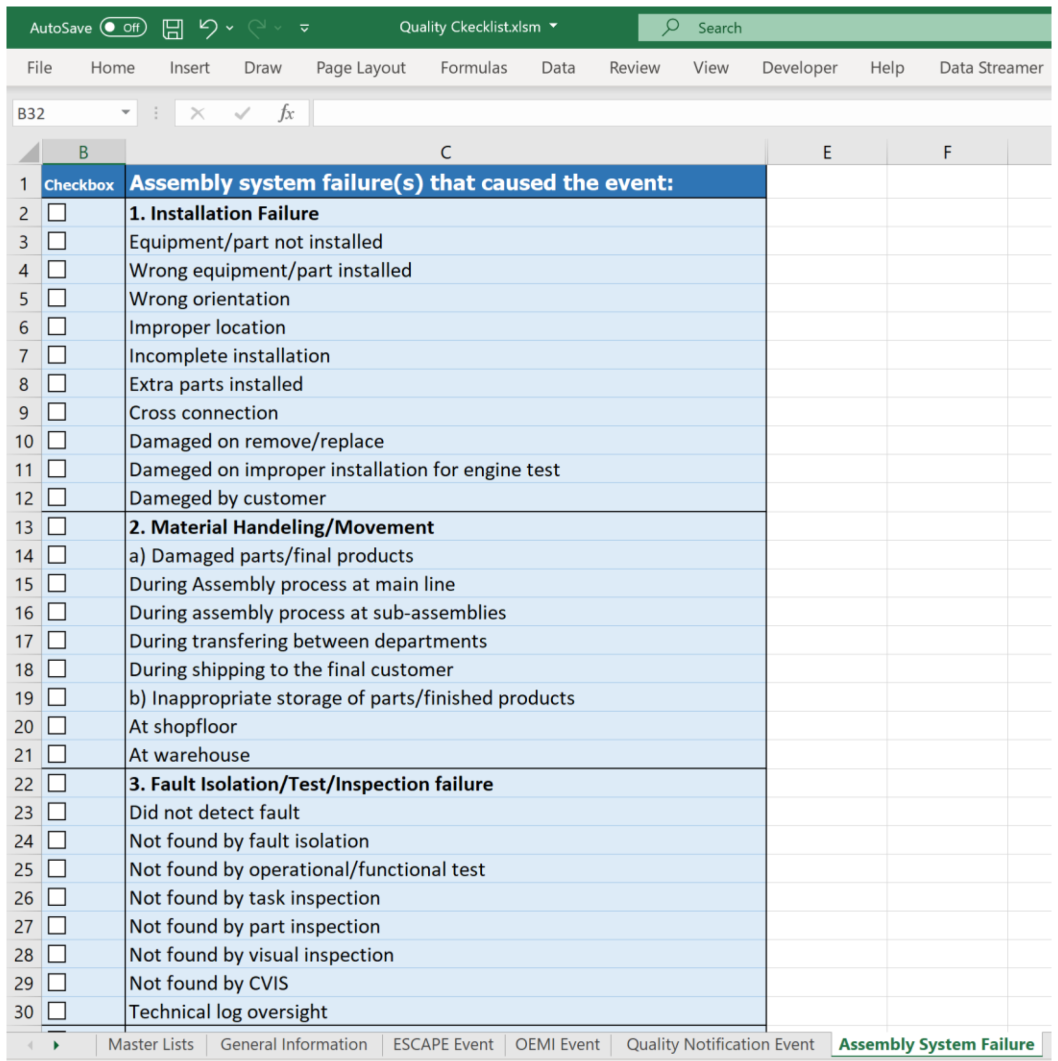
- **Quality Notification (QN) Event**

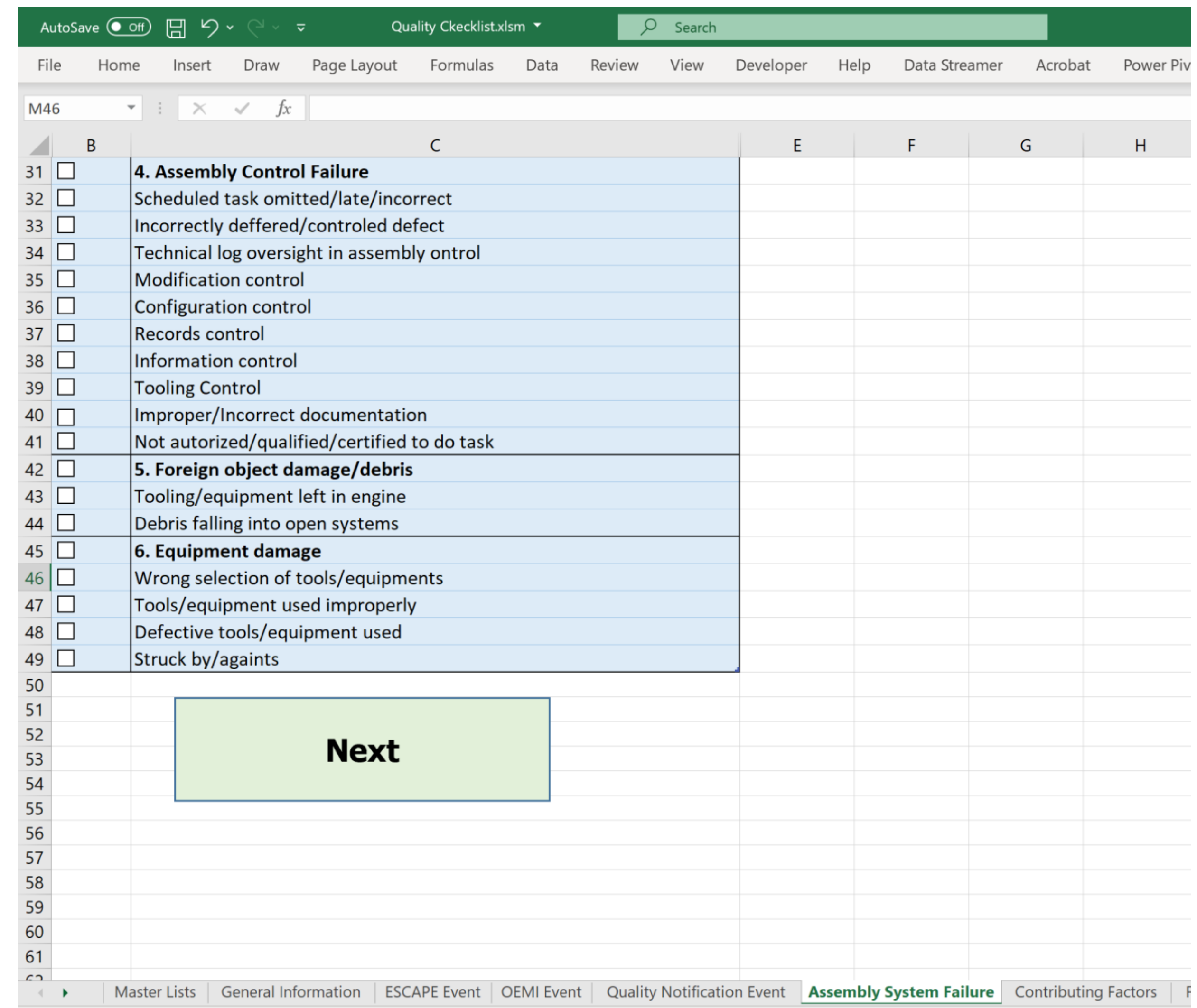


Quality Notification Event Details	
Title	
Description of the event	
QN Type	
QN Description	
Cause Code	
Defect Category	
Defect Type	
Defect Found/Happened During	
Involved Part Name	
Involved Part Family	
Involved Part Number	
Involved Part Condition	
Part Description	
Engine Serial Number	
Engine Section	
Description of Corrective Actions	

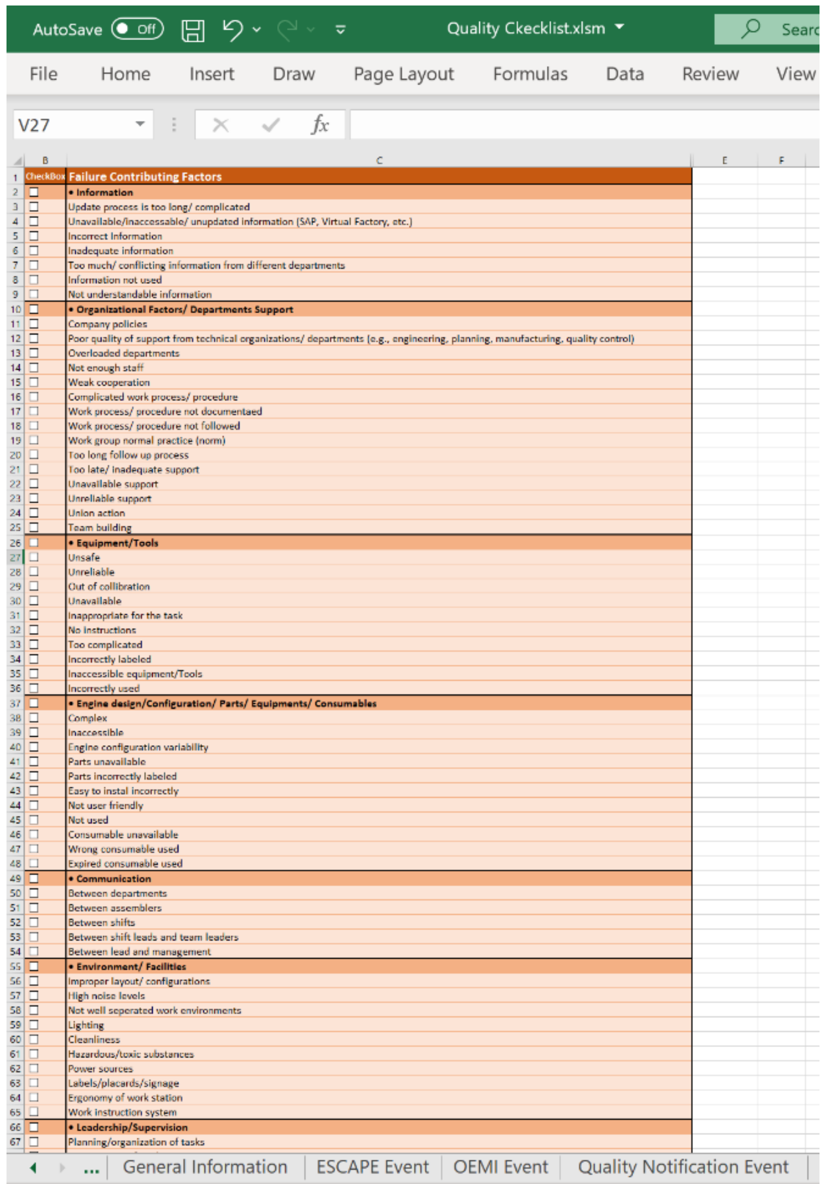
NEXT

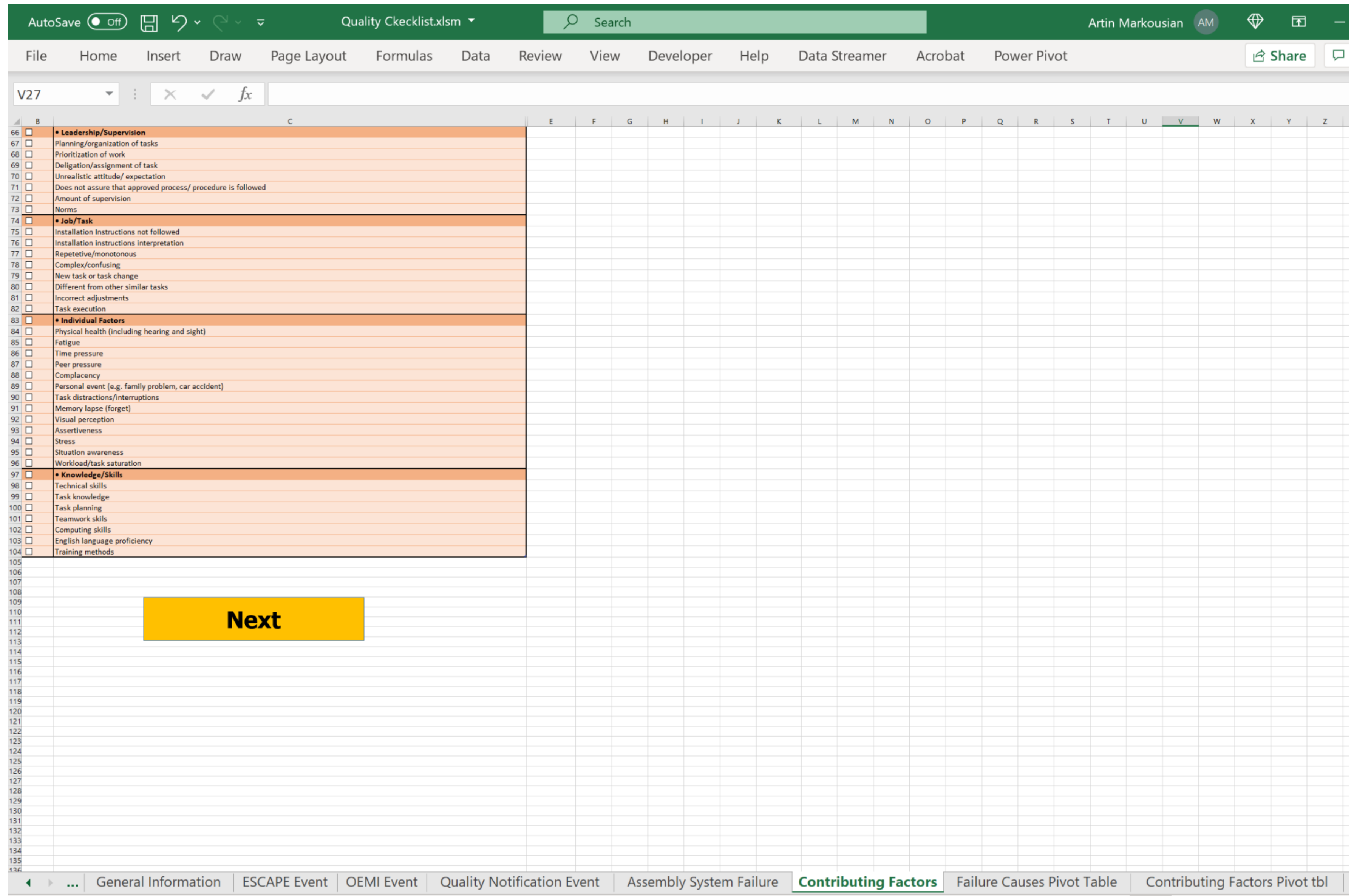
- **Assembly System Escape**





- **Escape Contributing Factors**





Appendix F

Split Mixed-Model VSM for Group A/B engines assembling in the aero-engine facility