Product Tracking and Direct Parts Marking System Optimization

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ABSTRACT

Product Tracking and Direct Parts Marking System Optimization

Dmitry Rozhdestvenskiy

Direct parts marking system (DPMS) plays extremely important role in the aircraft industry. Aircraft engine quality can be significantly improved through the increase of traceability of engines' components. That is why the appropriate implementation of DPMS into the manufacturing process is crucial from many points of view, from the aircrafts' safety to the bottom lines of the companies that are involved in the manufacturing process. However, the implementation of aircraft engine parts tracing strategy in production ramp-up faced various problems that have been defined, structured, and classified in this research.

In the scope of this research, the existing way of prioritizing quality improvement actions has been analyzed and the new evaluation approach has been developed. A new measurement system for unique identifiers (UI)-related issues tracking has been developed. The system has been proven to be able to highlight quality notifications (QN) with heavier impact on the production, prioritizing quality improvement actions.

Drawbacks of existing failure mode effect analysis (FMEA) methods were highlighted. Dynamic risk priority number (DRPN)-based FMEA system has been developed, tested and implemented into the prioritisation process of the UI-related problems. The system has been proven to be efficient in fast-changing hi-tech manufacturing environment. It was able to emphasise the importance of issues that conventional FMEA would have “filtered out”.

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LIST OF ABBREVATIONS

Abbreviation	Description
2-D	Two dimensional
2DM	2D missing
2DMR	2D miss-read
2DWD	2D wrong data
A&T	Assembling and Testing
AFS	Assembly Floor Sheet
AHS	Production management software
AI	Authorised Inspector
AIAG	Automotive Industry Action Group
AMAX	Production management software
ASIC	Application Specific Integrated Circuit
ATTS	Assembling and Testing Technology Specialist
BOM	Bill of Materials
CAGE (Code)	Commercial and Government Entity Code
CCM	CAGE Code Missing
DMAIC	Define-measure-analyse-improve-control
DoD	Department of Defence (US)
DPM	Direct Part Marking
DPMS	Direct Parts Marking System
EC	Engineering Change
EIA	Energy Information Agency (US DoE)

F2	Type of quality notification
F3	Type of quality notification
FMEA	Failure Mode Effects Analysis
FPS	Finished Parts Storage
FSM	Final Stamp Missing
FSWM	Final Stamp Wrong Marking
HMM	Data missing in human readable
HRI	Human Readable Identification
HWM	Human (readable) Wrong Marking
IS	Information System
IT	Information Technology
LEP	Legibility Problem
MSCP	System vs. Minimum Space Condition
NSCM	NATO Supply Code for Manufacturers
OEM	Original Equipment Manufacturer
OP	Operation
P&WC	Pratt and Whitney Canada
PCR	Part Change Request
PFMEA	Process Failure Mode and Effects Analysis
PN	Part Number
PO	Production Order
PWZZX	Engine model number
PWZZY	Engine model number
PWZZZ	Engine model number

QN	Quality Notification
QRA	Quality Release Authorisation
R&D	Research and Development
REVM	Revision Letter Missing
RFEA	Request for Engine Acceptance
RFM	Red Flag identification Missing
ROI	Return on Investment
RPN	Risk Priority Number
SAP	SAP AG Enterprise Resource Planning software
SCI#	Supplier Code Identification number
SEMI	Semiconductor Equipment and Materials Institute
SER	Serial Number
SERM	Serial Number Missing
SIPOC	Supplier-Inventory-Process-Output-Customer
SPCP	Spacing Problems
Spec 2000	Aircraft industry parts marking standard
SSON	Supplier’s Statement of Non-conformity
TEI	Text Element Identifier
TIMM	Timing "x" is Missing
TEIM	Text Element Identifier Missing
UI	Unique Identifier
UIM	UI Missing
VC	Vendor Code
VLJ	Very Light Jet

WCC	Wrong CAGE Code
WM	Wrong Marking method
WML	Wrong Marking Location
ZE	Type of quality notification
ZP10	SAP transaction
ZP15	SAP transaction
ZP78	SAP transaction
ZPRPT03	SAP transaction
ZS	Type of quality notification

1 INTRODUCTION

1.1 GENERAL BACKGROUND

Materials and product tracking tracing is an indispensable part of any manufacturing process. In life-critical products and their manufacturing, tracking and tracing play even more significant role in the company's success. Material traceability allows such company to address safety-related matters in a timely manner, and to assure the high efficiency of its operation.

1.2 RESEARCH OBJECTIVES

The objectives of this research are:

1) Support the implementation of aircraft engines tracking strategy in production ramp-up by optimizing Direct Parts Marking System (DPMS) based on Unique Identifiers (UI) or Serial Numbers (SER).

2) Investigate the impact of DPMS on aircraft engines production process.

3) Create a new measurement system for UI-related issues tracking.

4) Analyze the existing way of prioritizing quality improvement actions and develop a new evaluation approach by applying Six Sigma DMAIC methodology to DPMS.

1.3 THESIS ORGANIZATION

Literature review (**Chapter 2**) introduces two major theoretical basics for the thesis: direct parts marking principles, and Six Sigma tools: Define-Measure-

Analyse-Improve-Control (DMAIC) and Process Failure Mode and Effect Analysis (PFMEA).

Chapter 3 gives detailed description of the proposed approach for the research objectives. Unique Identifiers (UI)-related issues are classified there, and PFMEA with dynamic occurrence rating is introduced.

Chapter 4 is designated to the case study 1. UI-related problems that are unveiled at the assembly and test document closure process for engine shipment stage are analysed using DMAIC tool, and solutions are proposed.

Chapter 5 is dedicated to solving the second research objective: design and implementation of the improved FMEA methodology.

Chapter 6 summarises the performed work, draws conclusions, and defines the future work.

2 LITERATURE REVIEW

2.1 INTRODUCTION

Parts traceability is indispensable part of the manufacturing processes in the aerospace industry. There are many approaches to parts marking system. Standard, but rather legacy, way to assure the parts' traceability is to put on them human-readable numbers and keep track of them. Radio-frequency identification (RFID) is the state-of-the-art method. However, due to the specific industry segments' requirements, RFID tags have limited application. For example, aircraft engine parts cannot be marked with RFID tags due to the extreme environment, namely the heat and mechanical constraints, and the parts' material that are made of metal that shields the electromagnetic waves the RFID tags use to communicate with the reader.

The thesis deals with quality improvement in parts tracing in the aerospace industry.

2.2 DIRECT PARTS MARKING SYSTEM

Many industries profit from direct parts marking. Industry associations such as Energy Information Agency (EIA), Semiconductor Equipment and Materials Institute (SEMI), Automotive Industry Action Group (AIAG), Department of Defence (DoD), and the Spec 2000 (aerospace) have established and adopted standards for marking parts, components and modules for various applications.

Some companies use DPMS for internal applications. In this case, they might or might not follow the abovementioned standards. DPMS can be used to optimize line performance, identify the source of defects, increase first-pass yields and, as a result, it reduces the costs of manufacturing. Manufacturers also rely on DPMS for identifying incoming parts for maintenance and returns, resolving warranty issues and liability claims as well as tracking high-value components to prevent theft [14].

Rather than affixing a label to a product, we can put a 2D code directly on to the part or product and it is there for life. DPM is now being utilised a lot in sectors such as aeronautical and automotive, on parts such as engine blocks, camshafts, and connecting rods [36].

Two dimensional symbols such as Data Matrix are the most common symbologies used for direct parts marking identifiers (DPMI) applications because of their small size, data capacity, error correction, and ability to be applied by a variety of marking methods. All a manufacturer needs is 0.1 square inch of space on a component and it can be marked with a 5 or 6 digit Data Matrix symbol. As a result, Data Matrix enables the traceability of components such as crystal oscillators or custom ASICs that in the past could not accommodate any type of machine-readable form of identification [10].

The following Subsections will review different codes used for DPM.

2.2.1 1-D and 2-D codes comparison

1-D codes, known as bar codes, are often used as a reliable identifying method. With space at a premium, Code 128 is commonly selected due to its ability to encode both numbers and alpha characters. One disadvantage of Code 128 is the quiet zone at both ends of the data, a requirement for the reader. Code 128 specifications indicate that at least 0.20 inches on each side be used, diminishing its value in DPMS application, especially in the aerospace industry [14].

Finally, consider using the 2-D Data Matrix symbol. As its name implies, the information is encoded using two dimensions, allowing for the most efficient use of space. Figure 2.1 illustrates encoding 8 alphanumeric and 12 numeric digits at similar X-dimensions using Code 128 and Data Matrix. A bar code X-dimension refers to the dimension of its smallest bar-width usually measured in mils, or thousandths of an inch. The Data Matrix symbol remains the same whether carrying 12 numbers or 8 alphanumeric characters [14].

As one can see, a 2-D code allows to use the marking space more efficiently. Thus, it has been chosen for DPM in the aerospace industry. However, it requires more sophisticated and expensive equipment to read it because a simple laser scanner, used for 1-D codes cannot process a 2-D image. Cameras based on charge-coupled device (CCD) are used to read 2-D codes.

a) ZYA1B2C3

b) 120123456789

c)

Figure 2.1. Area occupied by a 1-D bar code (a) and (b) vs. the 2-D (c) [14]

2.2.2 2-D codes overview

2.2.2.1 Aztec Code

Aztec Code was invented by Andy Longacre of Welch Allyn Inc. in 1995 and is in the public domain. A sample of Aztec Code is shown in Figure 2.2. Aztec Code was designed for ease-of-printing and ease-of-decoding. The symbols are square overall on a square grid with a square central bulls eye finder. The smallest Aztec Code symbol is 15x15 modules square, and the largest is 151x151. The smallest Aztec Code symbol encodes 13 numeric or 12 alphabetic characters, while the largest Aztec Code symbol encodes 3832 numeric or 3067 alphabetic characters or 1914 bytes of data. No quiet zone is required outside the bounds of the symbol. There are 32 sizes in all with user-selected amounts of Reed-Solomon error encoding from 5% to 95% of data region. Recommended level is 23% of symbol capacity plus three codewords [4].

Figure 2.2 Aztec Code [1]

2.2.2.2 Maxicode

Maxicode (originally called UPSCode, sometimes called Code 6) is a matrix code developed by United Parcel Service in 1992. However, rather than being made up of a series of square dots, MaxiCode is made up of an 1-inch by 1-inch array of 866 interlocking hexagons. This allows the code to be at least 15 percent denser than a square dot code, but requires higher resolution printers like thermal transfer or laser to print the symbol. There is a central bull-eye to allow a scanner to locate the label regardless or orientation. A sample of Maxicode is shown in Figure 2.3.

Approximately 100 ASCII characters can be held in the 1-inch square symbol. The symbol can still be read even when up to 25 percent of the symbol has been destroyed and can be read by a CCD camera or a scanner [4].

Figure 2.3 2D Maxicode Sample [2]

2.2.2.3 Quick Response Code (QR Code)

QR Code is a matrix code developed by Nippondenso ID Systems and is in the public domain. QR Code symbols are square in shape and can easily be identified by their finder pattern of nested alternating dark and light squares at three corners of the symbol. Maximum symbol size is 177 modules square, capable of encoding 7366 numeric characters, or 4464 alpha numeric characters. One important feature of the symbology is its ability to encode directly Japanese Kanji and Kana characters. QR Code is designed for rapid reading using CCD array cameras and image processing technology because of the layout of the finder pattern [4]. A sample of QR code is shown in Figure 2.4.

Figure 2.4 QR Code Sample [27]

2.2.2.4 Data Matrix

Data Matrix from Siemens is a 2-D matrix code designed to pack a lot of information in a very small space. A Data Matrix symbol can store between one and 500 characters. The symbol is also scalable between a 1-mil square to a 14-inch square. That means that a Data Matrix symbol has a maximum theoretical density of 500 million characters to the inch! The practical density will, of course, be limited by the resolution of the printing and reading technology used [4]. A sample of Data Matrix code is shown in Figure 2.5

Figure 2.5. 2D Data Matrix example [4]

The code has several other interesting features. Since the information is encoded by absolute dot position rather than relative dot position, it is not as susceptible to printing defects as is traditional bar code. The coding scheme has a high level of redundancy with the data "scattered" throughout the symbol. According to the company, this allows the symbol to be read correctly even if part of it is missing. Each Datacode symbol has two adjacent sides printed as solid bars, while the remaining adjacent sides are printed as a series of equally spaced square dots. These patterns are used to indicate both orientation and printing density of the symbol.

Two main subsets of Data Matrix symbols exist. The first subset uses convolutional coding for error correction which was used for most of the initial installations of Data Matrix systems, these versions are referenced as ECC-000 to ECC-140 [33]. The second subset is referenced ECC-200 and uses Reed-Solomon error correction techniques. ECC-000 to 140 symbols all have an odd number of modules along each square side. ECC-200 symbols have an even number of modules on each side. Maximum data capacity of an ECC-200 symbol is 3116 numeric digits, or 2335 alpha numeric characters, in a symbol 144 modules square [4].

The most popular applications for Data Matrix is the marking of small items such as integrated circuits and printed circuit boards. These applications make use of the code's ability to encode approximately fifty characters of data in a symbol 2 or 3 mm square and the fact that the code can be read with only a 20 percent contrast ratio [4].

The code is read by CCD video camera or CCD scanner. Symbols between one-eight inch square to seven inches square can be read at distances ranging from contact to 36 inches away. Typical reading rates are 5 symbols per second [4].

2.2.3 2-D Data Matrix Aerospace Industry Standard

2.2.3.1 2-D Symbol

The Data Matrix symbol is preferred for direct part identification marking on NASA programs/projects unless otherwise directed by contract. The symbols shall be applied in addition, and in close proximity to, the human readable identification (HRI) markings currently used. On new programs/projects the HRI and symbol marking shall be applied simultaneously and by the same method whenever practical. The Data Matrix symbol is approved by the Automated Identification Manufacturers (AIM) for direct part marking. For new NASA applications, ECC 200, which uses Reed-Solomon error correction, is required [7].

2.2.3.2 2-D Symbol Content

As shown in Figure 2.6 (a), the full part identification data to be encoded into the 2-D symbol shall consist of a part number (PN) that is typically 15 to 21 characters, preceded by the Commercial and Government Entity (CAGE) Code or NATO Supply Code for Manufacturers (NSCM) and followed by a unique serial or lot number, separated by an asterisk (ASCII separator for machine readable identification symbols) or dash (used for HRI). In instances where space is prohibitive, the PN can be excluded from the data content and an abbreviated traceability number used (Figure 2.6 (b)). The traceability number or unique part identification number shall consist of the users CAGE Code or NSCM and unique seven-digit lot number or serial number, separated by an asterisk in the machine readable symbol or dash in the HRI. These data encoding and marking options provide program managers with the ability to use a more damage-resistant symbol (larger data cells) over a greater range of part sizes. Data Matrix symbols that are subsequently covered with paint, foam or other protective coatings shall have the same symbol content requirements as symbols that remain visible throughout their life cycles [7].

a) Data format to be used in areas providing sufficient marking area

b) Data format to be used where marking area is insufficient to place a symbol containing complete data content.

Figure 2.6. Preferred 2-D Symbol Data Content Format [7]

2.2.3.3 2-D Symbol Shape

The Data Matrix symbol can be created in square and rectangular formats, the square format being preferred. However, for some linear shaped parts, such as pipes, lines, narrow part edges, etc., it may be more desirable to use a rectangular shape symbol. The intent is to use a symbol shape providing the largest size data cells [7].

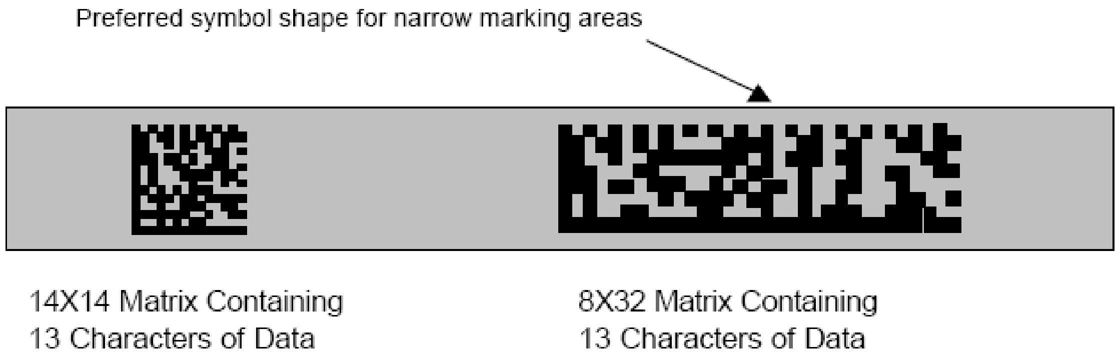


Figure 2.7. Matrix Symbol Shapes Applied to Elongated Part [7]

2.2.4 Marking Methods

DPM can be broken down into two primary categories: non-intrusive and intrusive.

2.2.4.1 Non-intrusive Marking Methods

Non-intrusive markings, also known as additive markings, are produced as part of the manufacturing process or by adding a layer of media to the surface using methods that have no adverse effect on material properties. These methods include [6]:

- Automated Adhesive dispensing
- Cast, forge, and mould
- Ink jet
- Laser bonding
- Laser engineered net shaping (LENS)
- Liquid metal jet
- Silk screen
- Stencil

2.2.4.2 Intrusive Marking Methods

Intrusive markings alter a part's surface (abrade, cut, burn, vaporize, etc.) and are considered to be controlled defects. If not done properly, they can degrade material properties beyond a point of acceptability. Consequently, some intrusive markings, especially laser, are generally not used in safety critical applications without appropriate metallurgical testing. Typical intrusive marking methods include [6]:

- Abrasive blast
- Dot peen
- Electro-chemical marking
- Engraving/milling
- Fabric embroidery/weaving
- Direct laser marking

2.3 FAILURE MODE AND EFFECTS ANALYSIS

The Failure Mode and Effect Analysis (FMEA) technique was developed in the mid 1960's by the aerospace industry. This technique has been further developed and adopted by the automotive industry as a systematic approach to analyzing failure modes and their associated causes, with the end objective of designing them out or reducing the probability of their occurrence. The technique has evolved into a practice in which one continuously analyzes what in his process can go wrong and affect his customer - an error proofing methodology. Its application to the design and manufacture of automobiles has been so successful that the Automotive Industry Action Group (AIAG) has started requiring its suppliers, including the integrated circuits (IC) Industry, the use of this methodology in their own operation and even goes as far as being able to demonstrate its application as part of QS9000 Certification [21].

In order to be able to assign priority levels to the issues based on their impact, FMEA has been chosen in this research as a tool for quality assurance. Within its scope, all the manufacturing/process issues are prioritized to help identify opportunities for the greatest impact upon the customer and return on investment.

2.3.1 Process Failure Mode and Effects Analysis

The most common tool used to identify/prioritize the issues is Process Failure Mode and Effects Analysis (PFMEA). The PFMEA method is used in a cross-functional team approach to answer all process-related questions, and to quantify the results in the form of a Risk Priority Number (RPN). The PFMEA method helps to ask the key questions necessary to identify and implement the proper error-proofing techniques to improve processes. PFMEA is a systemized group of activities intended to [23]:

Identify the way in which a product/process can fail to meet critical customer requirements;

- estimate the risk of specific causes with regard to these failures and their effect;
- evaluate the current control plan for preventing these failures from occurring;

- identify actions which could eliminate or reduce the occurrence;
- prioritise the actions that should be taken to improve the process;
- document the process, and
- track changes to process-incorporated to avoid potential failures.

PFMEA is being continuously updated. Unveiling in advance the potential failure modes and their effects, it allows to take actions addressed to eliminate or reduce the potential causes rather than implementing controls in the process [23].

The risk priority number (RPN) is used by many FMEA procedures to assess risk using the following three criteria:

Occurrence (O) – how likely is the cause to occur and result in the failure mode? Occurrence is related to the probability of the failure mode and cause. Occurrence is *not* related to the probability of the end effects. The Occurrence values are arbitrarily related to probabilities or failure rates (Table 2.1).

Severity (S) – how serious are the end effects? Severity of Effect measures the seriousness of the effects of a failure mode. Severity categories are estimated using a 1 to 10 scale. For example, S=10 can mean total lack of function and a safety risk; S=8 - total lack of function; S=4 - moderate degradation of performance; S=1 - effect almost not noticeable. Severity scores are assigned only to the effects and not to the failure mode or cause (Table 2.2).

Detection (D) – how likely is the failure to be detected before it reaches the customer? Detection estimates the chance of the customer catching the problem before the problem results in catastrophic failure (Table 2.3)

Table 2.1. Occurrence criteria (adapted from AIAG, 1995) [17]

Probability of Failure	Failure Rates	Occurrence
Very High: Failure is almost inevitable	>1 in 2	10
	1 in 3	9
High: Repeated Failures	1 in 8	8
	1 in 20	7
Moderate: Occasional failures	1 in 80	6
	1 in 400	5
	1 in 2,000	4
Low: Relatively few failures	1 in 15,000	3
	1 in 150,000	2
Remote: Failure unlikely	1 in 1,500,000	1

Table 2.2. Severity Ranking Criteria [28]

Criteria	Rating
Insignificant: Defect may not be noticed at all. Will not result in downstream processing problems or impair usability. The customer will probably not be able to detect variation in the product.	1
Low: Some downstream effect may occur in processing. May affect end user or cause less-than-optimal performance. Variation causes only slight customer annoyance. Customer will probably notice only very minor performance degradation, or minor.	2 3
Moderate: Will likely cause processing problems down- stream or result in degraded performance of end product if part reaches the customer. Customer dissatisfaction is probable.	4 5 6
Significant: Serious downstream proceeding problems may occur. If product reaches customer, equipment failure is likely.	7 8
Very High: Potential failure affects safety issues in operation or processing.	9 10

Table 2.3. Detection Rating Scale [28]

Criteria	Rating
Design controls almost certainly detect a potential cause and subsequent failure mode, machinery control not required.	1 2
Design controls may detect a potential cause & subsequent failure mode. Machinery controls will prevent an imminent failure & isolate the cause.	3 4
Design controls may detect a potential cause and subsequent failure mode. Machinery controls will provide an indicator of imminent failure.	5 6
Design or machinery controls do not prevent the failure from occurring. Machinery controls will isolate the cause and subsequent failure mode after the failure has occurred.	7 8
Design or machinery controls cannot detect a potential cause and subsequent failure, or there are no design or machinery controls.	9 10

Obtained ranks of severity (S), occurrence (O) and detection rate (D) are used for risk assessment via an index called Risk Priority Number (RPN) calculated by multiplying the severity, occurrence and detection ranking factors for every cause:

$$RPN = S * O * D \qquad \textbf{Equation 2.1}$$

Once all items have been analyzed and assigned a RPN value, it is common to plan corrective actions from the highest RPN value down. The intent of any corrective action is reduction of any of the severity, occurrence and/or detection rankings [8].

2.3.2 Drawbacks of existing FMEA methods

A group of experts make this quantification gathering information from memory and experience of the plant personnel. The most known way to implement this analysis is in an ordinary tabular form which is difficult to trace [30].

The FMEA matrix is a pictorial representation of relationships between several FMEA elements. Traditionally, the numbers in the matrix are a prioritization of failures based on ranked numbers evaluating concepts as severity, frequency of occurrence and detectability of failure. Vague or ambiguous information and subjectivity in the ranking scales adds inherent inconsistency. Some researchers eliminate this deficiency by introducing fuzzy logic by using linguistic variables to describe the severity, frequency of occurrence and detectability of failure [3]. Rivera et al. [29] made an attempt to “defuzzify” the input parameters using Root Mean Square algorithms. However, this method does not address the subjective nature of the problem. Palumbo [22] proposed an automated FMEA based on five attributes: modularity, structural model, finite state machine, discrete event simulation and strong typing. Price et al. [26] introduced another automated FMEA system. Targeted for the automotive industry, this system assisted FMEA design engineers. Standard components and their failure modes were entered in the system’s library. The system was meant to be used at the design stage, thus, it did not address the real-time problems. Krasich [18] states that when a product also has reliability requirements, performance of just FMEA without support from other reliability methods, will not guarantee or show that the required reliability is achieved. It is the well organized and managed overall reliability program with reliability and engineering tests and analyses (including FMEA) that can assure that the delivered product will meet Customer expectations.

2.4 SIX SIGMA DMAIC

As it has been described by Waddick [34], improvement of existing products or processes using the Six Sigma methodology is done in five steps:

Define	projects, goals, and deliverables to internal and external customers
Measure	current performance of the process
Analyze	root causes of the defects
Improve	process to eliminate defects
Control	performance of the process

This set of steps is referred to as DMAIC.

2.4.1 Define phase

When going into the Define phase, the first phase of the DMAIC process, executive management has an idea of which processes are not producing the results their customers expect and have a vague problem statement. However, this is not enough to begin a Six Sigma project. Since Six Sigma calls for unmistakable, measurable results, the goal of the Define phase is to clearly identify and articulate the problem in a clear and measurable way. Another goal of the Define phase is to identify customer(s) and segmented them according to their different needs and requirements. In order to better understand customer(s) critical needs and requirements, pertinent data should be collected and displayed [34].

The deliverables of the Define phase are a completed, verified, and validated high-level 'as is' (not 'should be' or 'could be') process map, and a completed SIPOC representation, describing the Suppliers, Inputs, Process, Outputs, and Customers [34].

2.4.2 Measure Phase

Taguchi's statement “You cannot manage what you do not first measure” highlights the importance of the phase.

Measure Phase includes evaluation of the existing measurement systems (if it exists). The actual condition might be measured using the existing system. Then valid and reliable metrics should be established to help monitor progress towards the project goals. Customer expectations are defined to determine “out of specification” conditions [34].

The deliverables of the Measure phase are the identified key measures, planned and executed data collection, displayed and communicated process variation, baselined performance, calculated sigma level [34].

2.4.3 Analyse phase

Within the scope of the Analyze Phase, the system is examined to identify ways to eliminate the gap between the current performance of the system or process and the desired goal. In this phase, project teams explore underlying reasons for defects. They use statistical and non-statistical analysis to examine potential variables affecting the outcome and seek to identify the most significant root causes. Then, they develop a prioritized list of factors influencing the desired outcome [34].

The deliverables of the Analyse phase are data and process analysis, root cause analysis, and the gap/opportunity quantification.

2.4.4 Improve phase

The Improve phase is the fourth step of the DMAIC process is the point where the hard work of defining, measuring and analyzing pays off - the point where the ideas for process improvement are formulated and implemented. In this phase, project teams seek the optimal solution, and develop and test a plan of action for implementing and confirming the solution. The process is modified and the outcome is measured to determine whether the revised method produces results within customer expectations [34].

2.4.5 Control phase

The final phase of the DMAIC process is control. Six Sigma calls for this step, which goes beyond improvement, and includes the control of your improved process. There are many factors that could affect the adjusted inputs and, thus, the output, so ongoing monitoring of the process to make sure it stays "in control" is critical. In most cases, this is done for a limited amount of time by the Six Sigma team or the Black Belt and then handed off to the process owner. The Control process involves quality and statistical concepts that have existed for decades. However, the advent of quality control software makes the process simple enough for anyone to perform [34].

2.5 CONCLUSIONS

In this chapter, DPM methods were reviewed and compared. Then, a deeper study of one of them, 2-D Data Matrix, adopted by the aerospace industry, was conducted. Later in this research, the analysis of potential problems of using DPM will be done and the solutions will be proposed.

In the second part of the chapter, FMEA principles were described and the drawbacks of existing FMEA methods were highlighted. Later in the research an alternative and improved approach will be developed. Six Sigma's DMAIC is a versatile tool, which is applicable to almost any process. In this research, DMAIC methodology along with FMEA will be applied to developing an approach to the aircraft engine quality improvement through the increase of traceability of its components.

3 PROPOSED APPROACH

3.1 UI ISSUES CLASSIFICATION

3.1.1 Overview

The aircraft engines are reflection of the most recent state-of-the-art technology. In the era of globalisation, it is common fact that a manufacturer has a number of suppliers that provide all necessary parts, components, and materials. The situation when a manufacturer has more than one supplier of a certain product is not only not rare, but ubiquitous. Among other innovations, a new traceability strategy has been adopted by the aerospace industry: beside industry mandate for serialisation of the most critical parts, in order to bring customer satisfaction to a new level, the industry has introduced its own Unique Identifiers (UIs) to items where serial numbers are not required, thus it assures traceability of materials through the whole manufacturing process and engine life time, starting from metal forging, and ending when a part finishes its life-cycle.

However, at the beginning of the program, adapted by the company where the present research has been conducted, managing the high volume of UIs and serial numbers created many problems. As the result, the usage of UIs affected the engines' production time.

Figure 3.1 depicts the summary of UI-related problems, challenges, and benefits. On the manufacturer's side, the following problem spots were identified:

- **Traceability owner**: the person directly responsible for the implementation of DPMS. His mandate is to assure that all stakeholders comply with the requirements.
- **Standardisation**. As it has been discussed earlier, some, mostly life-critical, parts, components, and modules must be serialised according to the industry standard. Other parts, considered critical by the manufacturer, are marked using its own standard. The manufacturer has to design and standardise the latter according to the production process and maintenance requirements. The manufacturer's own standards could be not comprehensive and, as a result, create ambiguous parts marking requirements.
- **Validation**. Once a requirement is ready for implementation, it must be validated. The validation checks various aspects such as feasibility, compliance with the standards, reasonability, etc. Some of these check points could be missed. Once the DPMS is deployed, system data validation takes place during manufacturing stage by the information technology (IT) means.
- **Resistance to UI mandate**. Implementation of the manufacturer's own serialisation requirements is often regarded as extra work with no clear benefits.
- **Human factor**. "In general, a human factor is a physical or cognitive property of an individual or social behaviour which is specific to humans and influences functioning of technological systems…" [35]. Humans are prone to making errors while performing duties. Though being not random, these errors

are hard to predict because they occur due to various factors and events of human life. It is difficult to quantify and register these factors.

- **Process/requirements change**. Taking into account that continuous improvement is a part of production process in the aerospace industry, the traceability requirements can be changed, i.e. new requirements can be introduced to an existing part; traceability requirements can be lifted for a part; a new part with or without traceability requirements can be added to the production process.
- **Incorrect/unclear/unfeasible requirements**. Unresolved problems with standardisation can result in incorrect or unclear DPM requirements. In some cases, a traceability requirement can be added to a part that cannot be marked using DPM due to various reasons, such as insufficient space for marking, marking is unfeasible due to specific manufacturing process, a label cannot be read, etc.

On the suppliers' side, few similar problem spots can be found along with supplier-specific ones:

- **Resistance to UI mandate**. The suppliers see no added value in DPM requirements. It incurs extra production cost.
- **Delay in implementing new requirements**. Due to the fast-paced production environment, short lag-time, and manufacturer's UI requirements change, the latter can come when a part of the batch is already produced.

- **Equipment**. As it has been discussed earlier in Chapter 2, the DPM process requires specific equipment that must be properly set-up, calibrated and maintained to meet the manufacturer's demands.
- **Certification**. If a supplier is certified in DPMS, it is likely to comply with the manufacturer's marking requirements.
- **Supply chain (outsourcing)**. A supplier could have its own suppliers down the supply chain. Thus, it must assure that its suppliers meet the manufacturer's requirements.
- **Miscommunication, misunderstanding**. Miscommunication and/or misunderstanding could happen at all levels of manufacturing process and management. DPM/UI requirements might be misinterpreted.

On the positive side, properly implemented and managed UIs make parts easily traceable. It dramatically improves equipment maintenance quality and, especially, defective parts recalls.

The problem spots will be reviewed in details in Section 3.4.

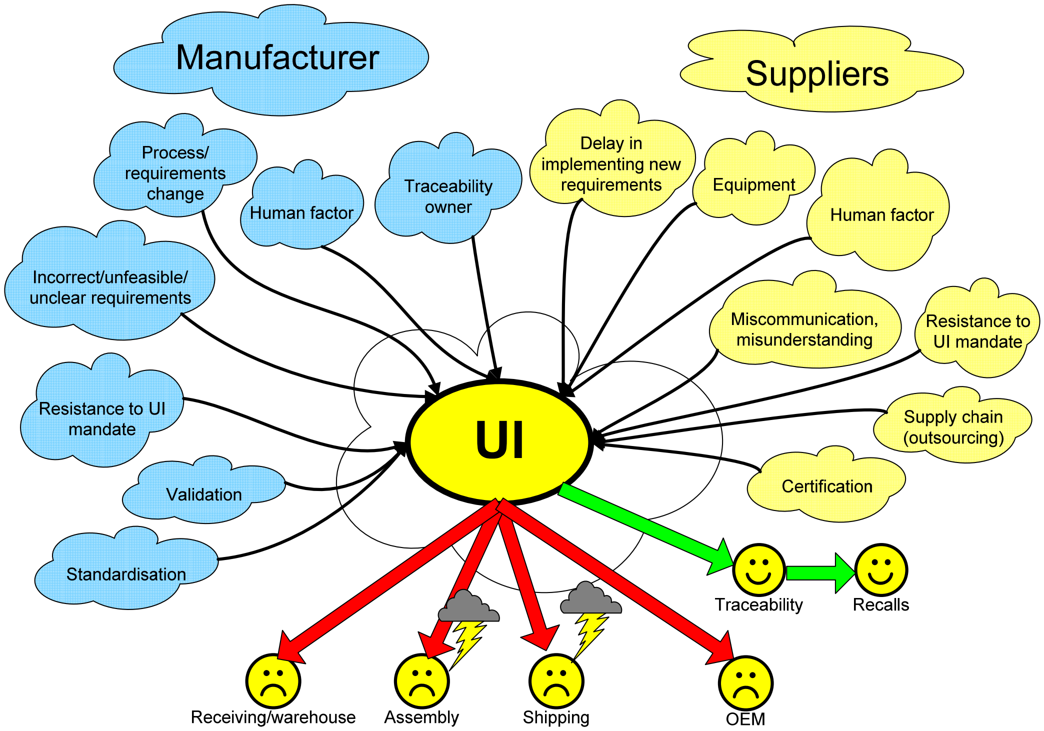


Figure 3.1. UI-related problems, challenges, and benefits

3.2 GENERAL PROBLEM VIEW

DPMS is the base of UIs implementation. However, like the majority of innovations in their infancy, UIs experienced a number of problems. As Figure 3.2 depicts, the preliminary analysis, conducted within the scope of this research at an aerospace company, showed that they have negative effect on production capacity and the issues could be classified by the result, source, and problem. Parts marking related issues were further structured (Figure 3.3). At first, the scope of the project was split into hardware and process organisation related problems. While the former includes issues that are “tangible”, the latter deals with the way the numbers are processed using IT systems and considering human factor, etc.

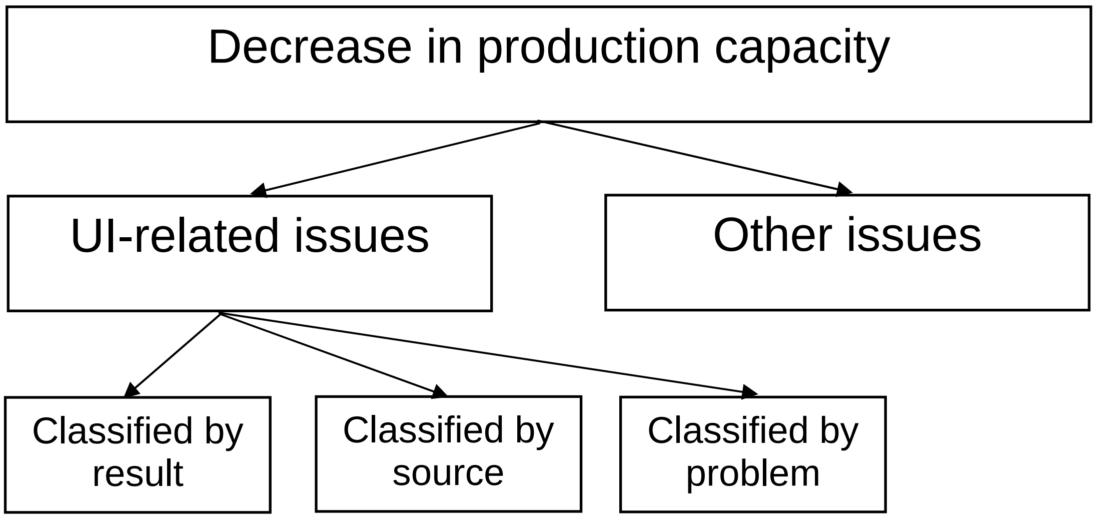


Figure 3.2. Problem statement: General view.

While hardware part is self-explanatory, its complement has some components that need further clarification.

UI is not registered: the actual number of a serialized part does not exist in the system. Among the causes, the following software setbacks were defined as potential root causes of the problem: the software allowed to ship the part without feeding the number in the system, or the system let a wrong number in, or the system has lost the number due to crash, etc.

Wrong format/structure is the result of requirements change. For example, removing serialization requirements from a "parent" will consequently remove traceability from all "children". Another example is a "famous" "spacing problem", when a wrong number of spaces is registered in human readable part of marking.

Wrong UI states for incorrect data registered 2D matrix or/and human readable part of the number. For example, the letter "O" is typed instead of the figure "0".

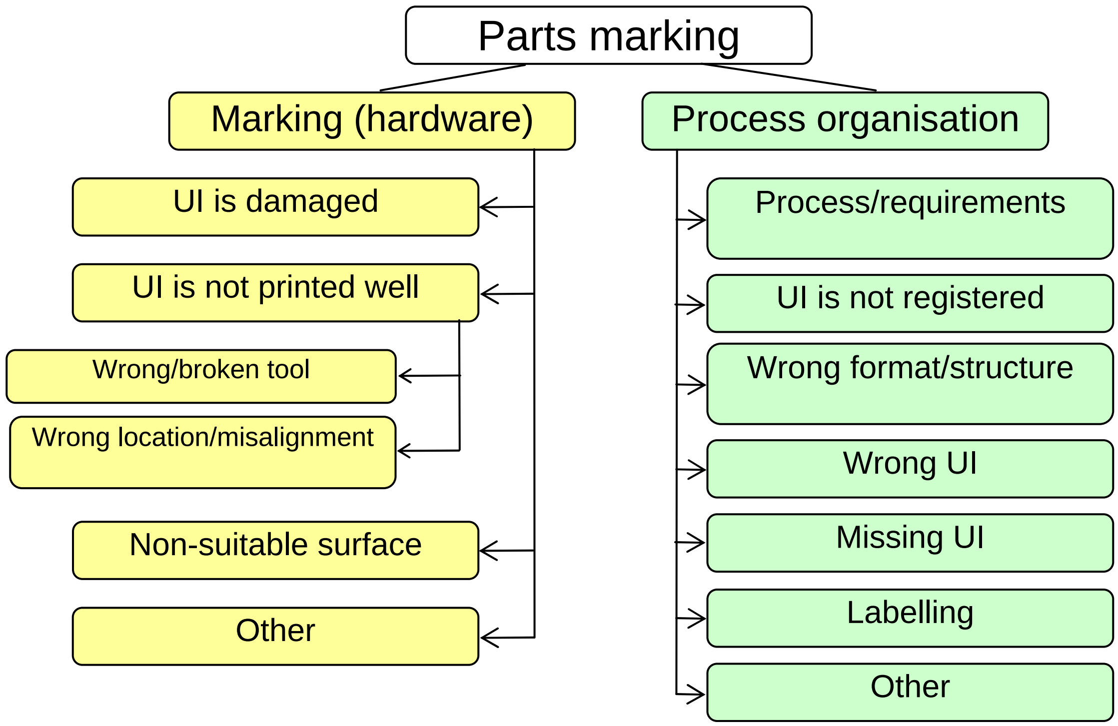


Figure 3.3. UI Issues Classification: DPMS problems

Further detailing the possible problem structure of parts marking, the diagram shown in Figure 3.4 has been derived. Being self-explanatory, it enlightens the paths to follow once an issue has been unveiled somewhere in the process.

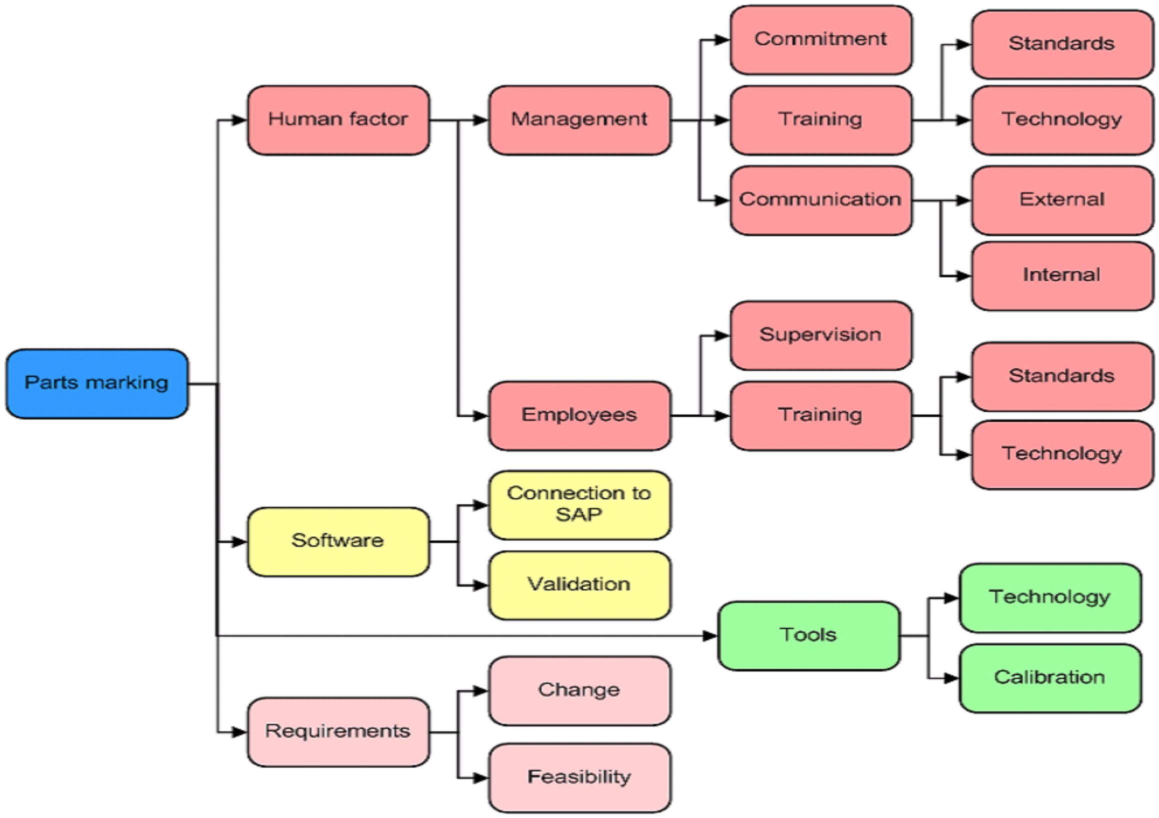


Figure 3.4 Parts marking problem structure

3.3 RESULT AND IMPACT

Another point of view on the problem is result and impact description. As Figure 3.5 depicts, UI related issues might result in either critical or non-critical quality notifications. Usually, the latter represent non-conformities that are declared by suppliers in advance. The former are discovered at the manufacturer's facilities during incoming inspection or assembling phase. Thus, they result not only in material shortage but in time losses as well.

From impact point of view, UI related issues could be split to parts marking and serial number processing. Both of them affect the assembly process, which, in its turn, coupled with the latter crashes the shipping process. (“X” sign in Figure 3.5 (b) states for problem worsening along the manufacturing process).

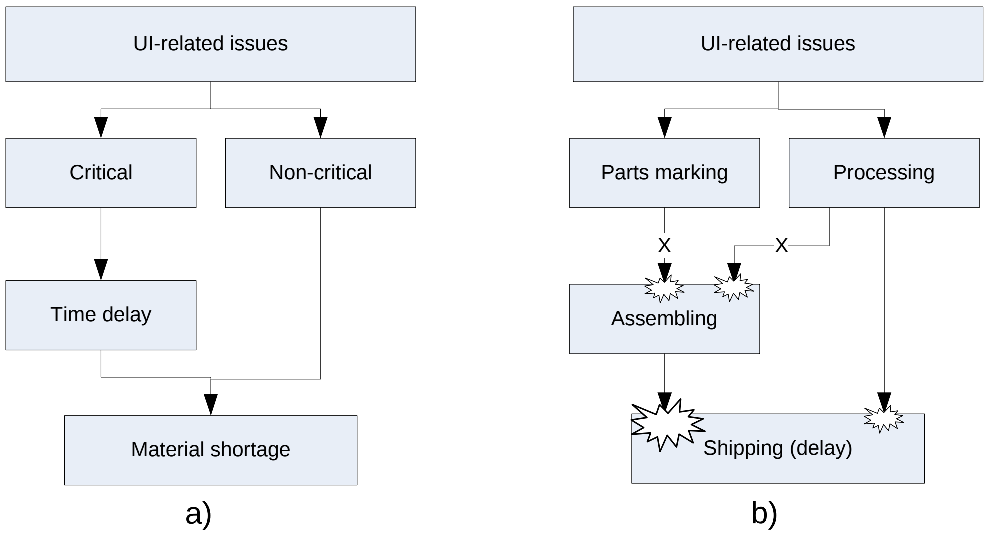


Figure 3.5. UI issues: result (a) and impact (b)

3.4 SOURCE-RELATED ISSUES

Having further studied the matter, a classification of serialisation-related issues by the source have been developed (Figure 3.6).

A Suppliers-Inputs-Process-Outputs-Customers (SIPOC) diagram is a tool used to identify all relevant elements of a process improvement project before work begins. It helps define a complex project that may not be well scoped, and is typically employed at the Measure phase of the Six Sigma DMAIC methodology. It is similar and related to Process Mapping and 'In/Out of scope' tools, but provides additional detail. The tool name prompts to consider the Suppliers (the 'S' in SIPOC) of the process, the Inputs (the 'I') to the process, the Process (the 'P') under improvement, the Outputs (the 'O') of the process, and the Customers (the 'C') that receive the process outputs. In some cases, Requirements of the

Customers can be appended to the end of the SIPOC for further details [31].

Within the scope of SIPOC, the two major parts of the scope are the suppliers and the customer – aerospace equipment manufacturer.

At the **customer's side (manufacturer)**, the following problem structure might be applied (see Figure 3.6):

- **Traceability owner** is supposed to coordinate all UI-related projects. Instead, each involved department has its own point of view on the matter and lack of communication comes into play here.
- **Process/requirements change** dramatically impacts the whole idea of unique identification. Due to rather long lag-time, the changes must be carefully prepared, discussed, and approved, which in turn takes time as well. Therefore, it is difficult to measure the effect of changes: they might come too late, so they would be applied to the system in a way different from the one they were initially intended to.
- **Input data validation and user-friendly interface** are indispensable part of any information system. IT systems ("Suppliers' portal") allow users make mistakes that later affect the production process.
- Once discovered, **incorrect/unfeasible/unclear requirements and/or specifications** lead to their review and process change that might create other problems of the same nature. Incorrect specifications affect the level of trust between the manufacturer and suppliers. Unfeasible requirements create unnecessary amount of extra work, which incur monetary loss for all parties.

- **Human error** is an inevitable factor, which heavily impacts classical human-based systems. Data validation, data input automation, automated data processing and other IT-based approaches mitigate risks of this type of problem.
- **Resistance to UI mandate** include, beside the abovementioned problems, includes unwillingness to change well-established procedures and other issues related to general human resistance to changes.

Supplier side:

- **Equipment**: issues associated with tools, their maintenance, alignment, etc. (see also Figure 3.3).
- Delay in implementing new requirements happens because they:
    - add cost:
        - investment in equipment
        - maintenance
    - add another activity (marking) in the production process.
    - have low or even negative classic ROI. (Real Options Approach should be used.)
    - are not clearly formulated/specified.
- **Communication** is one of the major factors that contribute to success. Due to lack of communication, misunderstanding of the standards and requirements might have place.

- **Certification** is an important part of supplier-customer relationships. Once certified, a supplier would be less prone to deviations in quality of production. That will assure consistency in manufacturing process.
- **Supply chain related issues** refer to suppliers of suppliers. Nowadays, outsourcing is a part of almost any supply chain. Therefore, it is extremely important that everybody involved in the process fully understands the requirements. However, it will reproduce the problem tree (Figure 3.3) with respect to the supplier that becomes a customer.
- **Other classes of issues** (i.e. human factor, resistance, etc.) are similar to the ones on the manufacturer's side.

The following scenario illustrates how problems can be generated. The parts arrive to the manufacturer's warehouse. It is possible to have there one batch of a specific part, which has UIs, a second batch does not have UIs, and a third batch has a different UI located in a different place. This situation will create problems with keeping the stock at the warehouse.

An assembly line might receive parts from all three abovementioned batches on the same day, thus it will confuse the assembly workers.

A shipping process, which will be discussed later in this research, is affected the most. To comply with the industry safety regulations and assure the quality of the final product, authorised inspectors (AI) must verify the production history of all serialised components. If a part is missing an UI due to any reason, the final document closure is put on hold until the matter is resolved.

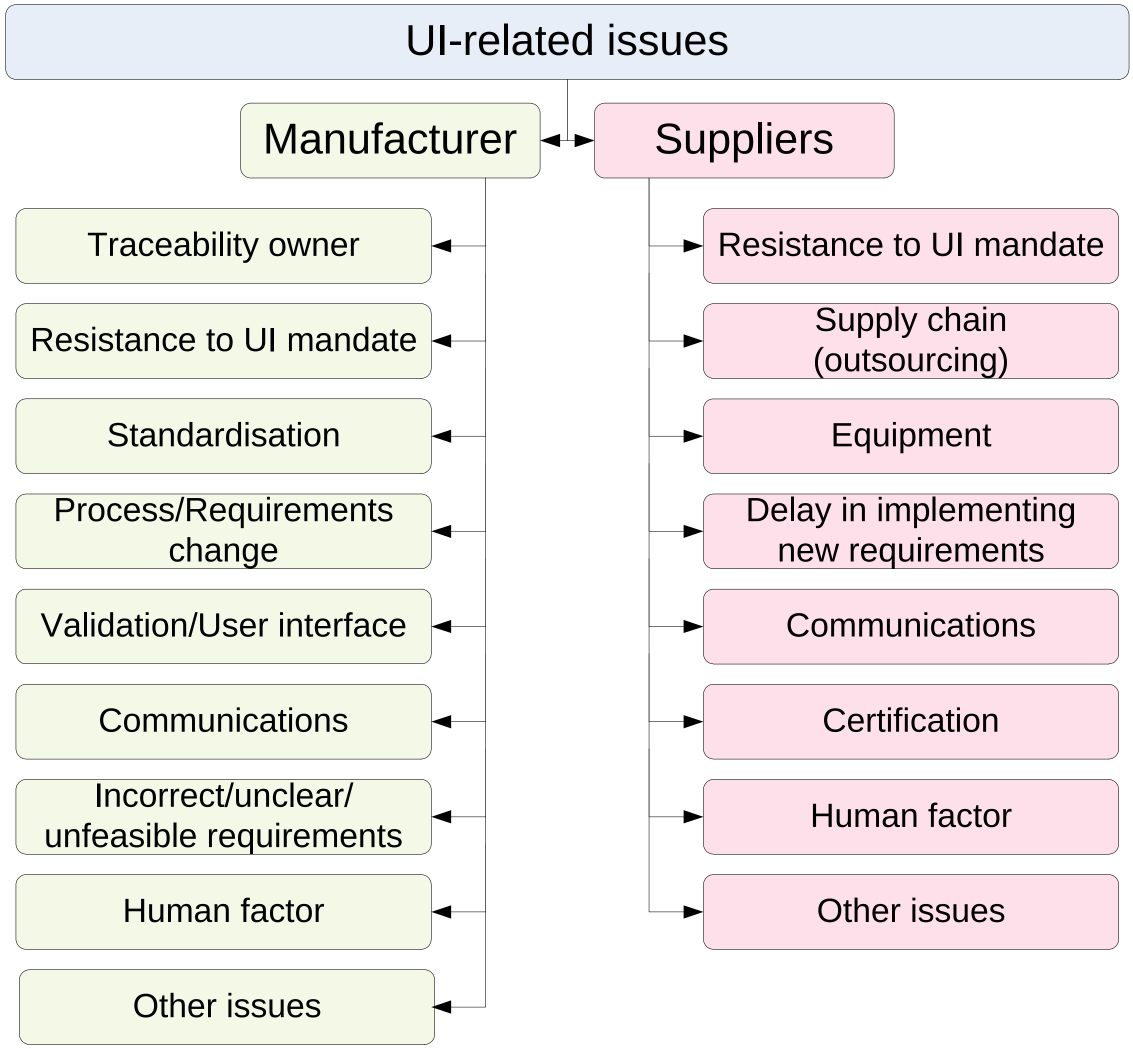


Figure 3.6. UI Issues Classification: by source

3.5 PFMEA

3.5.1 Proposed solutions for conventional PFMEA's drawbacks

The conventional PFMEA procedure is prone to some drawbacks. It relies on the data that comes from well established and running process, which is not the case when the production process is under development and fast reaction is required to deal with dynamically emerging failure modes, their severity levels, and the occurrences of existing modes.

If a production process is under consideration, there is no or very little historical data on the number of occurrences. Thus, it is difficult for the experts to evaluate the “occurrence” parameter. Instead, the live data on occurrence parameter are available. Conventional PFMEA, instead of basing occurrence parameter on these data, solely relies on expert estimation. Moreover, in some cases where limited number of trials is available, the proposed in Six Sigma rate of 1 in 1,500,000 is not feasible to calculate. This fact leads to shrinking of the range of possible coefficients, thus degrading validity of the results.

Another approach is to assign monetary value to each quality notification (QN), based on the QN severity and cost of the affected part, thus estimating financial impact rather than the number of occurrences a certain problem.

In addition, the severity, occurrence and detectability rankings are assigned based on experts’ estimations. Thus, PFMEA might result in a situation where a controversial number is assigned. For example, one expert gives “3” to the severity rank of certain even, while another expert gives “6”. Then, the final value should be “4” or “5”, which is different from both subjective opinions. Thus, it might create uncertainties. The proposed approach addresses this drawback and makes the occurrence parameter assignment objective.

3.5.2 Severity and detectability criteria definitions for DPMS

While Table 2.2 introduces a general approach to severity ranking, Table 3.1 gives detailed ranking description in regard to DPMS. Table 3.2 contains the detection ranking assignment in regard to DPMS.

Table 3.1. Severity ranking for DPMS

Criteria	Rating
Does not directly affect the parts' traceability	1
Very minor performance degradation or minor problems at next higher assembly, mostly related to the human-readable part of marking.	2 3
The labels are still legible, but have deviations from the DPMS requirements. For example, a missing part of identifier, wrong marking location, etc.	4 5 6
Illegible data that requires remarking. The defect has a severe effect on tracking system performance.	7 8
Major impact on part traceability such as impossibility to identify the part, or a part is damaged as a result of marking.	9 10

Table 3.2. Detection ranking for DPMS

Criteria	Rating
The problem is declared by the supplier of manufacturer.	1
Simple visual inspection can detect the problem. An inspector should refer to the drawings.	2 3 4

The use of scanner is required.	5 6
A scanner and simple SER/UI validation software are required.	7 8
Complex interaction with the SER/UI database is required.	9 10

3.5.3 PFMEA with dynamic occurrence assignment (DPFMEA)

To address the potential problems with expert ranking of the occurrence parameter, and eliminate the subjective parameter assignment, objective information is required from the system. However, not all parameters can be assigned objectively. The assignment of severity level should be done using expert evaluation of the risk taking into account how the risk affects the performance of the system from the point of view of traceability. The expert should use Table 3.1 as a guideline.

The probability of unveiling the problem is directly related to detection parameter assignment. The QNs, which were detected prior to processing the part at the manufacturer's facilities, received the lowest score. The issues that require special equipment coupled with operator attentiveness and skills should draw particular attention, thus they should be given high detection scores.

Conventional FMEA calculates the risk priority number (RPN) based on expert assigned coefficients (Equation 2.1).

Let us have a closer look at the occurrence (O) parameter. For conventional FMEA, it is calculated based on average number of occurrences per day or a probability of more than certain number of occurrences in predefined number of events [11].

However, the method will produce the correct results only if the variation of the occurrence is low. During the production set-up time, data on a particular risk occurrence varies dramatically from one batch to another. The novelty of the proposed approach is that, having "live" data on QNs, this information is fed into calculation.

Number of QNs might vary between 0 and up to 100 and more per month. Thus, in order to satisfy the occurrence parameter range:

$$1<O<10 \quad \textbf{Equation 3.1}$$

normalisation is required:

$$o_i(t)=\mathrm{INT}\left((R_{\max}-R_{\min})*\frac{O_i(t)-O_{\min}(t)}{O_{\max}(t)-O_{\min}(t)}\right)+R_{\min} \quad \textbf{Equation 3.2}$$

where: $o_i(t)$ – normalised dynamic occurrence rating;

R_{max}, R_{min} – max and min values of the normalised occurrence range [1, 10], i.e. $R_{max}=10$, $R_{min}=1$.

$O_i(t)$– number of occurrences of risk i during the period t.

$O_{max}(t)$, $O_{min}(t)$ – max and min number of occurrences of all risks during the period t.

As a result, we have analysis that precisely reflects the actual situation. The new system has been named Dynamic RPN (DRPN):

$$DRPN=S*D*o(t)$$ **Equation 3.3**

The observation/control period *t* should be chosen taking into account the production set-up stage, production volume, specific part, and other sensitive parameters. In time, as the result of quality improvement activities, the occurrence should decrease.

3.6 SUMMARY AND CONCLUSIONS

In this chapter, a proposal to classify the UI-related issues was made. UI-related issues were classified by the result, source and problem. Two main results of UI-related issues are the materials shortage and delays in shipping process. The source-related issues were split to the problems that originate from the supplier's side and the ones that come from the customer (aerospace industry manufacturer). Two types of problems were defined: marking (hardware) and process related. Detailed description of all parts of classification has been made. The methods of calculation of severity and detection with regard to DPMS were proposed. The classical definitions of severity and detection rates were adapted to the needs of DPMS application; the descriptions severity and detection rates that reflect the most common DPMS-related problems were written.

A new dynamic approach to classical RPN calculation was proposed. It improves the "response time" of classical PFMEA. The occurrence parameter is calculated based on "live" data as demonstrated in the case study in Chapter 5. Thus, the PFMEA with dynamic occurrence parameter can be applied to fast changing production processes, especially during set-up and production ramp-up times.

4 CASE STUDY 1: ASSEMBLY AND TEST DOCUMENT CLOSURE PROCESS FOR ENGINE SHIPMENT

4.1 INTRODUCTION

4.1.1 Pratt & Whitney Canada at a glance

This case study was done at Pratt & Whitney Canada (P&WC). P&WC is a world leader in aviation engines powering business, regional aircraft, and helicopters is a subsidiary of United Technologies Corporation, a high-technology company based in Hartford, Connecticut. The company also offers advanced engines for industrial applications. P&WC has built over 60,000 engines used in more than 190 countries and it is the largest R&D investor in the Canadian aviation industry. P&WC is doing business with over 1,500 Canadian suppliers [24].

P&WC has won three major competitions in the very light jet (VLJ) market within the past three years with its new PWZZZ engine family. The PWZZZ family spans the 900 to 3,000 pound thrust range and currently features three models: the PWZZY, selected by Cessna Aircraft to power its Citation Mustang introductory-level business jet; the PWZZX, selected by Eclipse Aviation Corp. to power its twin-engine Eclipse 500 jet; and the PWZZY selected by Embraer to power its Embraer VLJ business and general aviation aircraft. These first three engines programs focus on low ownership cost, performance and reliability through new engine core design, scalable technology, integration and manufacturing. The PWZZZ delivers the added reliability and ease of operation with its dual-channel FADEC (Full Authority Digital Electronic Control). The PWZZY successfully completed its maiden flight on a Citation Jet test bed on April 23, 2004 and the PWZZX's first flight on the P&WC's Boeing 720 flying test bed (FTB) was successfully completed on December 20, 2004. These very light jets have fostered the emergence of Jet Taxi business model, offering on-demand, same-day and point-to-point transportation at very affordable ticket price. Between the PWZZY and the PWZZX, P&WC has accumulated over 5,500 hours of total development testing, including stringent endurance running and extensive flight-testing on the Boeing 720 flight-test vehicle to validate engine performance and operability [25].

4.1.2 DPMS at P&WC

DPMS has been adopted by the company in order to define, specify and control marking methods that will ensure positive identification of items, castings and forgings, and to establish item marking requirements for identification purposes. DPMS is a process that permanently marks parts and provides traceability of serialised parts throughout the part’s life and is readable by a commercially available recognized data recognition system as defined or approved by P&WC Quality. In the legacy process, DPMS is used to mark human-readable number, which contains information on:

- part number
- manufacturer
- serial number

In addition to the industry mandate that requires serialization for the life-critical parts, in order to increase quality of service for new engines and solve the traceability problem, P&WC introduced Unique Identifier (UI). The UI, which identifies a single item, is used to provide traceability for items where Serial Numbers are not required.

4.2 PROCESS DESCRIPTION

The assembly and test (A&T) document closure process for engine shipment was one of the most affected by the emerged issues. Also, it does make sense to start an investigation from a place where the issues accumulate.

W. Edwards Deming observed: "Quality comes not from inspection, but from improvement of the process." It is a point that is too often forgotten. Rather than looking for defects after the fact, the true goal of manufacturing engineers and managers should be to install processes that yield zero defects [19].

The shipping stage is the final one of engine manufacturing. Within its scope, an authorised inspector (AI) verifies all assembling and test activities, assuring their successful completion. The assembly and test (A&T) document closure process for engine shipment starts after the engine passes the post-dress operation. It includes various activities related to document verification and validation, as well as the release of final documents.

4.3 PROBLEM STATEMENT

The process has been experiencing various problems that are claimed to be related to parts swapping, serial numbers (SER) and UIs, parts tracing, and

Assembly Floor Sheet (AFS) control. As a result, it takes up to four days to complete the routine. In order to improve the process, the Six Sigma approach has been chosen.

4.4 IMPLEMENTATION AND TESTING

4.4.1 Define phase

4.4.1.1 Process Mapping

At P&WC, the documents closure process consists of activities related to the documents validation. It is preceded by final engine testing and followed by packaging. The process' output is a complete package of documents that contain all build and testing information about an engine.

An Authorized Inspector (AI) should perform the following activities:

- Repeat activity validation (if applicable)
- Build folder (production management software (AHS), assembly floor management software (AMAX), Mainline, Sub-Assembly) validation
- Test folder validation
- Request for Engine Acceptance (RFEA) (if applicable)
- Service bulletin / engineering changes (EC) incorporations
- Serial/UI numbers validation and print
- Quality release authorisation (QRA) closure (if applicable)
- Log book
- Engine shipping closure (physical)

- Tag signal for finished part storage (FPS) delivery

4.4.1.2 List of problem spots with assigned numbers

The documents closure process has been mapped using the brain-storming technique (Figure 4.1). Related activities were grouped into potential problem spots for future analysis.

- Cut order - #1
- ZP10 (SER/UI issues, Swap, pink sheets, etc.) - #2
- RFEA - #3
- EC / Service bulletin - #4
- QRA closure - #5
- Test folder validation - #6
- Lost Pink sheet - #7
- AMAX (mainline) - #8
- AMAX (sub-assemblies) - #9

4.4.1.3 List of potential delays

Next step towards the definition of potential problems was the best/worst processing time assessment. It was done using the brainstorming technique. AIs were involved in the activity.

Table 4.1. Potential delays assessment

Problem	Time		Comments
	best	worst	
Cut order	40 min	1 day	

SER/UI assignment	2.5 h	2 days per part	might result in the necessity for repeat activity (+ 3 days)
Test folder verification/correction		2 days	
EC / Service bulletin		1 day	
RFEA	3 h	unpredictable	
QRA		2 days	
Operation (OP): sub-assemblies		2 days	
OP: mainline		2 days	

4.4.1.4 Conclusion

As a result of performing activities of this step, the shipping process has been mapped; problem spots and potential delays have been identified.

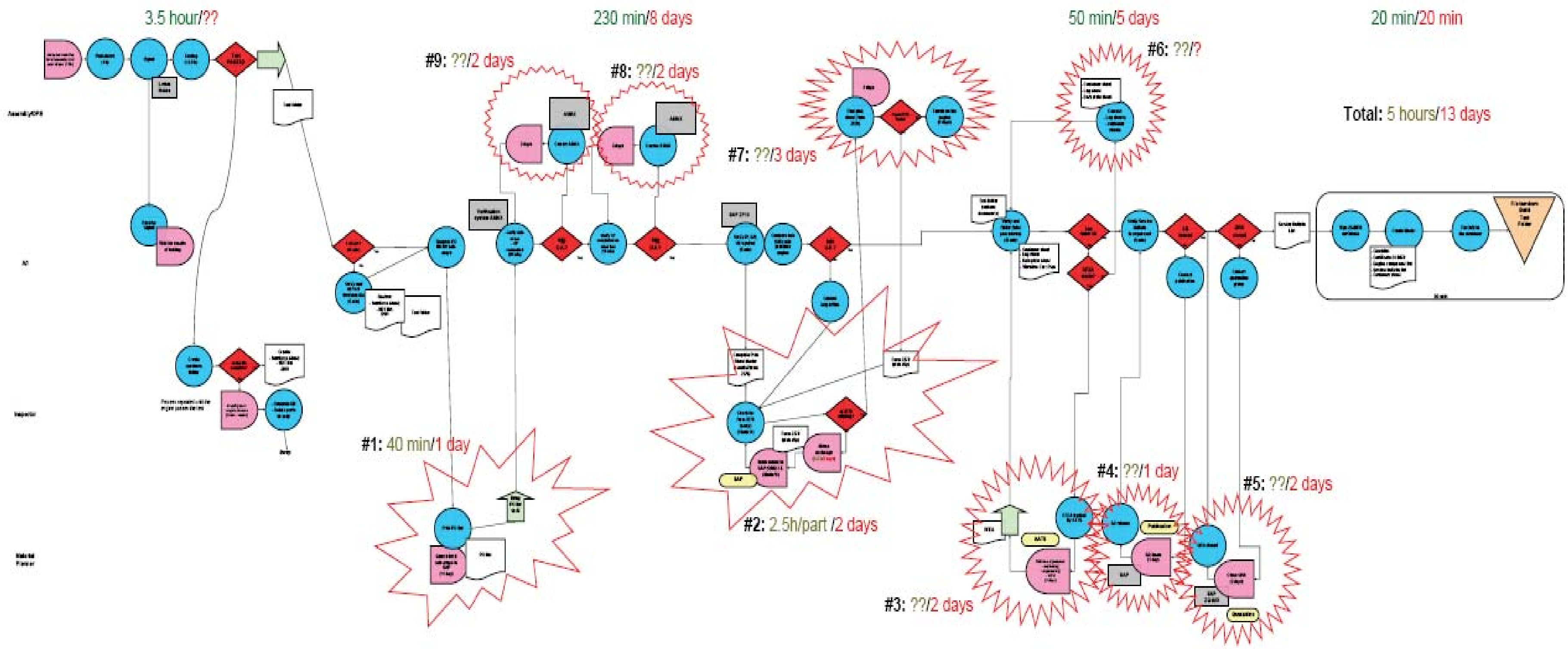


Figure 4.1. Document closure process map

4.4.2 Measure Phase

4.4.2.1 Existing measurement system analysis and validation

Once the process has been mapped and activities that might potentially cause the major problems were defined and underlined on the map, the pertinent data available up to date have been searched for. AIs had been occasionally filling up the tables that they called “snag-sheets”. It was the only source of data available at that time. The acquired data included:

- Period covered: June-October 2006
- Engines (total: 17): Z1, Z2 (initial & upgrade), Z3, Z4, Z5, Z6, Z7; Z8, Z9, Z10, Z11, Z12, Z13, Z14, Z15, Z16, Z17
- Snags registered: 125

Having done preliminary analysis of the snags, new problem spots have been added to the process map and a few existing ones have been redefined. Below are the modifications that have been done:

- Repeat activity folder - #10: Though it existed as activity on the map, it was not defined as a problem spot and potential delay was not listed.
- Undefined - #0: Despite the fact that, in general, the activities listed on the snag-sheets matched ones on the process map, a few issues were mentioned that fall outside of the scope of the process. Nevertheless, because they arose during the course of action under consideration and, thus, caused delays, the issues were included in the analysis.

- Having studied the actual process “on the floor”, it has been learnt that the AIs first spot the issues with AMAX sub-assemblies and mainline, and then solve them in one batch. Thus, two problem spots (8 & 9) were joined into one and assigned #8 to it.

Since SER/UI related issues were in the area of the primary interest, a “SER/UI related” field with possible choices “Yes”/”No”/”Undefined” have been added.

“Name” parameter defines the nature of snag:

- Doc – problem with document processing.
- SER or UI – DPMS related issue.
- Decision – a delay caused by pending decision.
- Operation – problem with incomplete or not properly documented operation.
- Stamp – issue with an activity closure.
- Signature – issue with an activity closure authorisation.
- Quality – non-conformities.
- Date – wrong or missing date.
- Ref. table – issue with the reference table.
- SCI# - issue with the supplier identification code.
- P/N - issue with the part number.
- Undefined – the nature of the issue is unknown of does not fall into any category of interest listed above.

As an extension of the abovementioned class, an “Issue” parameter has been introduced:

- Missing

- Wrong
- Pending
- Incomplete
- Quality
- Not identified (blank)

Since the name of the process is “A&T document closure process for engine shipment” it is logical that a classification by documents and activities involved has been included:

- QRA – quality release authorisation is necessary when an actual parameter’s value of a component falls outside of the specified range.
- RFEA – request for engine acceptance from the customer.
- Log Sheet – contains information on the activities performed on the engine.
- ZPRPT03 – SAP transaction, part of the closure process.
- Cut Order – the list of all parts installed on the engine.
- QN – quality notification is issued when a non-conformity is discovered.
- AFS - contains information on the assembling-related activities performed on the engine.
- Repeat activity folder – contains information on repeated activities.
- Data Sheet
- Data Plate – contains specific part-related information.
- Customer Sheet – a part of the final documents package that contains information on the customer that ordered the engine.
- Pink Sheet – a serialised part replacement form printed on pink paper.

- IS – information system and its components.
- AHS – production management software.
- Test Folder – a set of documents that contains the data on the actual engine's parameters
- EC – engineering change is a document that reflects a specific change in an engine or part specifications.
- PCR – once a non-conforming part is discovered, it is replaced. A part change request contains the information on the details of non-conformity.
- ZP10 – SAP transaction that validates serialised parts.
- Pick List – a form that is required to receive parts from the warehouse.
- PO – production order contains information on all materials used for the engine.

Primarily targeting information systems (IS) issues, the snags have been linked to IS, where it was possible:

- AMAX – the software used on the assembly floor
- SAP – multifunctional enterprise management software

The analysis yielded the following results. For the period of June-October 2006, the SER/UI-related issues accounted for 13.6% of total number of registered problems. Non-SER/UI-related and other issues were identified in 86.4% (Figure 4.2). AMAX (problem spot #8), RFEA (#3) and ZP10 (#2) accounted for 75.2% of registered issues (Figure 4.3 and Figure 4.5). The data for Figure 4.5 are summarised in Table 4.1. Problems with documentation were distributed evenly between all problem spots and contributed the most (23.2%) to the total number of issues. Problems with operations were the second largest contributor (21.6%). Missing and wrong stamp issues accounted for 17.6%. Problems directly related to SER/UIs contributed 10.4%, bringing the total of the first four problem areas to 72.8% (Figure 4.4).

The analysis based on total number of snags allows us to rate “Top 3 Contributors” as follows:

1. OP completed (AMAX) (problem spot #8, 29.1%).
2. SER/UI and their processing related (problem spot #2, 27.3%).
3. RFEA (problem spot #3, 18%).

The analysis based on average number of snags per engine rearranges “Top 3 Contributors” as follows:

1. SER/UI and their processing related (problem spot #2, 37.6%).
2. OP completed (AMAX) (problem spot #8, 23.5%).
3. RFEA (problem spot #3, 12.6%).

Please note, that there is no discrepancy between Figure 4.2 and Figure 4.6, since problem spot #2 is responsible for SER/UI processing as well (e.g. “Pink sheet missing” snag is not SER/UI issue, but a processing one).

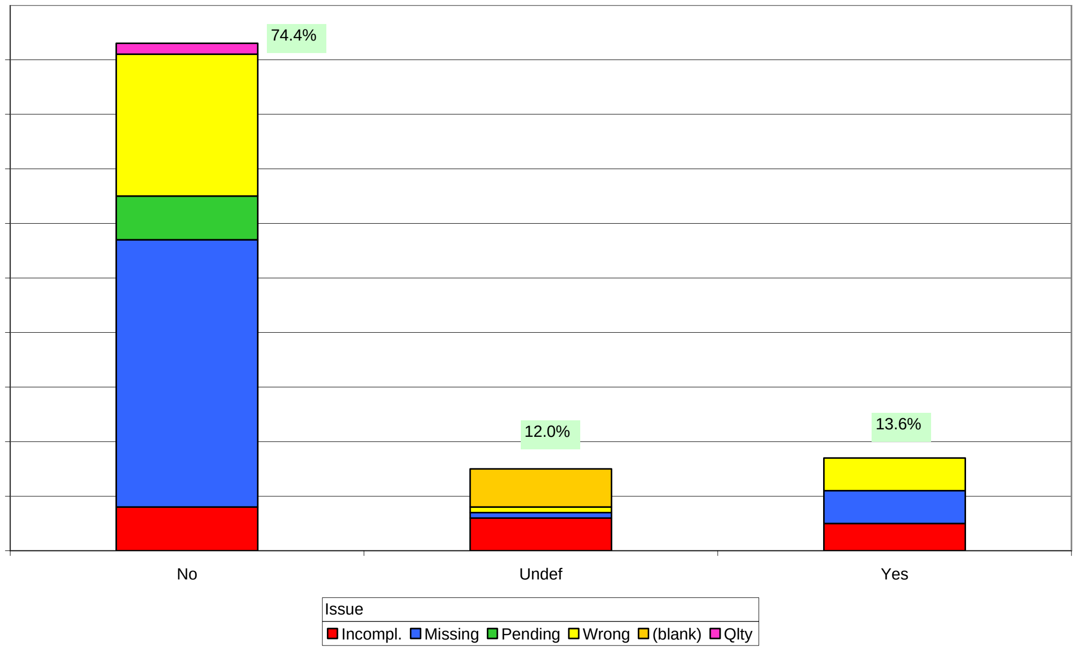


Figure 4.2. Contribution of SER/UI related issues (June-October 2006)

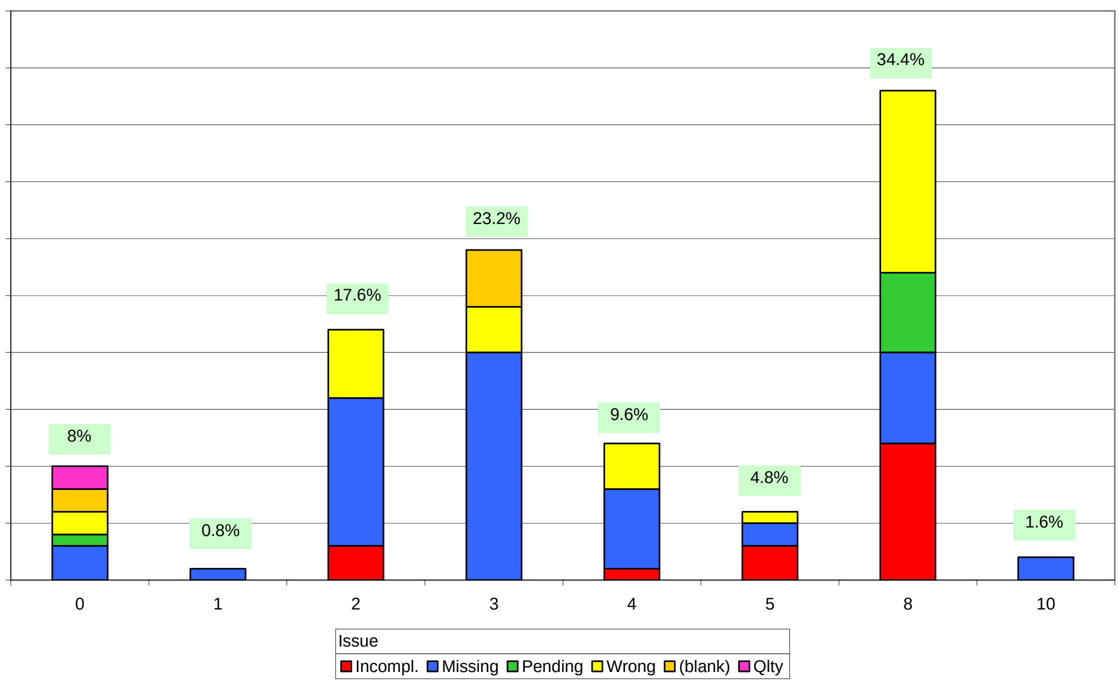


Figure 4.3. Issues distribution by location (June-October 2006)

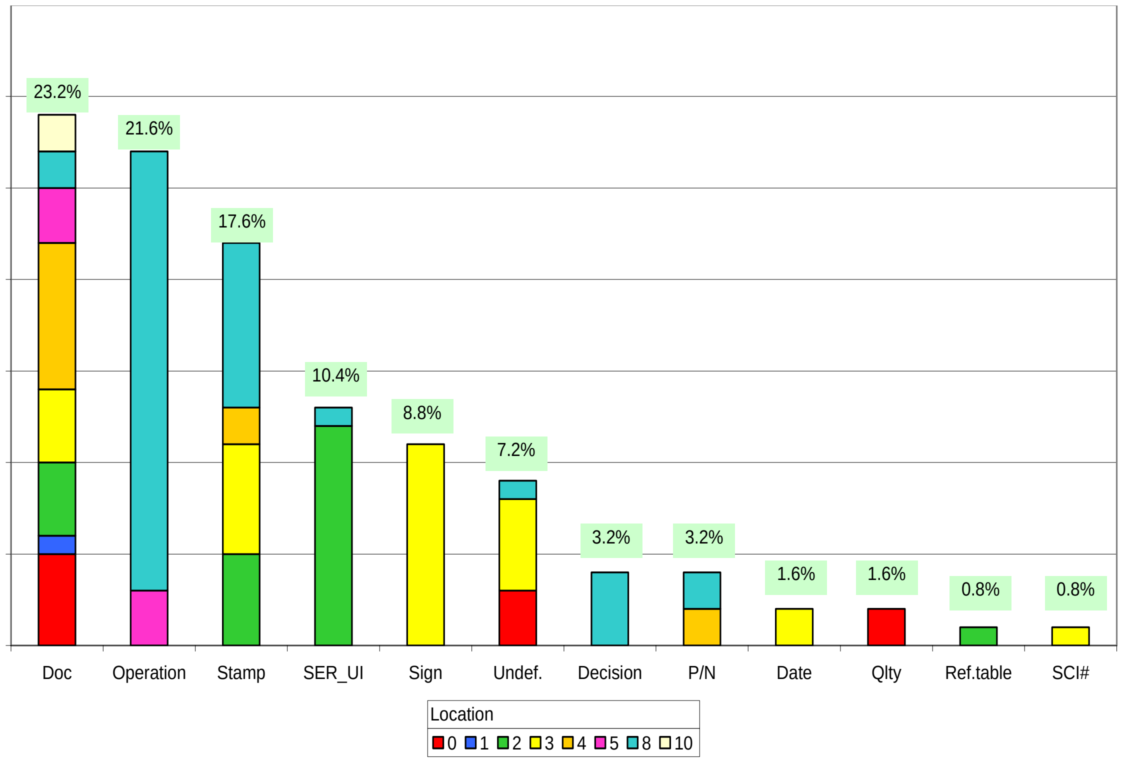


Figure 4.4. Issues contribution (June-October 2006)

Table 4.2. Pareto analysis: Issues location (June-October 2006)

Location	%	% cumulative
OP completed (AMAX, #8)	34.4%	34.4%
RFEA (#3)	23.2%	57.6%
SER/UI (#2)	17.6%	75.2%
SB/EC inc. (#4)	9.6%	84.8%
Other (#0)	8.0%	92.8%
QRA (#5)	4.8%	97.6%
Repeat activity (#10)	1.6%	99.2%
PO list (#1)	0.8%	100.0%

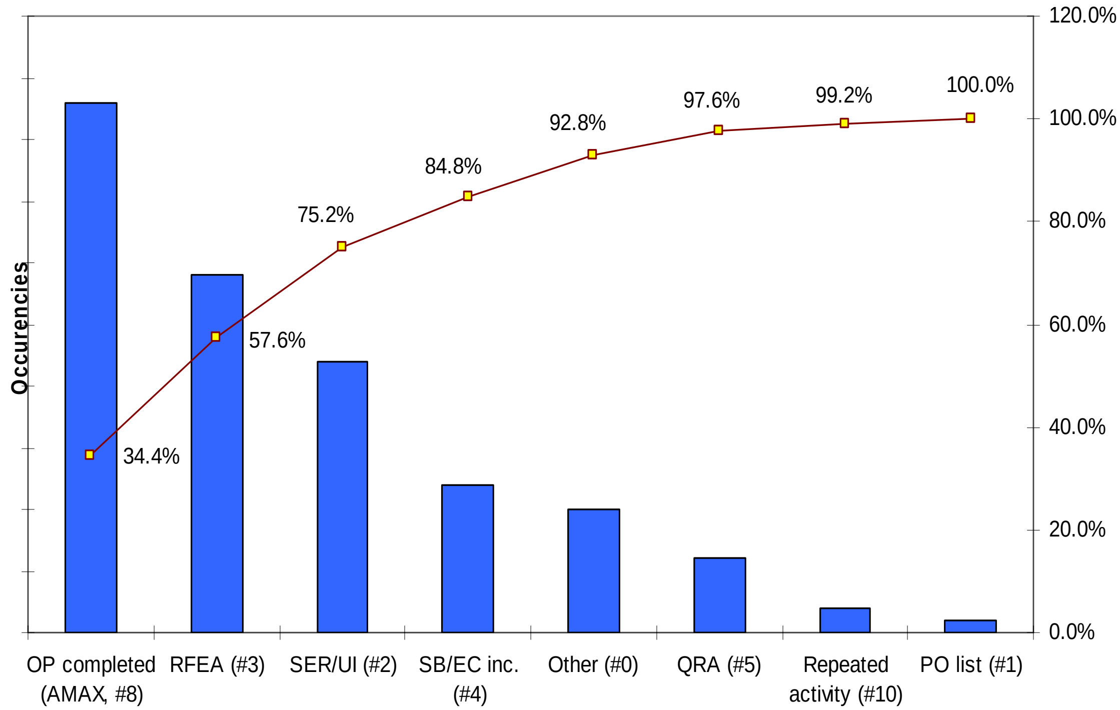


Figure 4.5. Pareto analysis: Issues mapping (June-October 2006)

The data gathered on November 16, 2006 has been analyzed the same way. That time, five engines were covered. The analysis based on total number of snags allows us to rate “Top 3 Contributors” as follows (Figure 4.7):

- Swap (problem spot #2, 53.2%).
- OP completed (AMAX) (problem spot #8, 14.9%)..
- Other (problem spot #0, 12.8%).

The analysis of the documents-related issues rated “Top 3 Contributors” as follows (Figure 4.8):

- “Pin sheet” (problem spot #2, 40.4%).
- AFS (problem spot #8, 19.1%).
- ZP10 (problem spot #2, 10.6%).

It is clearly seen that the problem spot #2 suffers from the documentation processing issues the most. Once again, please note, that there is no discrepancy between Figure 4.9 and Figure 4.10, since problem spot #2 is responsible for SER/UI processing as well (e.g. “Pink sheet missing” snag is not SER/UI issue, but a processing one).

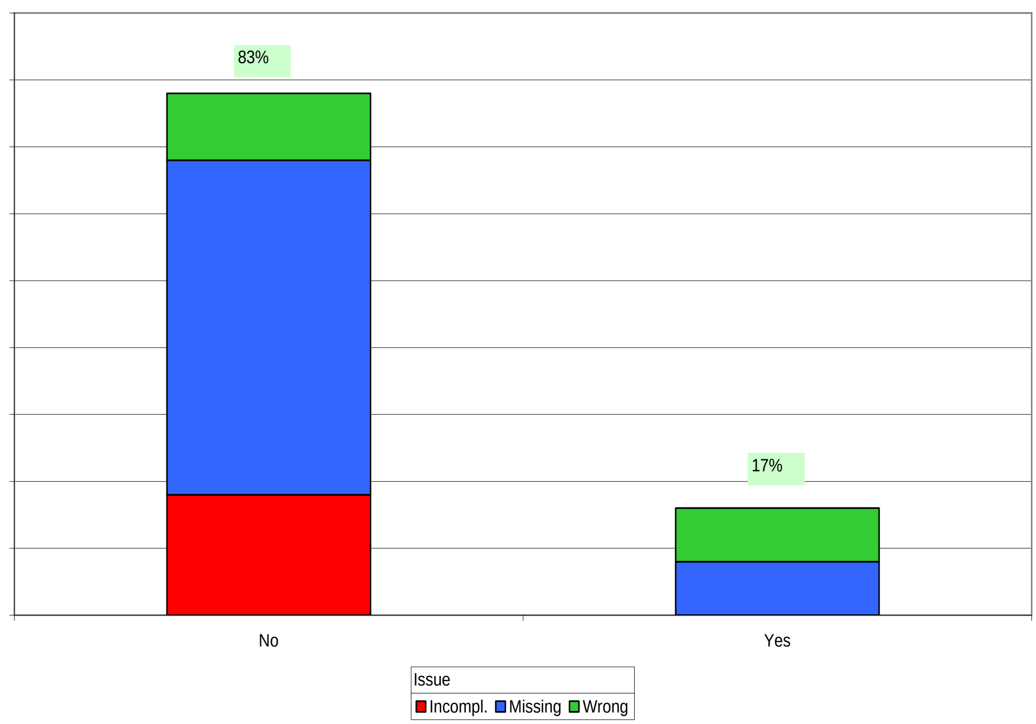


Figure 4.6. Contribution of SER/UI related issues (November 2006)

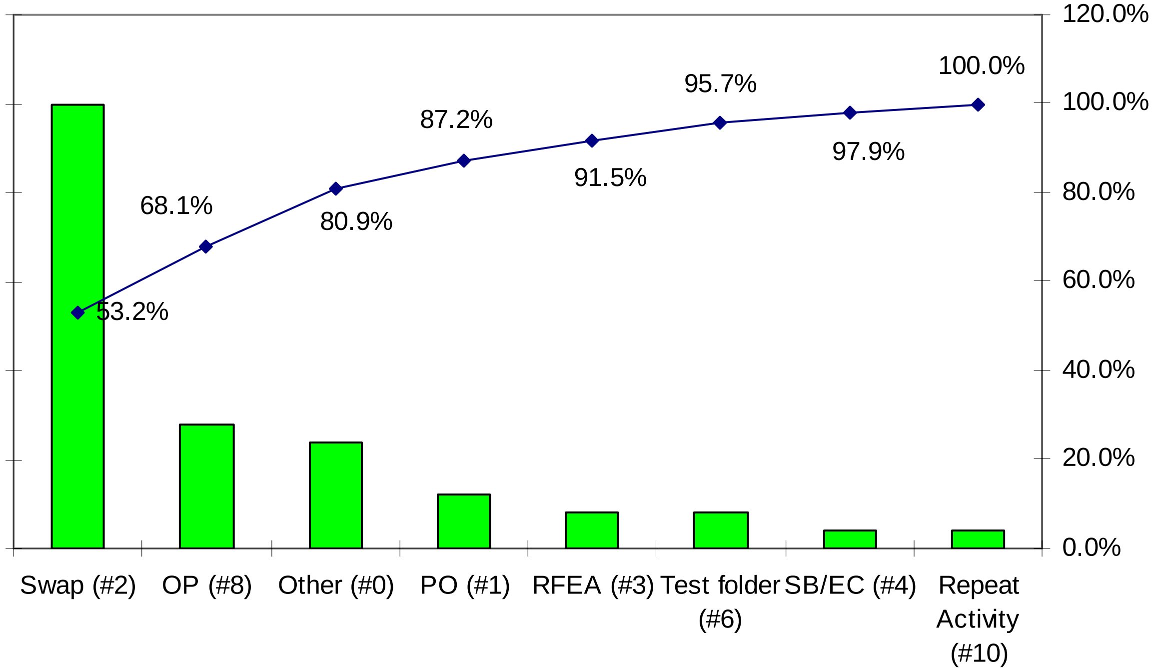


Figure 4.7. Pareto analysis: Issues mapping (November 2006)

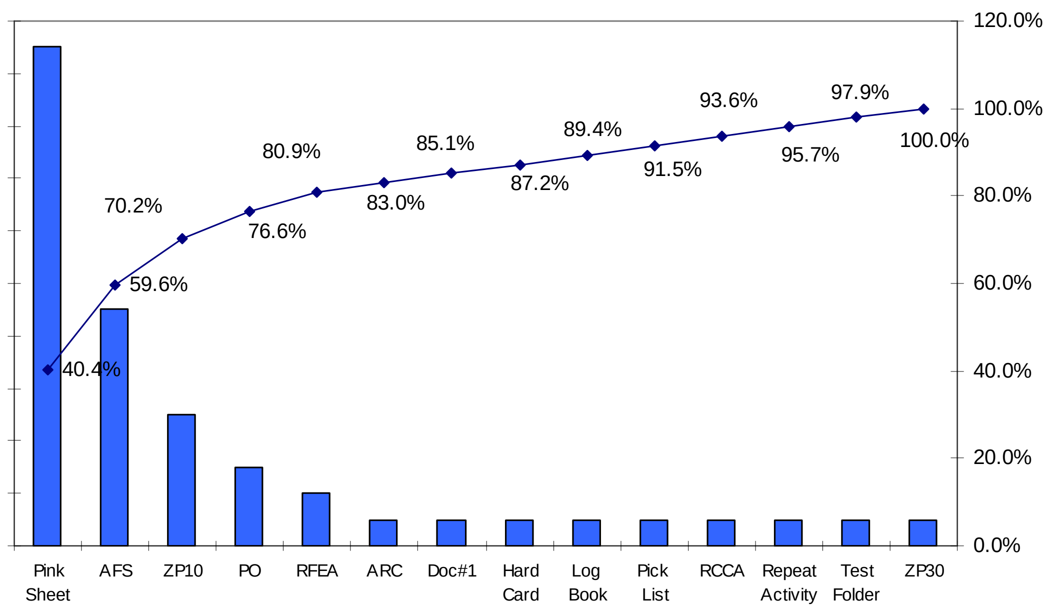


Figure 4.8. Documents' contribution (November 2006)

4.4.2.2 Results provided by the existing system

Three "Top contributors" to the problem structured in Figure 4.1 have been identified using the existing system. Their total contribution is 74.4% (Table 4.3, Figure 4.9).

Table 4.3. Existing data analysis

	Location	%	% cumulative
1.	OP completed (AMAX, #8)	29.07%	29.07%
2.	SER/UI (#2)	27.33%	56.40%
3.	RFEA (#3)	18.02%	74.40%
4.	Other (#0)	9.30%	83.70%
5.	SB/EC inc. (#4)	7.56%	91.30%
6.	QRA (#5)	3.49%	94.80%
7.	Cut Order (#1)	2.33%	97.10%
8.	Repeat activity (#10)	1.74%	98.80%
9.	Test folder (#6)	1.16%	100.00%

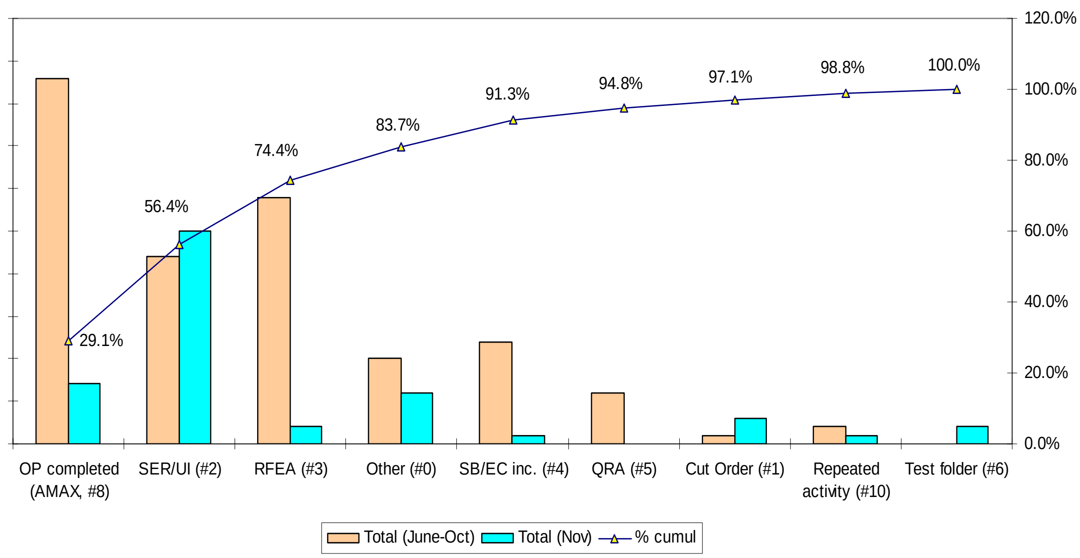


Figure 4.9. Total snags registered

However, the fact that problem spots #2 and #8 switched places, when the average of issues per engine was calculated, rang the bell. The question was raised about the validity of the existing system. As Figure 4.10 depicts, in November the hike in SER/UI –related issues in terms on number per engine was registered. It reflected the increased number of DPM-ed parts and improved quality requirements to DPM.

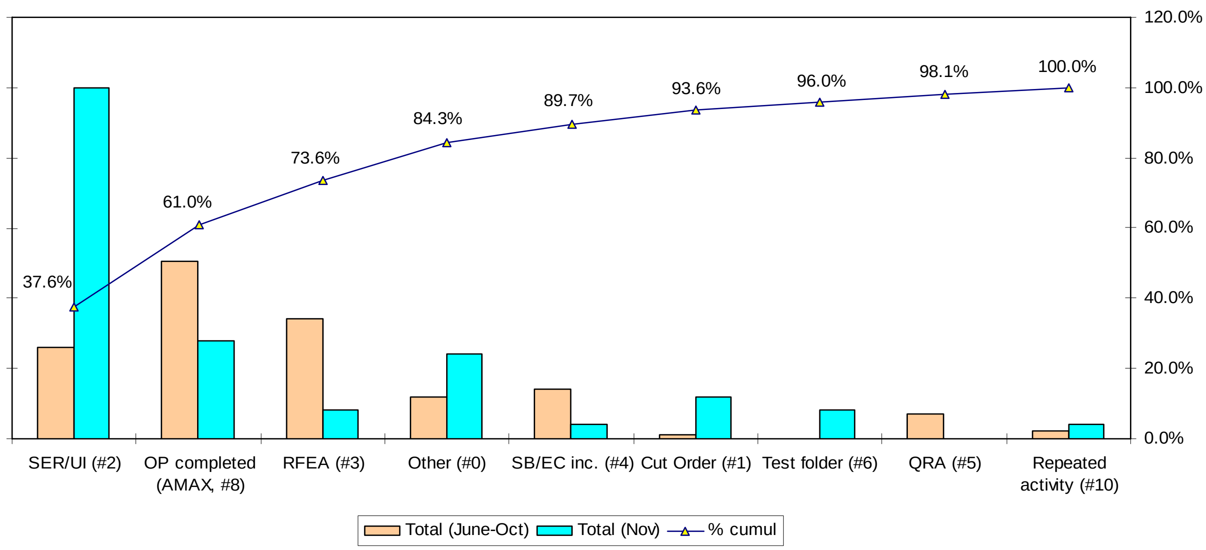


Figure 4.10. Snags registered in average per engine

4.4.2.3 Conclusion on the existing measurement system

The data validation yielded the following results:

Positive observations

The management and AIs have the similar vision of problem spots.

AIs showed initiative in data collection and motivation towards the process improvement.

The process map comprehensively reflects the activities involved in the process.

Negative observations

- The major drawback of existing measurement system is that it is straight-forward quantitative. There is no issue impact estimation. In other words, as the graphs illustrate, ten minor snags would attract more attention that one big problem.

- Severity of certain snags (OP, RFEA, “pink sheet”) is rather overlooked.

4.4.3 New measurement system establishment and validation

It is not possible to draw any conclusion based on the available data because there is no impact measurement of the issues.

The results of the quantitative analysis were presented at a team meeting and valuable feedback was received. Based on this feedback, new data collection forms (Appendix 2) have been developed. The target for data acquisition was to specify and quantify the following parameters:

- Place (location in the process, operation)
- Delay
- Resources (material affected, people involved)

Later, since it was found not feasible to define the resources involved, the last parameter was transferred to DPMS system analysis (Chapter 5).

During the first phase of implementation, the AIs themselves filled the forms in. During the second phase, with the purpose of validating the gathered data, all activities have been logged by the author.

In order to ease the gathered data analysis and make the data and, consequently, the results more visible, decision to use Gantt charts was made. In the case under consideration, the charts cover all activities involved in the document closure process.

As shown below, using the Gantt chart-based representation, a similar picture to the one of AIs has been obtained. Thus, the acquired data is valid.

At the next step, the acquired data was visualised (Figure 4.11 - Figure 4.15). The engine document closure process starts at the moment when the engine post-dress is finished, and ends when an AI signals for FPS delivery. The problem spots were defined as tasks and their related activities were defined as sub-tasks. Milestones represent events associated with the tasks and activities. The figures depict extremely high level of process variation, which is normal for the process set-up and tune-up time at the beginning of any serial production.

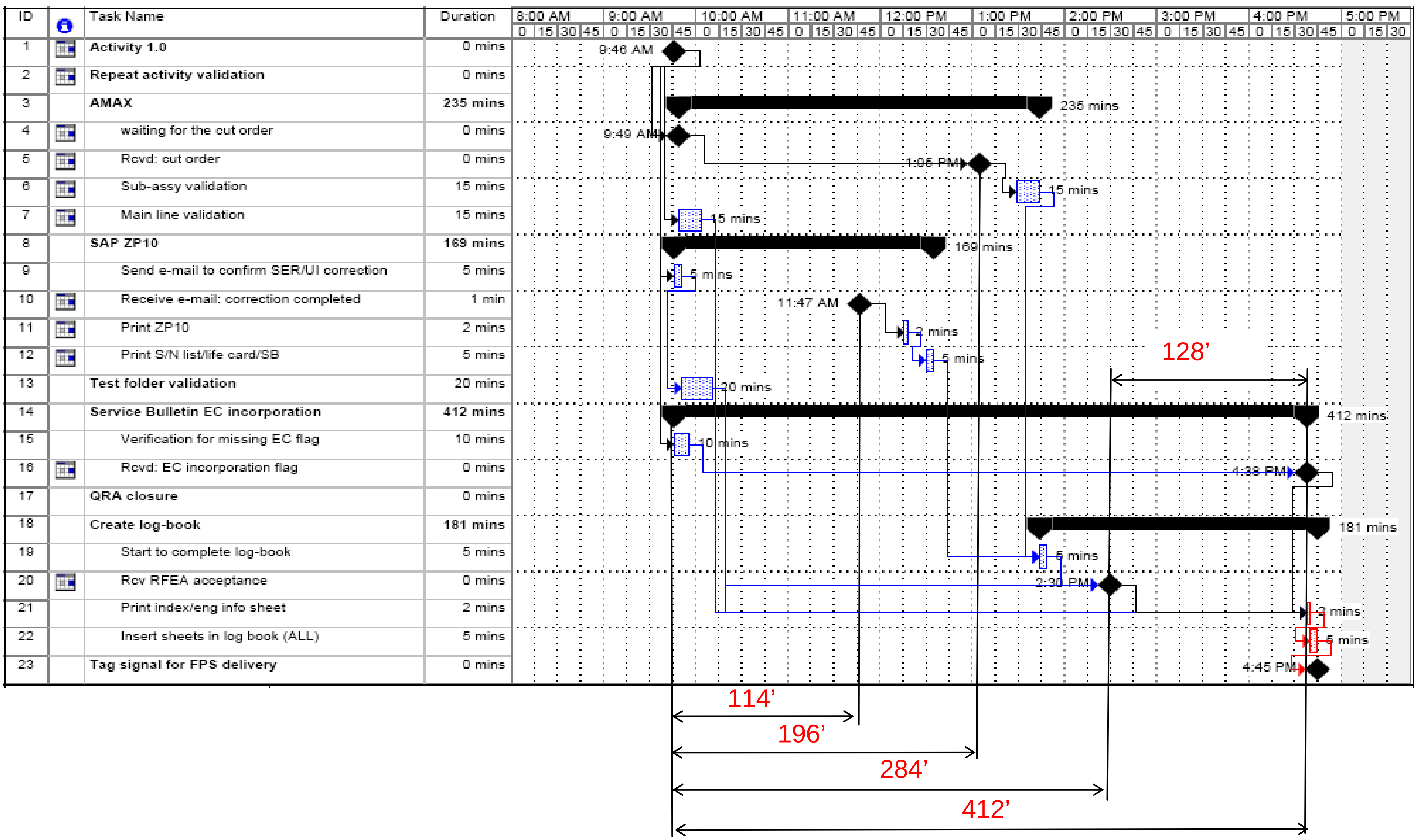


Figure 4.11. Activities and delays chart (Z19)

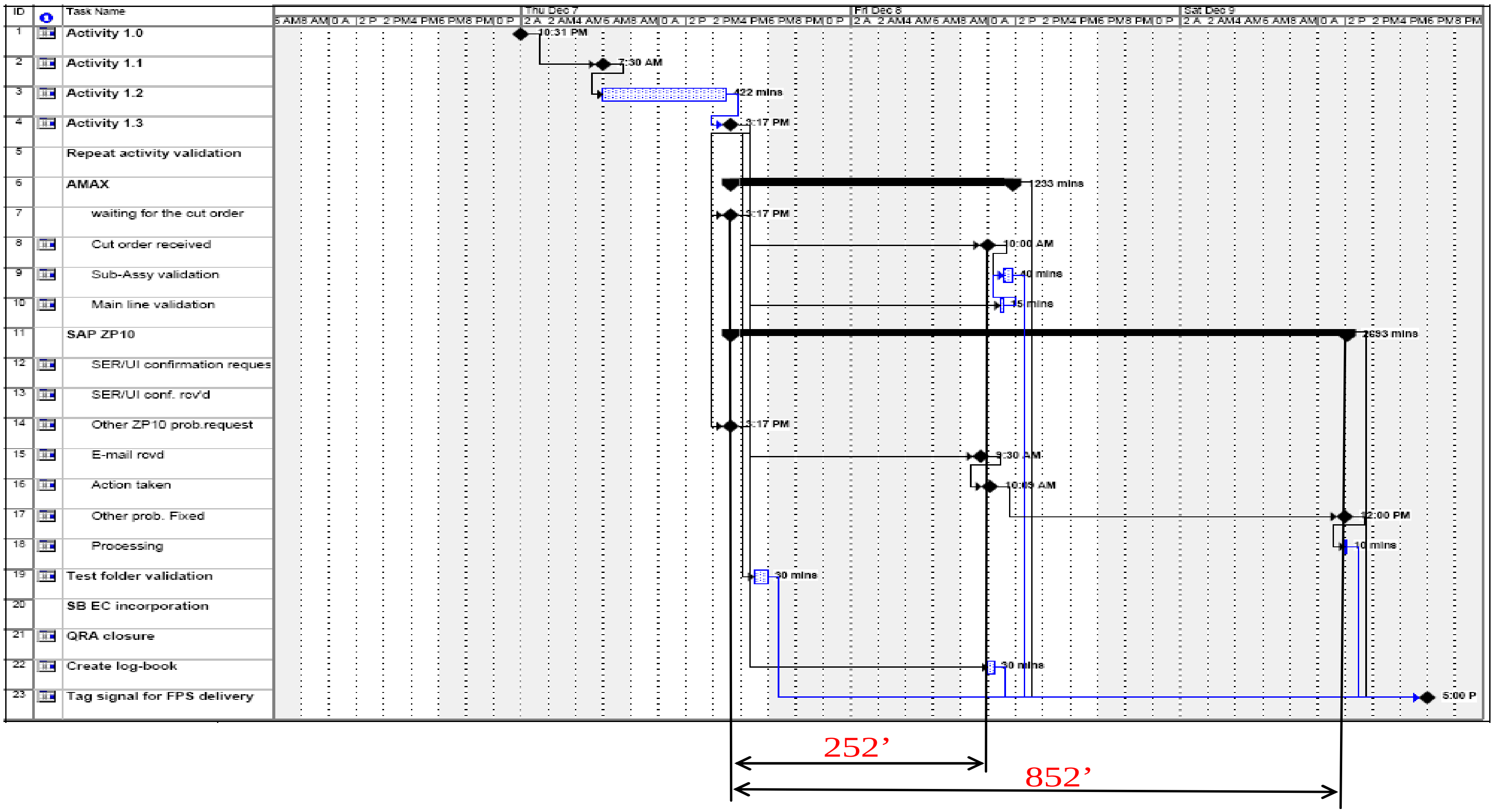


Figure 4.12. Activities and delays chart (Z21)

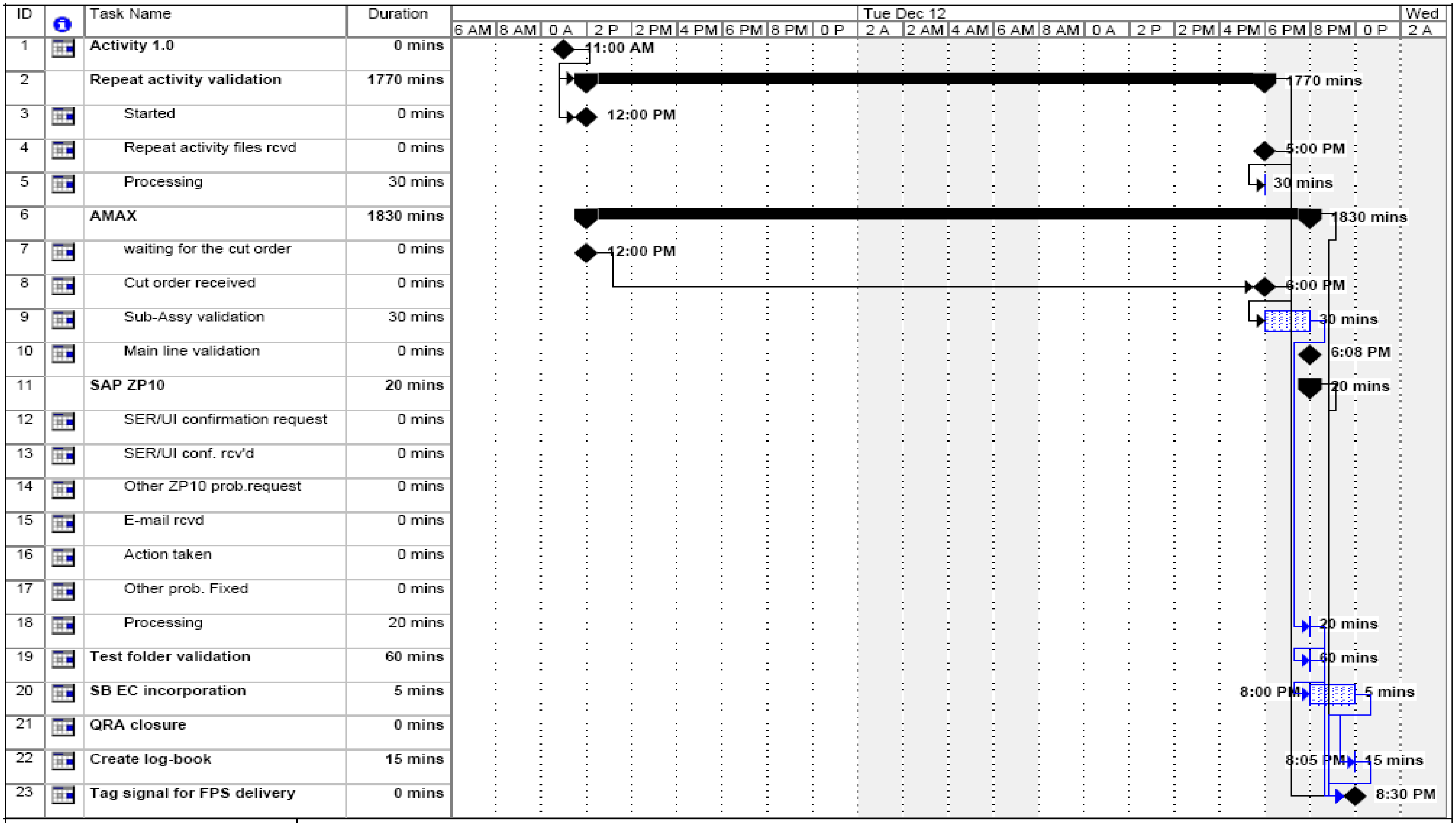


Figure 4.13. Activities and delays chart (Z18)

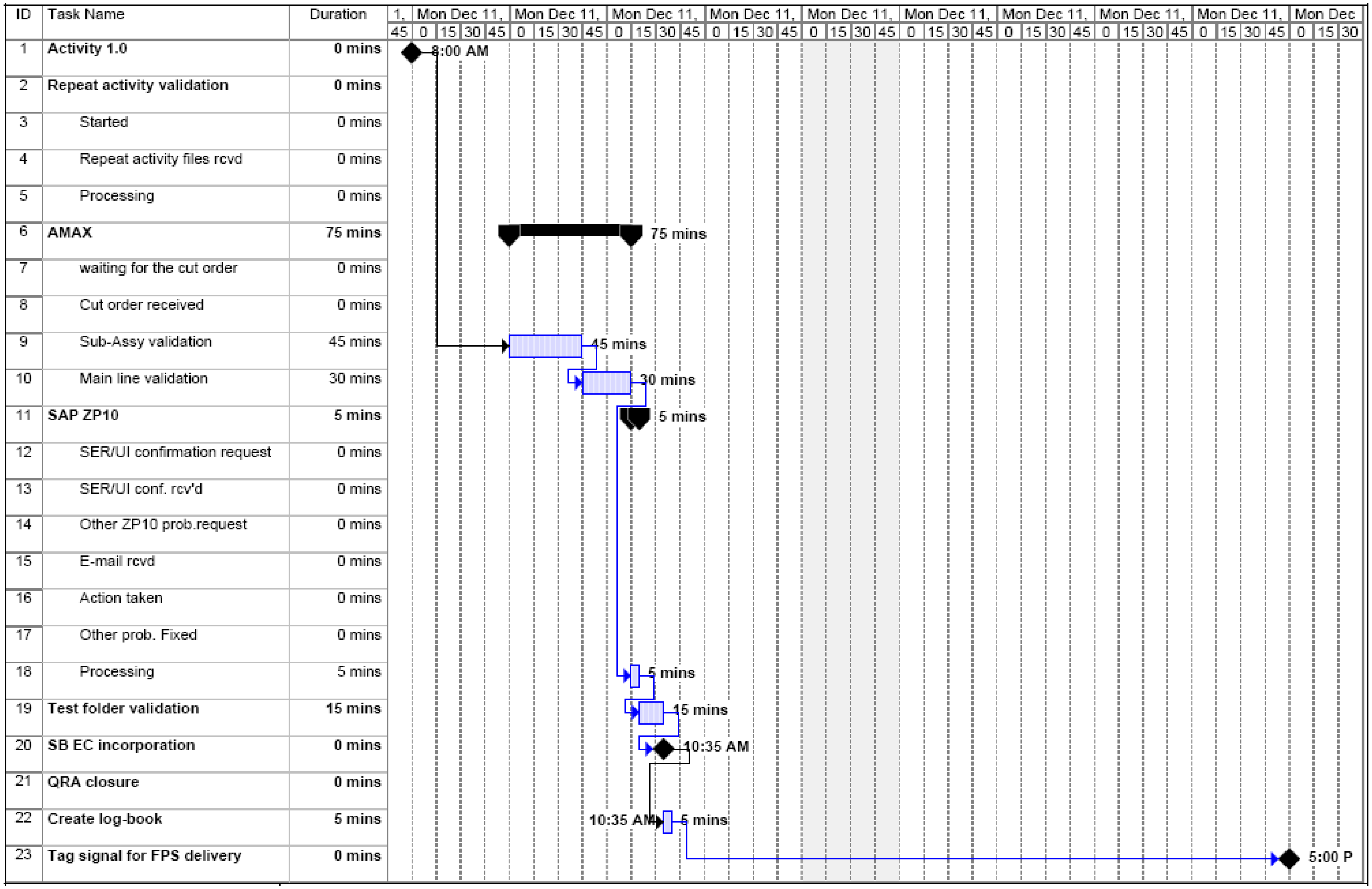


Figure 4.14. Activities and delays chart (Z20)

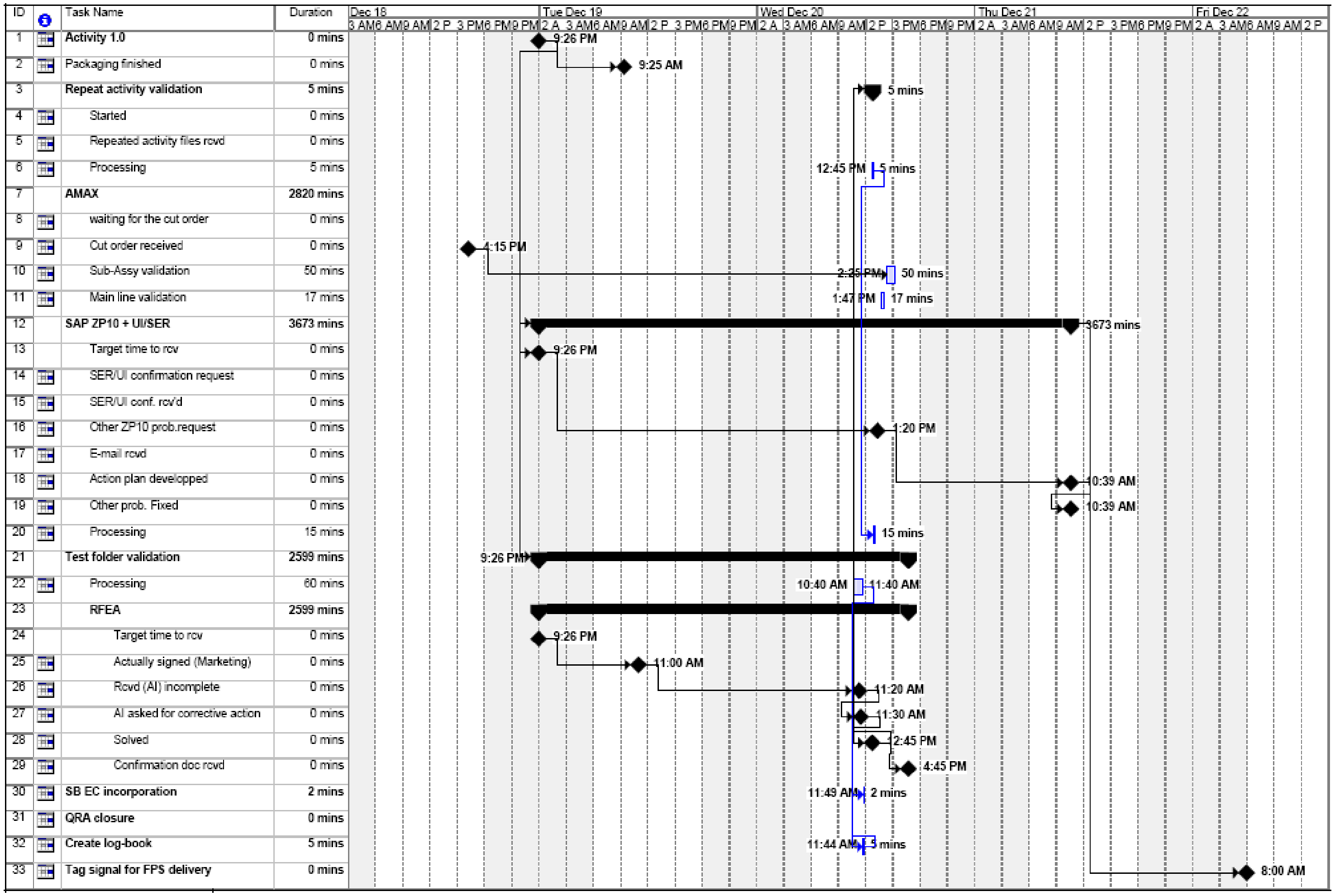


Figure 4.15. Activities and delays chart (Z23)

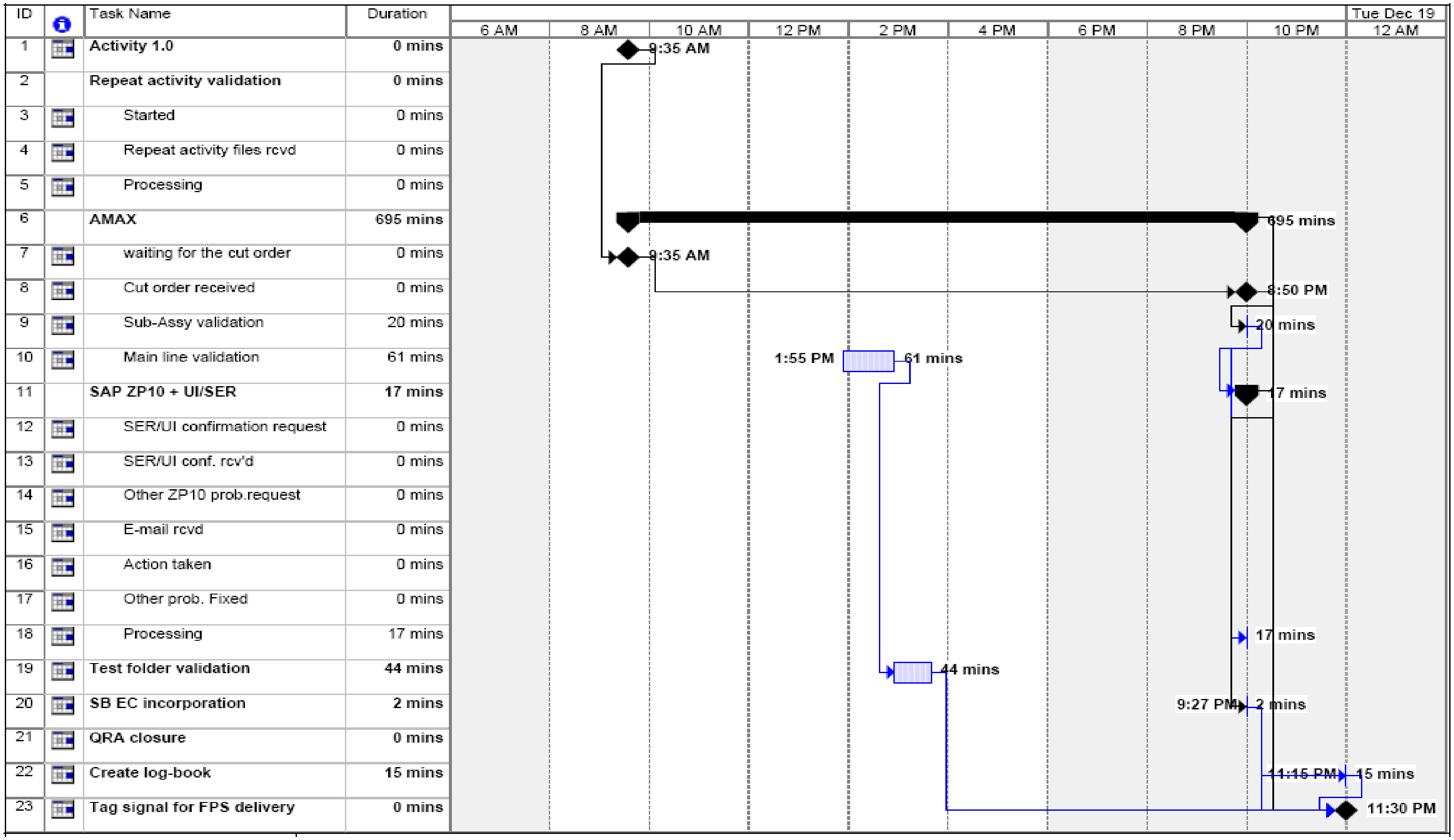


Figure 4.16. Activities and delays chart (Z24)

4.4.4 Analyze Phase

4.4.4.1 Gathered data summary

Due to the nature of the process under consideration, the decision to measure the impact of the snags in terms of incurred delay was made. If needed, financial impact could be easily derived once we learn the monetary value of a unit of time. Since loss ratio perfectly serves the purpose of process improvement, the delays minimization was chosen as the primary goal of the analysis. The information, collected using new forms, allowed to estimate each problem's impact in minutes and hours of delay it caused in addition to more precise classification of the problem area and the event count.

The results of analysis of Figure 4.11-Figure 4.15 were compiled in Table 4.4 and depicted in Figure 4.17. In Table 4.4, "Duration" represents the time interval between the engine post-dress finished and the signal to FPS delivery, "Required" corresponds to the time an AI actually worked on the engine, and "Lost" represents the difference between these two.

Cut order processing delays were observed in 4 out of 6 cases (66%). ZP10 completion delays were registered in 50% of cases. However, no direct correlation between these problem spots was noted. Repeat activity was registered only once, but it resulted in a significant delay.

Note that rather high (31%) level of average required time is due to an "outlier": Z20, which was shipped without any delay. If Z20 is not taken it into account, the rate would have dropped to 17%.

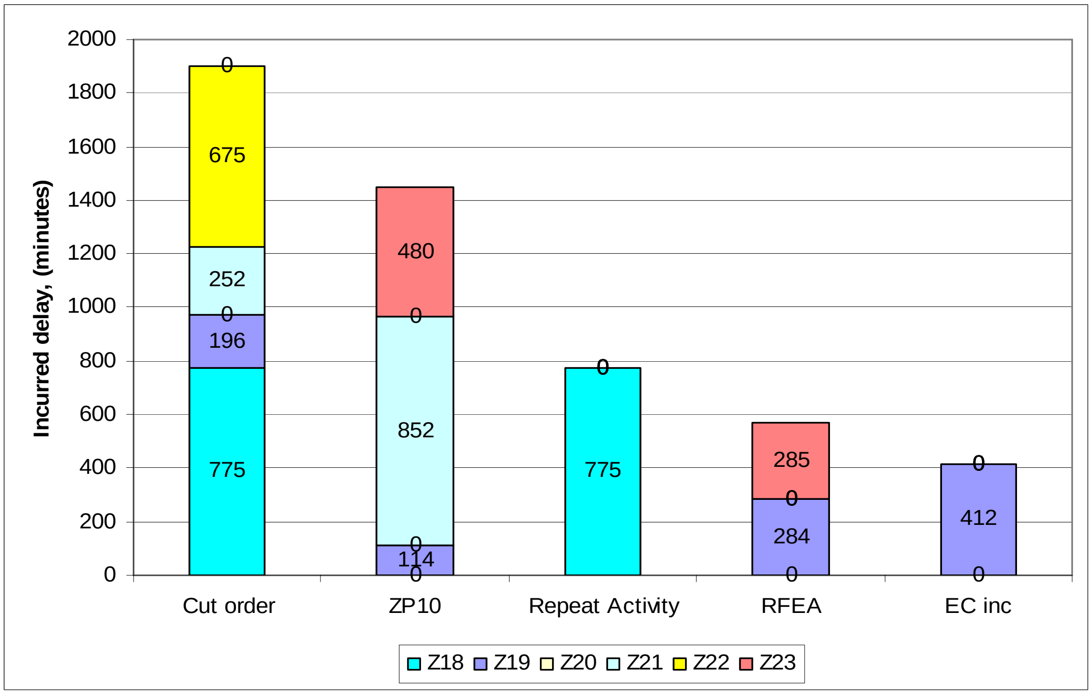


Figure 4.17. Problem spots summary

Table 4.4. Processing time summary

Parameter \ Engine	Z18	Z19	Z20	Z21	Z22	Z23	Average
Duration (min)	985	419	95	1092	840	960	731.83
Required (min)	170	69	95	125	100	270	138.17
Lost (min)	815	350	0	967	675	690	582.83
Required %*	17.3%	16.5%	100.0%	11.4%	11.9%	28.1%	30.9%
Lost %*	82.7%	83.5%	0.0%	88.6%	80.4%	71.9%	67.8%

*) Denominator for percentile is duration of the process.

4.4.4.2 Vital problems identification

Having done Pareto analysis (Figure 4.18), the following conclusions have been drawn:

Three activities are responsible for 80% of the delay time:

1. Cut order (37.2%)
2. ZP10 (28.4%)
3. Repeat activity validation (15.2%)

Even though RFEA was rated #4 (11.1%), it should be taken into consideration as well.

No direct relationships between the abovementioned activities have been observed.

The results obtained using the new system were quite different from what was summarised in Subsection 4.4.2.2. Issues with cut order and the repeat activity, due to the fact that they were low in numbers, were overlooked. However, as it is shown in Figure 4.18, they are among “Top three” major contributors into the average delay time.

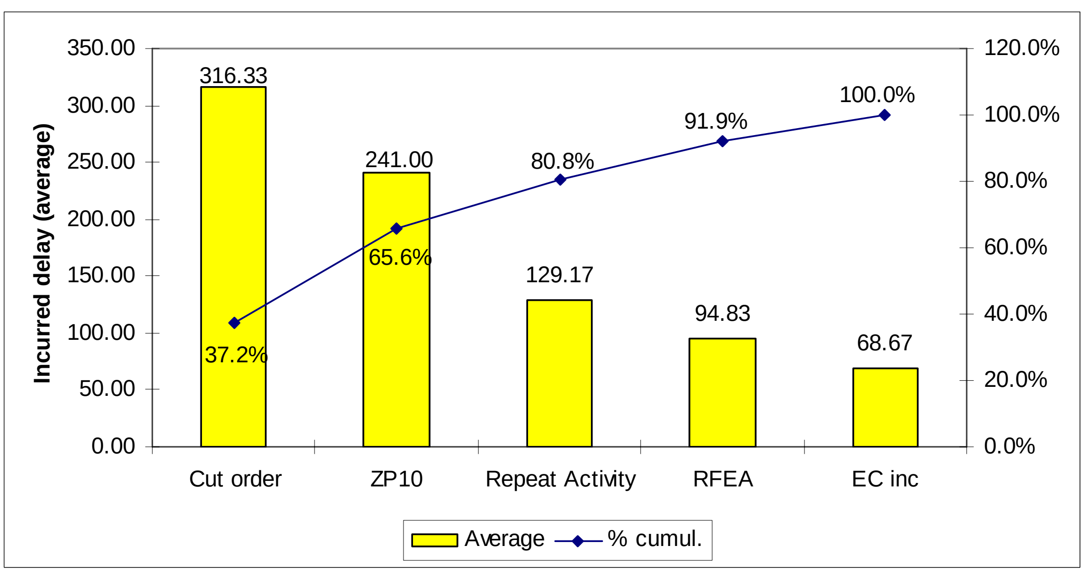


Figure 4.18. Average delays (min. per engine) summary

4.4.4.2.1 Cut order

Cut order is one of the essential documents and PWZZZ specific. In order to assure traceability of materials assigned to an engine, the parts used to build an engine must be correctly registered under its number, i.e. parent-child relationship. Cut order contains information on parts used to build an engine, so an AI could verify the production history of each part. Due to extremely high workload of AIs, though it is possible for them to retrieve all pertinent information, a production planner is responsible for the document compilation. The information becomes available once the engine goes off assembling process. The information is requested once the engine passes post-dress and the file delivered to an AI. In order to assure that no illegitimate (i.e. declared as "scrap", on quarantine, etc.) parts were installed on the engine, it would be better if the cut order was verified *prior* to testing. This would serve two purposes: in addition to the abovementioned improvement, it would assure zero delay due to the matter during the shipping phase.

4.4.4.2.1.1 Process statistics

- Baseline: post-dress phase finished.
- Min. delay = -311 minutes (Figure 4.15. Activities and delays chart (Z23))
- Max. delay = 775 minutes (Figure 4.13. Activities and delays chart (Z18))
- Average delay = 316 minutes (Figure 4.18. Average delays (min. per engine) summary)

4.4.4.2.1.2 Process capacity

As it follows from Figure 4.15, it is feasible to compile a cut order in advance. In fact, given that test runs longer than it requires to complete the cut order, the document may be done prior to testing.

4.4.4.2.1.3 Root-cause analysis

The problem has been tracked to the source – the production planner, who explained that even though he had been well aware of the problem, he was not able to prevent it due to high workload. Thus, the problem is defined as lack of process capacity causing bottle-neck. In addition, since a cut order is a paper document, it itself should be considered as a setback, thus it should be eliminated.

4.4.4.2.2 ZP10 delay

SAP transaction ZP10 displays Engine Serialized Component Summary. Thus, it is important that all information retrieved by this transaction was correct and valid. A typical record consists of:

- AFS number
- Material number
- Description of material
- Serial number
- Type of serialization: SER or UI

- Other information related to the part’s production/installation/working history and current status.

Due to the nature of PWZZZ manufacturing process, ZP10 issues should be considered from two points of view:

- Standards
- Process

Considering traceability issues from the point of view of standards, traceability requirements changes were classified as follows:

- Add traceability requirements to an existing part/kit/module
- Delete traceability requirements from an existing part/kit/module
- Add a new part/kit/module with traceability requirements
- Remove a replaced part/kit/module and traceability requirements (if applicable)

Process-related issues include:

- Entering a part serial number in the system
- Replacing non-conforming part already assigned to an engine (swap)
- IT: Database and database management software (Oracle and SAP) integrity issues

4.4.4.2.3 Standard related issues

Engineering changes affect the system in a way that depends on the type of change. If a new material with traceability requirement is added to the bill of materials, it will not automatically affect already open production orders. It will appear only on engines that are on planning orders. Thus, if modification of production orders is necessary, it will involve human intervention.

If a new traceability requirement is added to an existing part, it will apply immediately to all open orders. However, by many reasons, it might be impossible to feed the system with a valid serial number. As a result, the system will report incomplete ZP10 information causing delayed shipping. Human intervention is required to resolve the problem.

Due to everlasting traceability requirements change, the number of serialised parts changes from engine to engine. Involving many people and activities, the tasks as stated on the process map must be completed to implement the changes.

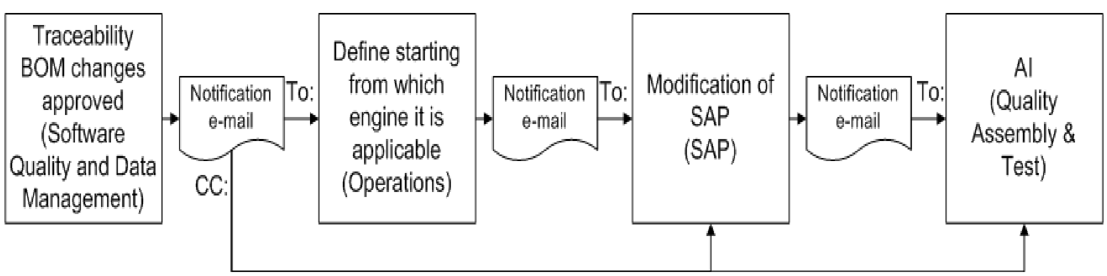


Figure 4.19. Traceability BOM changes implementation [1]

The problem unveiled is that, having received notification e-mail from Software Quality and Data Management Department, AIs got confused: on one hand they had an engine to ship with actual number of serialised parts, while on the other hand the e-mail, giving a different number, stated, “This is simply a note in order

[1] P&WC

to stress that we have modified the status of traceability of PWZZZ engines. This modification will be applicable as of today Friday, Nov. 24, 2006”[2].

Since this is the only information on traceability BOM changes the AIs receive, once they spot a discrepancy between the actual number of serialised parts and the one mentioned in this e-mail, they make inquires trying to figure out what the requirements applicable to that particular engine are.

4.4.4.2.4 Process related issues

Engine Z21 gave us a good example of IT-related issues. AI noticed that one UI was missing. Below is mapped action log.

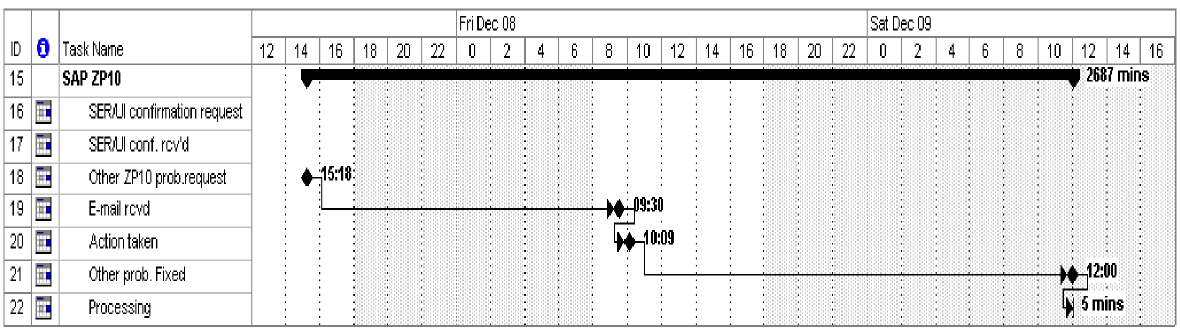


Figure 4.20. ZP10 IT-related delay structure

4.4.4.2.4.1 Action log

- December 7, 15:18 - December 8, 9:28 – no information on activities;
- December 8, 9:28 – notification e-mail sent;
- December 8, 10:14 – The manager having contacted the person responsible for the matter and learnt that she was pretty busy, sent e-mail to the originator

[2] From Software Quality and Data Manager’s e-mail of 24/11/2006 11:26 AM

explaining the situation and asking to call the person-in-charge if the issue was critical.

- December 9: the issue was fixed.

4.4.4.2.4.2 Summary

- Response time: 44 minutes
- Incurred delay: 852 minutes
- Target time: 0 minutes

4.4.4.2.4.3 Root-cause analysis

Preliminary analysis showed a possibility that a water-spider did not enter UI in the system. However, a database (SAP) error was finally pleaded guilty.

4.4.4.2.4.4 Follow-up action

A notification e-mail was sent to all people involved.

4.4.4.2.5 RFEA

Request for engine acceptance (RFEA) is a necessary evil during the early phase of production. Among the root-causes, we can specify elevated defect rate and specifications unfeasibility. As Figure 4.10 justifies, comparing the related data for June-October to the one for November, we can see that the number of RFEA per engine dropped significantly (by 4.25 times, see Figure 4.10). Due to the nature of the issue, RFEA processing time might vary from a few hours up to few days, if communication with the customer's engineering department is involved.

Based on expert's evaluation, two major causes of the delay have been unveiled:

- Distribution system is not developed.
- Many activities, involved in the issue resolution, are based on personal contacts, but there are quite a few newly hired ATTS.

4.4.4.3 Conclusions

4.4.4.3.1 General

- It is feasible to provide AIs with all required documentation, except RFEA, upon and even well prior to the test completion.
- AIs work more efficiently than estimated:
    - According to the process map, the best estimated time=5 hours,
    - Measured average processing time = 2h18'.
- "Cut order":
    - Snags appeared in 67% of observations, incurred the longest average delay;
    - They took long time to process. Long processing time caused by lack of automation, since AIs manually check sub-assemblies one-by-one.
- AIs are overloaded, thus an engine might wait for its turn for days.
- The data collected under the existing system (snag-sheet based) became usable once an impact estimation of each category of issues had been

calculated using a new measurement system and assigned to corresponding class of the existing one.

- Although RFEA is rated #4 in the chart (Figure 4.17), the problem must not be overlooked for the reason that:
    - There are many people involved in the process, which has steps that cannot run simultaneously. Therefore, a delay at any step directly affects total performance.
    - The process has the same dependency as the document closure one, i.e. the finish of testing phase initiates the start of it.

4.4.4.3.2 SER/UI related issues

SER/UI related issues have been found in 50% of observations.

Though it takes 1.5 hour in average to respond to a ZP10 snag, the problem is overlooked and its priority level is rather low. Thus, it dramatically increases lead-time.

Repeated problem: AIs are not aware of ECs related to number of UI-ed parts per engine (traceability BOM).

The information system (SAP) and the process are not robust. They are prone to human and machine errors.

Documents to be completed BEFORE the test:

- Cut order
- Pink sheets + ZP10 (chef d'équipe)
- Repeat activity folder
- Traceability BOM changes (SER/UI adding/removing)

Documents to be completed A.S.A.P. AFTER the test:

- RFEA

4.4.5 Improve Phase

4.4.5.1 Cut order

4.4.5.1.1 Suggested solution

- Short term: Transfer the activity to another person.
- Long term: modify the information system, so the document:
- First stage is generated automatically
- Second (final) stage is no more needed (included in the system)

4.4.5.1.2 Action plan (short term solution)

- Map the process
- Compile a cook-book
- Train a person
- Transfer process ownership

4.4.5.2 ZP10

4.4.5.2.1 Preventive action plan

In order to cope with the existing system, an interim solution was suggested where the operators and the team leader should check the completeness of ZP10 once the engine goes to the testing.

4.4.5.2.2 SWAP

- Suggested paperless operation
- The process has been developed and mapped
- The responsible person has been trained
- The process has been launched

Due to AIs' request, it has been decided to keep the paper justifications of swaps for a while, so they could be sure that the automated procedure works fine.

4.4.5.3 Traceability BOM changes implementation

Action plan

- Review current process
- Reassign roles and responsibilities to appropriate persons

4.4.5.4 RFEA

Since RFEA tend to fade away when the production process matures, it is reasonable to treat them as a temporary problem.

Action plan

- Develop and implement distribution process
- Assign a process owner

The follow-up, improve and control activities for this task fall outside of the current project scope.

4.4.6 Control Phase

4.4.6.1 Issue-independent action plan

The established log-sheet based measurement system is suitable for evaluation of process improvement. Once the proved process is transferred to the process owner, a sample of at least five engines should be evaluated. This evaluation has the following purposes:

- Measure performance of the improved process:
  - calculate average delay per engine
  - calculate occurrence of the issues
- Validate effectiveness of implemented solution:
  - compare new values to the ones listed in Analysis phase (Subsection 4.4.4)
  - draw conclusions on the matter
  - depending on the output, either declare the problem solved or analyze the residual snags, and develop and implement corrective actions
- According to continuous improvement strategy, define and prioritize next-on-the-list problem spots.

4.4.6.2 Issue-specific action plan

Cut order

- Perform DMAIC for the cut order processing;
- Develop requirements and specifications for software implementation.

ZP10

Verify and validate the effectiveness of the interim solution.

Swap

- Having confirmed that ZP78 works flawlessly, verify if the swap process map correctly reflects actual situation. If it is the case, develop requirements for full process automation in SAP.
- Map claimed-to-be-defective parts processing.
- Perform DMAIC for it.

4.4.6.3 Traceability BOM changes implementation

Taking into account that traceability BOM changes tend to fade away once the serialization requirements are finally defined, the main focus should be given to activities that are permanent part of the manufacturing process. Nevertheless, in order to assure snagless operation, the following actions should be executed:

- Measure performance of improved traceability BOM changes implementation process
- Depending on the result, consider the problem solved or reinitiate process revision

4.5 CONCLUSIONS

UI-related issues draw a lot of attention, and pleaded to be the major contributor to the overall number of issues. However, once the issues are structured and categorised, one can see that processing delays and deficiencies in documentation indirectly related to DPM play a significant role. In the present case study, the major snag was the document (“pink sheet”) issuance during the swap operation. Being a paper-based document, it did not fit into the state-of-the-art production process. The problems associated with “pink sheets” emerged in the parts swap activity and resulted in delays at the engine shipping phase.

5 CASE STUDY 2: APPLICATION OF IMPROVED FMEA TO DIRECT PARTS MARKING SYSTEM

5.1 TARGET OF THE CASE STUDY

The target of this case study is to analyze the existing way of prioritizing quality improvement actions and develop a new evaluation approach. The new approach should assess impacts of quality issues.

5.2 PROBLEM STATEMENT

This case study used the problem definitions and structure as it was described in Section 3.2, and shown in Figure 3.3 and Figure 3.4.

Applying the principles from the proposed approach to the DPMS-related issues at P&WC, all problems the process meets with can be formalized to a list[3]:

- 2D miss-read (2DMR): A scanner cannot read 2D matrix due to various reasons (i.e. the matrix is damaged, not suitable surface; the matrix is incorrectly printed, etc.)
- 2D missing (2DM): there is no 2D matrix on the part.
- 2D wrong data (2DWD): 2D matrix is printed on the part and is legible, but the data encoded in it are incorrect (wrong format, some characters missing, wrong number, illegal character, etc.)

[3] Quality Assurance Specialist, P&WC

- Cage Code missing (CCM): there is no Cage Code on the part, although the requirements ask for it.
- Data missing in human readable (HMM): A human readable part of SER/UI does not contain all required information (i.e. manufacturer code, part number, etc.).
- Final Stamp missing (FSM): Final inspection stamp is missing on the part. Not related to serialization; however, it is a part of parts marking.
- Final Stamp wrong marking (FSWM): Similar to FSM.
- Human wrong marking (HWM): The human readable part of SER/UI contains mistakes.
- Legibility problem (LEP): The human readable part of SER/UI is not legible.
- Red Flag identification missing (RFM): A part had problems that are registered in the system, but there is no indicator printed on the part.
- Revision Letter missing (REVM): No revision letter, although the requirements ask for it.
- Serial Number missing (SERM): No Serial Number, although the requirements ask for it.
- Spacing problems (SPCP): Extra or missing space(s) in the human readable part of the serial number.
- System vs. minimum space condition (MSCP): Serial numbers composed in accordance with minimum space conditions occupy less space but carry

less information about the part. Thus, this QN reflects minimum space conditions applied to a part that does not qualify,

- Text Element Identifier Missing (TEIM): There is no indication of the nature (serial number or unique identifier) of the number on a part.
- Timing "x" is missing (TIMM): There is no “synchronisation” mark on a round part or there is more than one way to install a part and it is not indicated which one is correct. This problem is not related to serialisation; however, it is a part of parts marking.
- UI missing (UIM): No Unique Identifier, although the requirements ask for it.
- Vendor Code and Prefix (VC): Error in Vendor Code and Prefix
- Wrong CAGE Code (WCC): CAGE Code is incorrect.
- Wrong marking location (WML): The part is marked on an area different from the one specified on the drawing.
- Wrong marking method (WM): The method used for marking or cancelling marking is not appropriate for the part or not specified in CPW-10.

Thus, the process has been mapped and the problem spots have been defined. The define phase is considered completed.

5.3 CURRENT MEASUREMENT SYSTEM EVALUATION

A measurement system that provides valid data is the base of Six Sigma. Since Six Sigma targets the bottom line, the decision to look for the data that contain information sufficient for drawing conclusions has been made. Within the scope of this activity, the following information was requested:

1) Time delays (h/day, h/engine, h/issue, etc.) caused by:

- UI issues
- Consequences of UI issues
- Human factors related to UI
- Other types used in the system that might be related to UI.

2) Monetary values:

- Waste ($/engine, $/day, etc)
- Rework ($/engine, $/day, etc)
- Inventory costs:
    - Reserves (ex.: to cover possible material shortage)
    - Decompleted/disassembled (“cannibalised”) kits
    - “Hospital”: parts and modules with suspected non-conformities awaiting a thorough inspection.
- Other types used in the system that might be related to UI. For example, incentives for the suppliers to comply with UI mandate; cost of testing equipment; labour overhead, etc.

Answers received:

‘This type of information is not readily available and would take a lot of time to gather. We do not have the resources to support this activity.’

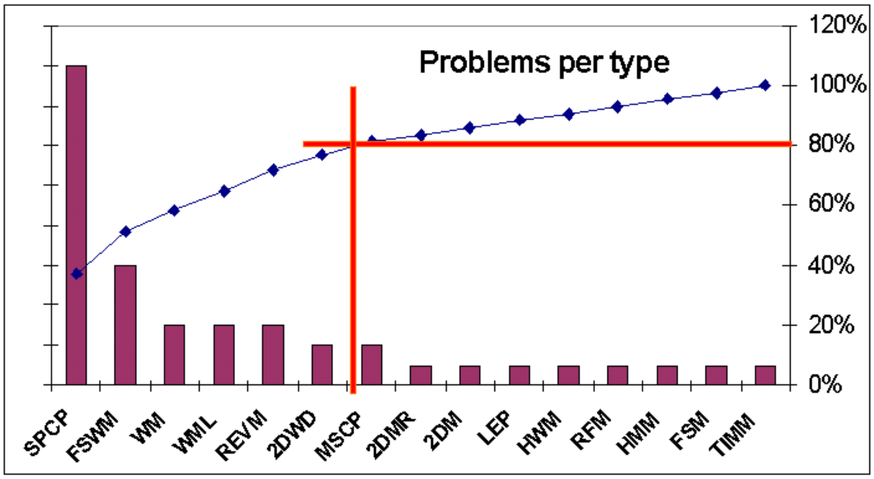
‘The data we have is related to the number of deviations/errors on UI per month and by Producers.’

‘…data we have are coming from ZP15. As we discussed last week those data include vendor error (F2), manufacturing error (F3), escape (ZE) and SSON (ZS).‘ Therefore, no impact-related information on the UI-related issues was readily available. A hypothesis was made that the lack of such information might affect the decision making when it comes to prioritising the UI-related risks.

Figure 5.1 represents classical Pareto analysis of serialisation-related issues as it was done under the existing system. Note that the existing system simply counted the number of registered QNs. Problems are classified by their type. According to the figure, the majority of problems (80% level) were caused by:

- Spacing problems
- Final stamp wrong marking
- Wrong marking method
- Wrong marking location
- Revision letter missing
- 2D wrong data
- 2D misread.

The numbers on the item list represent level of importance of the problem, thus it reflects its priority level.



code	%	% cumulative
SPCP	37%	37%
FSWM	14%	51%
WM	7%	58%
WML	7%	65%
REVM	7%	72%
2DWD	5%	77%
MSCP	5%	81%
2DMR	2%	84%
2DM	2%	86%
LEP	2%	88%
HWM	2%	91%
RFM	2%	93%
HMM	2%	95%
FSM	2%	98%
TIMM	2%	100%

SPACING PROBLEMS	SPCP	REV. LETTER MISSING	REVM
FINAL STAMP WRONG MARKING	FSWM	2D WRONG DATA	2DWD
WRONG MARKING METHOD	WM	SYST. VS MS CONDITION	MSCP
WRONG MARKING LOCATION	WML		

Figure 5.1. DPMS: Type of issues analysis[4]

Positive sides of existing system:

The types of issues are well defined

It provides quantitative data. So there was some numerical data to start with.

Drawbacks:

Does not evaluate the impact of issues; thus a single high-impact problem might be overlooked.

Based on quantitative analysis only. The issues were simply counted and priorities were assigned based on the total count per problem.

[4] Data provided by the Quality Assurance Specialist, October 2006

5.4 NEW MEASUREMENT SYSTEM DEVELOPMENT AND VALIDATION

5.4.1 Severity criteria definition for DPMS

While Table 2.2 introduces a general approach to severity ranking, and Table 3.1 adapts it to the DPMS application, Table 5.1 gives detailed ranking description with regard to DPMS. It minimises the subjectivity in the severity ranking assignment, by defining two levels of classification.

The assignment of severity level has been done using expert evaluation of the risk taking into account how the risk affects the performance of the system from point of view of traceability. For example, 2DWD received the highest rating of 10 because the wrong machine-readable data about the part was fed directly into IT system making impossible to trace the part. On the other hand, TIMM was assigned severity rating of 3 because it did not affect the part's traceability, but it required special attention from the assembly worker while he was installing the part. Table 5.1 was used as a guideline.

Table 5.1 Detailed severity ranking for DPMS

Criteria		**Rating**
General description	**Detailed instructions**	
Does not directly affect the parts' traceability	None	1

Very minor performance degradation or minor problems at next higher assembly, mostly related to the human-readable part of marking.	Extra/missing spaces in the human-readable	2
	Special (non-traceability related) characters missing	3
The labels are still legible, but have deviations from the DPMS requirements.	Wrong marking method that does not affect the part's performance	4
	Missing minor information, mostly in human-readable part; wrong marking location	5
Illegible data that requires remarking. The defect has a severe affect on tracking system performance.	Illegible human-readable part	6
	Missing non-serialisation-related data	7
	Impossible to read 2D matrix; wrong non-serialisation-related data	8
Major impact on part traceability such as impossibility to identify the part, or a part is damaged as a result of marking.	Missing marking/key data (UI)	9
	Wrong key data; SER missing; part is damaged	10

5.4.2 PFMEA with dynamic occurrence assignment

Based on the proposed method described in Subsection 3.5.3, the following information was requested from the system:

- Affected part number
- Type of QN
- Supplier of the part
- Cost of the part
- Quantity of affected parts.

The probability of unveiling the problem is directly related to detection parameter assignment. The QNs, we are aware of prior to processing the part at the P&WC facilities, received the lowest score (all F3 and ZS QNs). The issues that require special equipment coupled with operator attentiveness and skills (ex.: 2DWD) should draw particular attention, thus they got high “D”-scores (Figure 5.2). The S*D rating of the risk was calculated as the product of its severity and detection ratings. The comprehensive table is available in Appendix 2.

The occurrence parameter was calculated using actual data and Equation 3.2. The final Dynamic RPN (DRPN) number was calculated using Equation 3.3. The difference between RPN and DRPN is the way the occurrence rating was calculated. DRPN, instead of static, based on expert evaluation, occurrence rating assignment, used live data for the purpose. Thus, DRPN for a part might vary from one observation period to another.

Potential Failure Mode	Problem code	Potential Effect of Failure	S	D	S*D
2D WRONG DATA (2DWD)	2DWD	**F2**	10	9	90
	2DWD	F3	10	1	10
	2DWD	**ZE**	10	9	90
	2DWD	ZS	10	1	10
2D MISS READ (2DMR)	2DMR	**F2**	8	8	64
	2DMR	F3	8	1	8
	2DMR	**ZE**	8	8	64
	2DMR	ZS	8	1	8
2D MISSING (2DM)	2DM	**F2**	8	5	40
	2DM	F3	8	1	8
	2DM	**ZE**	8	5	40
	2DM	ZS	8	1	8

Figure 5.2. S*D risk rating calculation

5.4.3 Results analysis: Classical vs. DRPN-based

October 2006 (Figure 5.3 and Figure 5.4): Classic analysis suggested focusing on vendor V5 (mainly SPCP, few FSM and REVM). DRPN-based system unveiled menacing problems that vendor V6 is responsible for 2DWD and MSCP. Also, the DRPN-based system reassigned proportion of QN rating, emphasizing the importance of F2 over ZS. The classical approach just provides total number of events and it could be perceived that the major contributor QN ZS has the heaviest impact. DRPN approach has corrected this existing system deficiency. It also showed that V3 and V4 have alarming levels of heavy-impact quality issues.

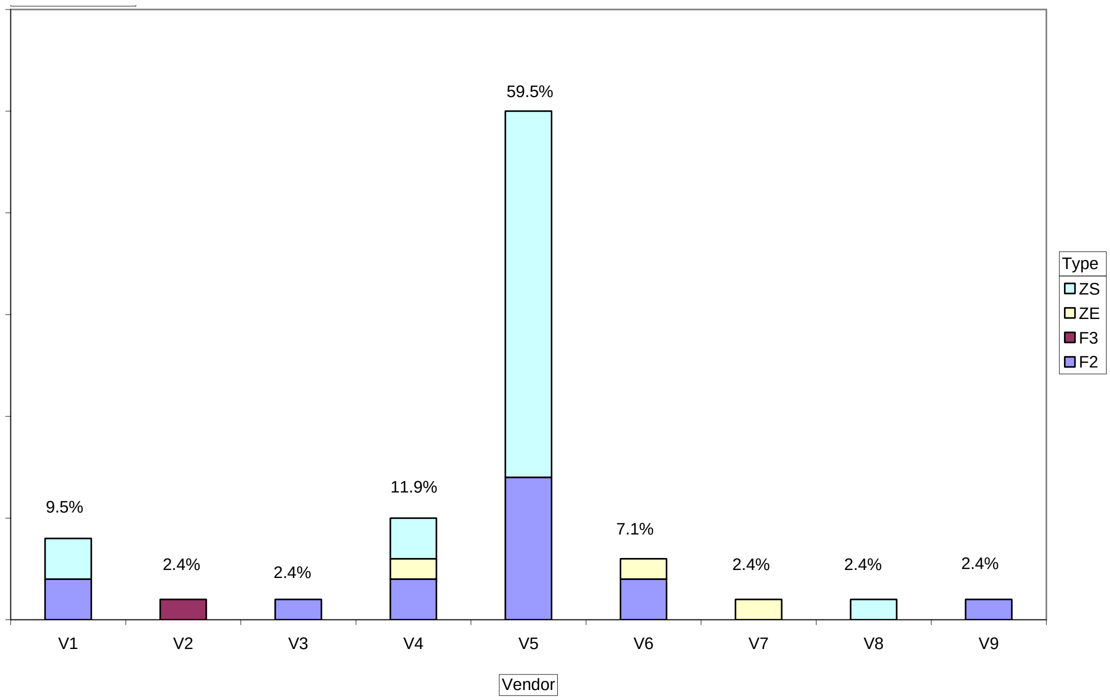


Figure 5.3. DPMS QN classic analysis (October 2006)

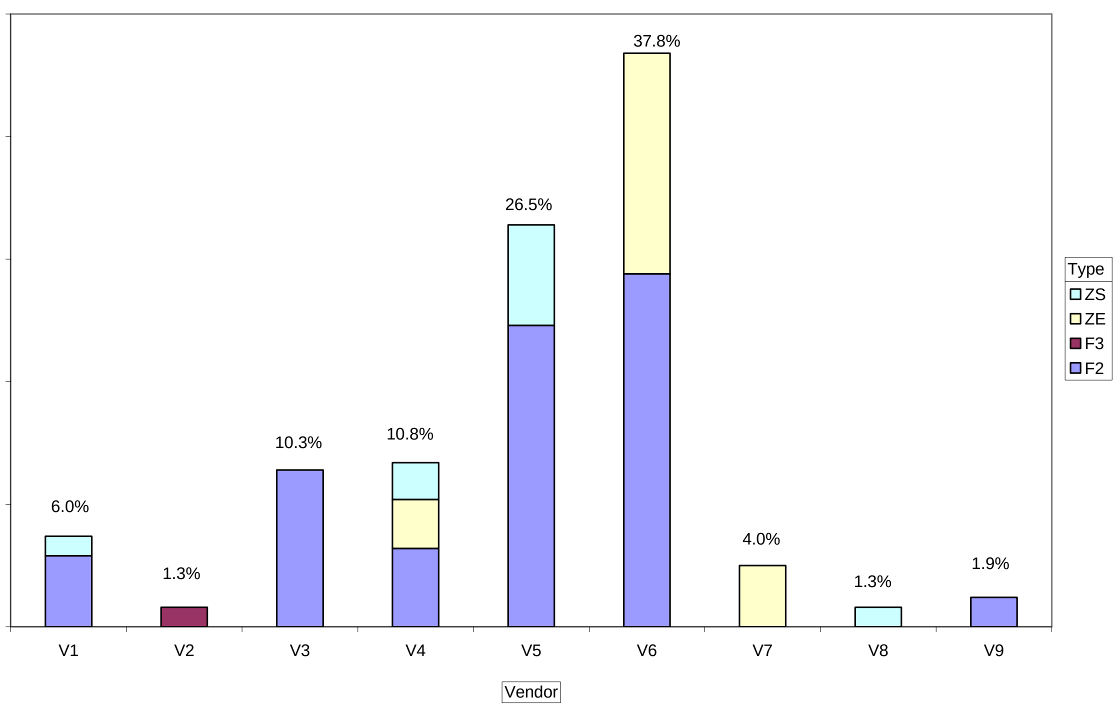


Figure 5.4. DPMS QN DRPN-based analysis (October 2006)

November 2006 (Figure 5.5 and Figure 5.6): Confirming the consistency of the results, the conclusions for November came out quite similar. As a validation of the chosen approach, the fact that at the end of December 2006 an escape caused by materials supplied by vendor V06 should be considered.

In **December 2006**, a few engines were not accepted by AI due to the problems with a specific part's serial numbers that came from the vendor V06. The engines were disassembled to ensure the compliance with the quality requirements, resulting in significant financial losses. DRPN-based method was able to predict this situation and moved V06 from the fifth risk priority place to the second. V05 is still the "leader" mainly due to the high volume of materials that it supplied to P&WC.

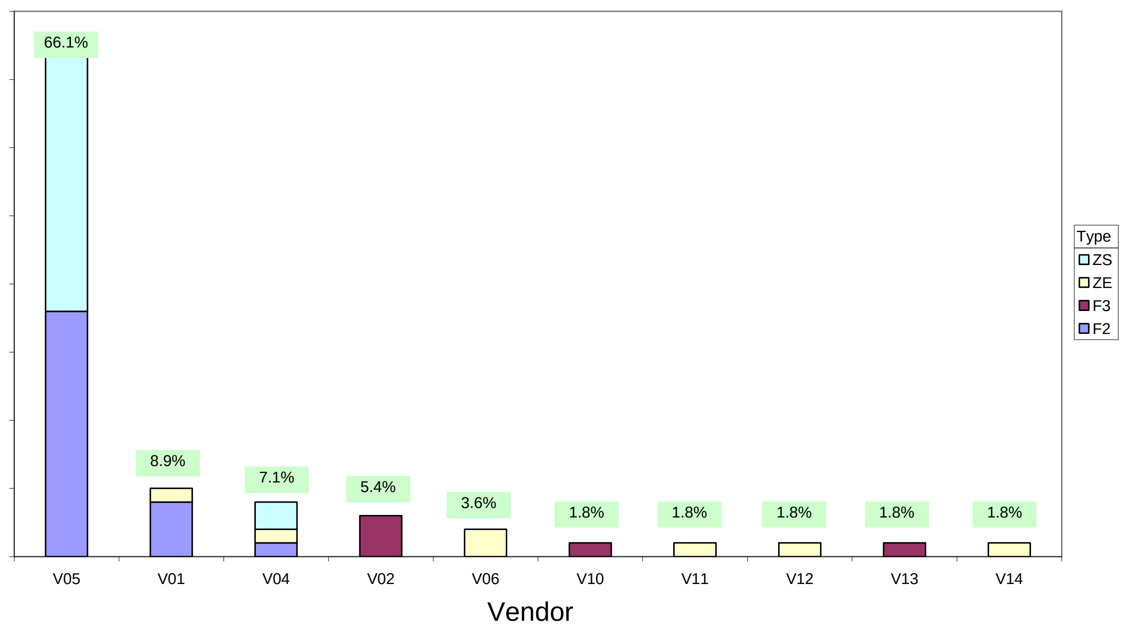


Figure 5.5. DPMS QN classic analysis (November 2006)

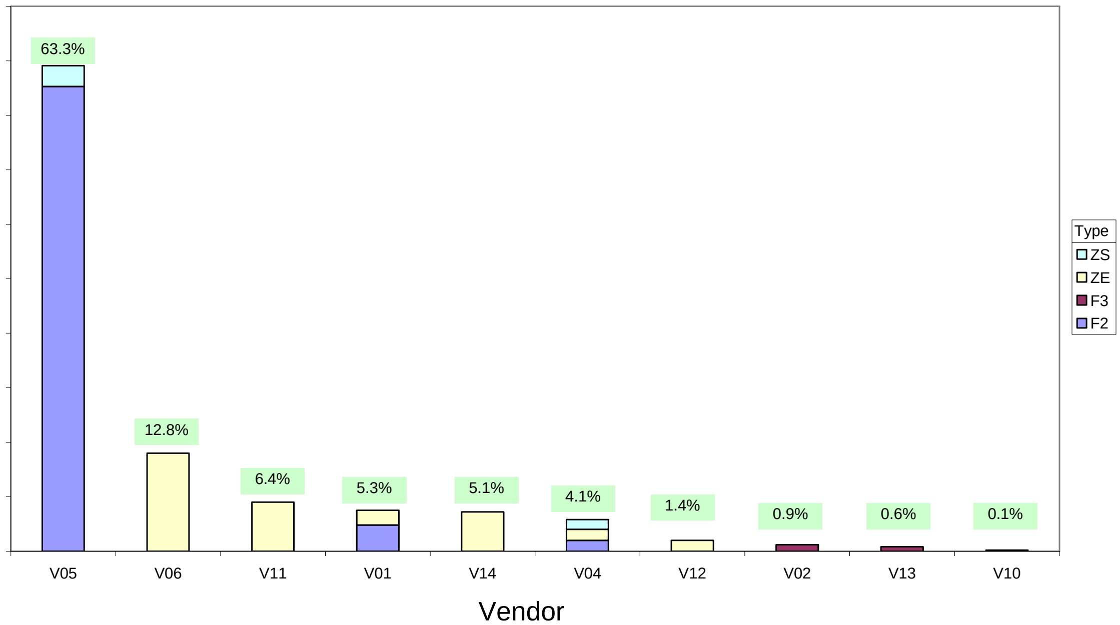


Figure 5.6. DPMS QN DRPN-based analysis (November 2006)

December 2006 (Figure 5.7 and Figure 5.8): The data tells for itself. The problems priority order was changed completely.

Let us see why vendor V3 moved from the eights place to the first one. According to the classic approach, there is only one QN registered. However, due to the nature of this QN (2DMR), the RPN-based system assigned high priority score to it. The similar situation was observed with V12 (RFM) and V7 (UIM).

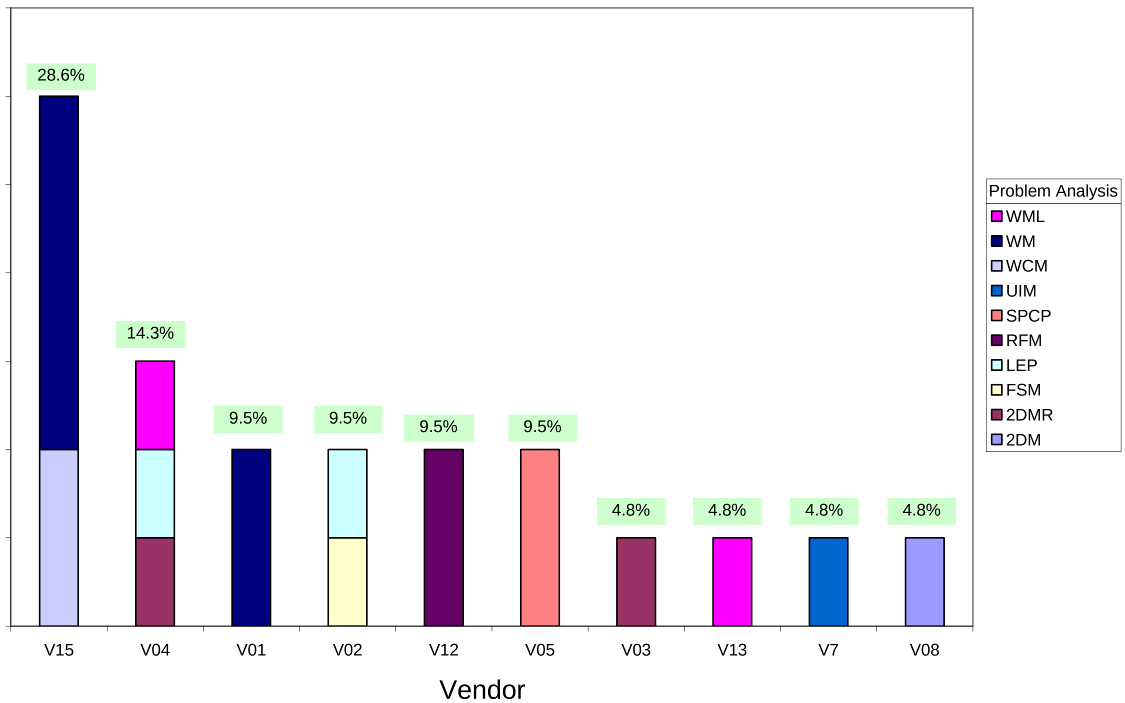


Figure 5.7. DPMS QN classic analysis (December 2006)

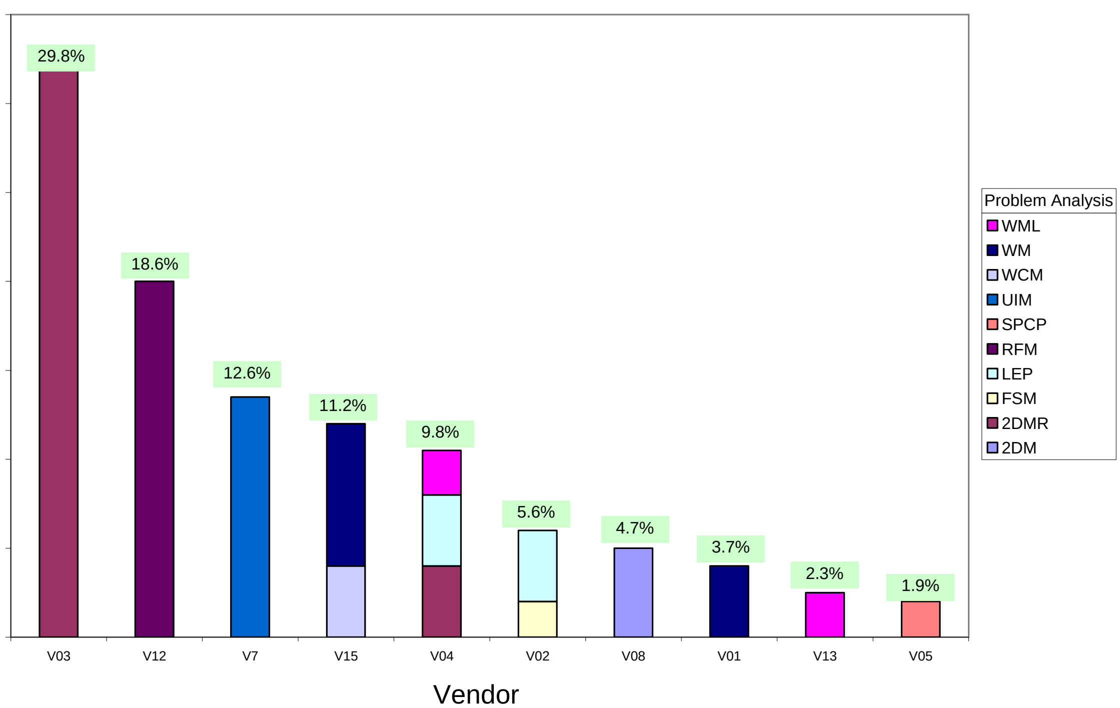


Figure 5.8. DPMS QN DRPN-based analysis (December 2006)

5.5 CONCLUSIONS

The developed, tested and implemented DRPN-based FMEA system has proven to be efficient in fast-changing due to production ramp-up and set-up hi-tech manufacturing environment. It was able to detect issues “invisible” for the conventional FMEA.

6 SUMMARY, CONCLUSIONS AND FUTURE WORK

6.1 SUMMARY

In this research, the following has been done:

1. Investigated the impact of DPMS on PWZZZ production process.
2. Designed, tested and implemented the new impact measurement system for UI related and unrelated problems for PWZZZ A&T process in production ramp-up in order to optimise Direct Parts Marking System (DPMS) based on Unique Identifiers (UI) or Serial Numbers.
3. Developed a new evaluation approach to existing QN prioritisation system.

6.2 CONCLUSIONS

DPMS plays extremely important role in the aircraft industry. That is why its appropriate implementation into the manufacturing process is crucial from many points of view, from the aircrafts' safety to the companies involved in the manufacturing process bottom line.

In order to better understand the scope of the problem, DPM methods were reviewed and compared. Then, a deeper study of one of them, 2-D Data Matrix, adopted by the aerospace industry, has been conducted.

DMAIC methodology along with FMEA has been applied to developing the approach to the aircraft engine quality improvement through the increase of traceability of its components.

In the scope of this research, the implementation of aircraft engines tracking strategy in production ramp-up has been supported by optimizing Direct Parts Marking System (DPMS) based on Unique Identifiers (UI) or Serial Numbers (SER).

The impact of DPMS on aircraft engines production process has been investigated. DPMS-related issues have been defined, structured, and classified. Their impact has been assessed.

The existing way of prioritizing quality improvement actions has been analyzed and a new evaluation approach has been developed. Six Sigma DMAIC methodology has been adapted and applied to DPMS.

The new measurement system for UI-related issues tracking has been developed. As it is shown in Chapter 4, there was no measurement system in place before the case study was done. The developed measurement system focused on time delays, especially on the delays at the final production stage. The system has been proven to be able to highlight QNs with heavier impact on the production, prioritizing quality improvement actions. The quality assurance specialist was able to focus on quality improvement of the vital parts and eliminate the critical defects.

FMEA principles were described and the drawbacks of existing FMEA methods were highlighted. DRPN-based FMEA system has been developed, tested and implemented into the prioritisation process of the UI-related problems. The system has been proven to be efficient in fast-changing hi-tech manufacturing environment. It was able to emphasise the importance of issues that conventional FMEA would have “filtered out”.

6.3 FUTURE WORK

The development of an FMEA system based on monetary value of each QN is one of the goals for the future work. In addition to DRPN, the system should take into account the QN’s severity based on the cost of correction measures caused by the affected part, thus it will make possible to estimate the financial impact of each QN and focus the efforts on the ones with the highest impact. As a result, a system that counts two real-time parameters (occurrence and severity) will be developed:

$$DRPN=S(\$)*D*O(t) \qquad \textbf{Equation 6.1}$$

The S($) parameter will include the cost of replacement part, shipping, labour and management cost, and other costs incurred due to the problem.

Another direction is to link each of the potential failure modes (Figure 5.2) with parts marking problem structure (Figure 3.4) and trace each failure mode to its origin.

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Appendix 1. Partial FMEA table

Potential Failure Mode	Potential Effect of Failure	S	D	S*D
2D WRONG DATA (2DWD)	**F2**	10	9	90
	F3	10	1	10
	ZE	10	9	90
	ZS	10	1	10
2D MISS READ (2DMR)	**F2**	8	8	64
	F3	8	1	8
	ZE	8	8	64
	ZS	8	1	8
2D MISSING (2DM)	**F2**	8	5	40
	F3	8	1	8
	ZE	8	5	40
	ZS	8	1	8
TEI MISSING (TEIM)	**F2**	5	5	25
	F3	5	1	5
	ZE	5	5	25
	ZS	5	1	5
VENDOR CODE AND PREFIX (VC)	**F2**	7	5	35
	F3	7	1	7
	ZE	7	5	35
	ZS	7	1	7
CAGE CODE MISSING (CCM)	**F2**	7	5	35
	F3	7	1	7
	ZE	7	5	35
	ZS	7	1	7
WRONG CAGE CODE (WCC)	**F2**	8	6	48
	F3	8	1	8
	ZE	8	6	48
	ZS	8	1	8
UI OR SER MISSING (UISNM)	**F2**	10	3	30
	F3	10	1	10
	ZE	10	3	30
	ZS	10	1	10

UI MISSING (UIM)	**F2**	**9**	**3**	**27**
	F3	**9**	**1**	**9**
	ZE	**9**	**3**	**27**
	ZS	**9**	**1**	**9**
SER MISSING (SERM)	**F2**	**10**	**3**	**30**
	F3	**10**	**1**	**10**
	ZE	**10**	**3**	**30**
	ZS	**10**	**1**	**10**
WRONG MARKING METHOD (WM)	**F2**	**4**	**3**	**12**
	F3	**4**	**1**	**4**
	ZE	**4**	**3**	**12**
	ZS	**4**	**1**	**4**
SPACING PROBLEMS (SPCP)	**F2**	**2**	**5**	**10**
	F3	**2**	**1**	**2**
	ZE	**2**	**5**	**10**
	ZS	**2**	**1**	**2**
LEGEBILITY PROBLEM (LEP)	**F2**	**8**	**3**	**24**
	F3	**8**	**1**	**8**
	ZE	**8**	**3**	**24**
	ZS	**8**	**1**	**8**
HUMAN WRONG MARKING (HWM)	**F2**	**5**	**5**	**25**
	F3	**5**	**1**	**5**
	ZE	**5**	**5**	**25**
	ZS	**5**	**1**	**5**
WRONG MARKING LOCATION (WML)	**F2**	**5**	**4**	**20**
	F3	**5**	**1**	**5**
	ZE	**5**	**4**	**20**
	ZS	**5**	**1**	**5**
SYST. VS MS CONDITION (MSCP)	**F2**	**8**	**9**	**72**
	F3	**8**	**1**	**8**
	ZE	**8**	**9**	**72**
	ZS	**8**	**1**	**8**
RED FLAG IDENT MISSING (RFM)	**F2**	**4**	**5**	**20**
	F3	**4**	**1**	**4**
	ZE	**4**	**5**	**20**
	ZS	**4**	**1**	**4**

DATA MISSING IN HUMAN READABLE (HMM)	**F2**	**5**	**5**	**25**
	F3	**5**	**1**	**5**
	ZE	**5**	**5**	**25**
	ZS	**5**	**1**	**5**
REV. LETTER MISSING (REVM)	**F2**	**5**	**5**	**25**
	F3	**5**	**1**	**5**
	ZE	**5**	**5**	**25**
	ZS	**5**	**1**	**5**
FINAL STAMP MISSING (FSM)	**F2**	**4**	**5**	**20**
	F3	**4**	**1**	**4**
	ZE	**4**	**5**	**20**
	ZS	**4**	**1**	**4**
FINAL STAMP WRONG MARKING (FSWM)	**F2**	**4**	**3**	**12**
	F3	**4**	**1**	**4**
	ZE	**4**	**3**	**12**
	ZS	**4**	**1**	**4**
TIMING "x" IS MISSING (TIMM)	**F2**	**3**	**3**	**9**
	F3	**3**	**1**	**3**
	ZE	**3**	**3**	**9**
	ZS	**3**	**1**	**3**
Wrong Serial Number (WSN)	**F2**	**10**	**9**	**90**
	F3	**10**	**1**	**10**
	ZE	**10**	**9**	**90**
	ZS	**10**	**1**	**10**

Appendix 2. Data acquisition forms

A&T document closure process for engine shipment

Log-sheet

Engine #________________ Post-dress finished: ___d ___m, ___h ___ min

#	Operation	Date/Time		Comments/ Suggestions
		Start	End	
1	Repeat activity validation			
2	Cut order sheet received			
3	Sub-Assy validation			
4	Main line validation			
5	SAP ZP10			
6	Serial/UI numbers validation& Print (form 2379)			
7	Test folder validation			
7.a	RFEA			
8	Service Bulletin EC incorporations			
9	QRA closure			
10	Create log book			
11	Tag signal for FPS delivery			

A&T document closure process for engine shipment

Problem log-sheet

#	Problem	Date/Time		Material/ part/assy affected	Cause/Type/ Comments/Kaizen suggestions
		Discovered	Solved		