Automated Verification of Raw Material. (Scrap reduction)

Project Thesis

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Abstract: Human error is an important aspect in production quality. The occurrence of human error in a manufacturing environment impacts on quality, productivity, operational efficiency, operational and economic results. Contributing factors, such as product design, process design, organisational structures, training methodologies and working hour patterns, influence the risk factors for operations staff with a direct influence on the quality of a product or process. This paper presents a project concerning human error in manufacturing processes with the aim of investigating, by analysis, the current status in manufacturing environments and highlighting the research and practice gaps. A literature review was conducted using three databases (Emerald, Research Gate and Science Direct) using a set of relevant keywords in order to identify and review papers that presented evidence on the relationship between human error and quality results. Papers were identified for review and then examined using a pre-determined methodology. This facilitated the classification and critical assessment of the selected papers as belonging to: process and product design contributions; organisational factors as error contributions; methodologies for human error analysis; error consequences; industrial sectors. The analysis explores the importance of considering human error and human factors in industry because varying error types occur during the processes with measurable effects on the quality and operations outputs. Certain engineering environments had more research available, specifically Aviation, Mining, Construction and Heavy industries. This suggest that there is a greater focus on human error in these areas, which could be defined as “high-risk”, where the impact(s) of human error may be more pronounced. In the sectors of Automotive and electronics manufacturing there were less studies on effects of human error, and fewer still focusing on the possible underlying causes of human error.

This review suggest that there is scope for additional research in the automotive and electronics manufacturing sectors, as demonstrated by the research gap.

The knowledge gained from the literature review was used in conjunction with quality tools to perform an in-depth analysis of the problem in a manufacturing environment, specifically electronics component assembly for the automotive sector.

The main focus of the project is reduction or elimination of scrap through understanding of underlying causes or human error, lessons learned can then be applied across the organisation improving the readiness of the organisation to address production challenges.

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1.0 Introduction

The scope of this project is to evaluate the causes and effects of human error during a manufacturing process and develop robust mechanisms to reduce or eliminate the risks.

Human error is the single largest contributor to scrap costs at laser etch. Incorrectly loaded raw material is undetected at point of failure. Each occurrence of "wrong material" has multiple costs associated with it.

- Direct cost of the raw material (PCB).
- Associated consumption of additional assembly parts (SMD).
- Cost of manufacturing, (labour, and equipment costs, manufacturing time).
- Lost order fulfilments though delays, rescheduling.
- Material shortages through incorrect ERP transactions.

Failure to achieve a right-every-time methodology is a critical point of failure in a multi-stage, high speed manufacturing process.

Occurrences are unpredictable yet occur periodically. This suggest that there may be more than one root-cause, or most likely a systematic failure in the various process steps from raw material storage to consumption.

While steps have been taken to action perceived points of failure, no defined study has been conducted on the process. Current methods have increased the workloads on operations staff, thus efficiency losses have occurred as a by-product of the additional inspection steps.

This document attempts to discover a correlation between existing published works and the issues raised by the core project. The study focused on works that relate to the areas of human error, published between 2005 and 2018, divided into 2 primary elements.

- Human Error – causes, measurements and quality tools to understand occurrences.
- Human Error – changes to product, process and systems design to reduce occurrence.

An analysis of the literature identified several consistent findings.

Errors were related to the fatigue of Operations staff (physical, cognitive, psychological, biomechanical, muscular, emotional, and social).

Initiatives included changes to work practices, providing additional resources to operation staff to help them perform their roles, and awareness training to address changes to process flow.

Many improvements involved training, shared workload, and communications. Research and operations focused on the areas of: a) training and experience, b) communications, c) fatigue, d) Human Machine Interaction (HMI), e) manual detection (poke-yoke).

Significantly the use of newer methodologies, such as participatory ergonomic design, shows promise. The involvement of end-users earlier in product and process design had demonstrated benefits. The use of computer modelling and full-scale mock-ups is an advanced approach that considers the impacts for poor process and product design on the real-world performance of these systems – as factors that affect the risk of human error.

This review concluded that, historically, much research was conducted that explained why Human errors occurred. Similarly, many initiatives were implemented, but the underlying causality was unchanged. There appears to be an acceptance that if humans are involved in a process, human errors are an inevitable result, particularly in manufacturing

environments where shift-work is the norm and fatigue is an accepted consequence of long working hours.

This mind-set will continue to be prevalent until underlying causal dimensions typically associated with human errors are better documented and understood. Fatigue is often cited as a main causal dimension, yet current process and product design mythologies underestimate the impacts of poor design on being a contributor to fatigue and the incidence of human error occurrence.

The information and knowledge gained from the literature review was adapted to attempt and understand the faults within the production facility. Specifically the ideas around measuring and assessing the risks of human error in a process and how to work with this. The literature review findings are therefore a stepping stone to increased knowledge of problems, causes and solutions for this real-world problem, and will form part of a toolset for future studies.

2.0 Literature review:

The text presented here is a review of a body of work dealing with the areas of human error, causes and effects.

Four initial questions were addressed in this study:

1. Is there a body of research established in the areas of human error in production?
2. Can the contributing factors for human error be defined or categorised?
3. What are the main effects or consequences of human error?
4. How is human error evaluated and integrated to a manufacturing environment?

For the purpose of this study 3 main research databases were chosen;
Emerald, Research Gate and Science Direct.

A search for suitable papers was conducted on each of the databases using the following keywords: (both single string and joined searches)

"Human error", "Human reliability", "Error proofing", "Risk assessment", "Quality", "Manufacturing", "Electronics", "Automotive", "Assembly", "Error probability", "Ergonomics".

The search took place in October/November 2019, for papers published after 2008. Only articles where the full text was available were included, where necessary the papers were requested from the authors.

Suitable papers were then downloaded where possible or stored in the online document repositories, before a more detailed reading occurred to assess how the documents met the questions outlined above. Papers that failed, or inadequately answered question 2, 3 & 4 were subsequently excluded. This stage involved the reading of the full text, or as much as was required to form an opinion on its eligibility. In a number of cases older papers were cited, where specific papers were cited on more than one occasion the original paper was accessed (if available), and assessed to determine relevance. Thus there are papers from before 2008 that are also included.

Each of the remaining papers was read in full, the key points were noted. These points, and the paper as a whole were categorised into the following broad divisions.

- State of the art – Historical approaches – Current approaches.
- Do the papers conclude a link between quality and human error?
- Do the papers conclude a link between product/process design and human error?
- Do the papers discuss a measurement methodology to assess risk factors?
- Do the papers propose methods or techniques to reduce human error?

The final selection of papers form the basis of this review.

2.1 Human Error: State of the art.

Across almost all areas of manufacturing there are still many tasks that have yet to be automated. While automation is certainly replacing human effort in many areas *humans are an essential part of operations systems that are difficult to replicate (unlike technology) and hence improving their performance could eventually lead to sustainably competitive operations systems (Ahmad and Schroeder,2003; Onyema, 2014*).

Understanding human error is therefore a key consideration when processes are being developed. Failure to correctly identify and mitigate against the key failures associated with human (manual) actions and activities, as well as failure to systematically eliminate or reduce the environmental factors that contribute to human errors may lead to an unstable process, with an increased incidence of quality related defects.

Much effort has been devoted to the areas of ergonomics, the primary focus has been Human Resource centred; specifically in optimising productivity (throughput), reducing headcounts, and maintaining a safe working environment. *There is a whole discipline of Human Factors (HF) (to be considered as synonymous with Ergonomics), which is devoted to optimizing the design of the human-system interaction to improve system performance and operator wellbeing (IEA, 2014).*

While laudable, this strict application of ergonomic principles has not translated in the realms of human-proof engineering. There is a dearth of research from the engineering community and this *discipline has not been widely attended to in engineering and management research literatures (Dul et al., 2012).*

A possible explanation for this is that historically Human Resource lead ergonomic policies were primarily concerned with health and safety. Dul and Neumann, 2009, cite a prior review of 97 business and management journals, *93% of the journals had no human factor contributions at all (Dul,2003)*. *Thus the strategic potential of ergonomics has not been widely considered at the company level in either research or practice (Dul and Neumann, 2009).*

More recent studies, and indeed advances in technologies have necessitated a re-think on the roles human play in processes. The impacts of human factors in production engineering is now being studied more frequently. An area of process mapping and analysis focusing on the specific impacts of humans is developing as illustrated below in Figure 2.1.

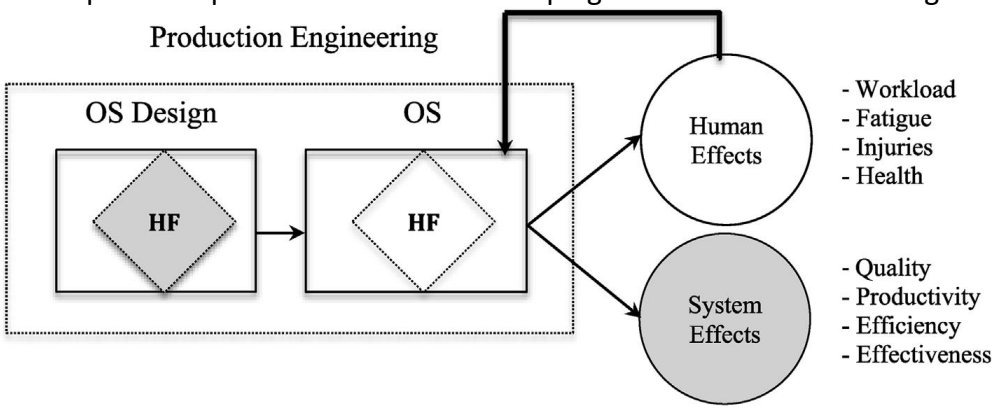


Fig. 2.1. A framework illustrating how HF within the OS have both human and system effects (adapted from Rose et al., 2013).

Fig. 1 illustrates a cascade of design and management choices that ultimately determine the mental and physical demands on the system operator. The effects of these demands can include learning and competency, or fatigue, discomfort and injury. These human effects will

have a feedback effect on operator performance in the next cycle of production. If the Human Factors are not attended to in the Operations System design and management decisions, then a negative spiral can occur. (Kolus, Wells, Neumann, 2018)

2.2 Human Error: Impacts to Quality.

The volume of research focusing on the effects on quality by human error is immense, specifically where operation systems and/or ergonomics are seen as contributors to the causes of human error, and by extension contributors to the actual quality reduction.

The bulk of research, and tools developed from research, has by-and-large been conducted within the sectors of Aeronautics, Nuclear, Petro-Chemical and Nuclear industries. All, high risk sectors, where failures could have catastrophic results. Many of the current quality tools were developed as a response to problems in these sectors, although other industries, particularly automotive and electronics manufacturing have refined these tools for specific requirements.

Perhaps the most significant tool, and one which is the subject of considerable research is HP-FMEA – Human Process - Failure Mode and Effects Analysis, routinely used in the Aeronautical sectors and most strikingly used during the NASA space program.

Mei et al, (2008), conducted a review on HP-FMEA details for a single aspect of the space program. Their research concluded that the analysis of human error during the FMEA process *makes an outstanding contribution to system safety.* Detailed analysis of the process steps found that over 5,000 potential human errors were identified – including 280 defined as “serious”.

Decomposing each task into a series of reduced instruction sets mitigates the risks, as human interaction is defined and limited – to the specific task at hand. Regular inspection steps ensure the any errors are detected earlier in process. Thus, simplification of the actual human efforts reduces the overall impact of errors as each step is treated as a sub-process. The process flow must be logical and sequential, with a continuous combination of task steps that flow from step to step. Human work steps should follow the required sequence, incorrect sequence would lead to an error. Task decomposition must therefore make absolutely clear the relationships between each step and the influences between each event, (Figure. 2.2). The focus and attention given to defining, mitigation and inspection clearly demonstrates the impacts of Human Error on Quality.

Task Decomposition Task Objectives: Human-Machine Interface: Filled By: Date:		
Task Steps	Input	Output
Step 1		
Step 1.1		
Step 1.1.1		
…		
Step 1.2		
…		
Step 2		
Step 3		
…		

Fig. 2.2. Task Decomposition example.

2.3 Human Error: Product / Process design as a contributor.

Process system flow and design is a focus of research by *Kolus, Wells, Neumann, (2018), which builds on previous research by Neumann and Medbo (2009, 2016), Givi et al., (2015), Di Pasquale et al., (2015).* The underlying causal factors are examined by probing 3 research question.

- *Is there a relationship between human factors and quality performance in operations?*
- *What are the human factor design characteristics that may cause poor quality?*
- *Is there a relationship between human effects (e.g., fatigue) and quality performance? (Kolus, Wells, Neumann, 2018)*

During their research it was found that the highest percentage of published papers were concerned with the automotive (26%) and electronics (20%) industries.

Both of these industries have undergone immense technological changes, where miniaturisation, automation, increased competition and cost reductions have driven major improvements in production metrics, and an overall improvement in quality metrics. However the same production improvements may not have been adequately designed to factor in the human elements in the process chain, thus the higher number of research papers to address the issue encountered.

The deep-level analysis concluded that significant quality risk factors were attributed to human factors.

A breakdown into four key groupings of Product – Process – Workstation – Individual identified the associated human factors. (Table 2.1)

Category of QRF	QRF	Description of QRF
Product	Load	Load in physically exerting tasks (e.g. posture)
	Difficulty	Task difficulty (e.g. visibility)
	Task characteristics	Factors related to task (e.g. static vs. dynamic work)
	Complexity	Knowledge demanding, memory intensive and many choice options (e.g. no. of components in assembly)
Process	Instructions	Work procedure (e.g. method of inspection)
	Management	Managerial activities and policies (e.g. waging policy)
	Training	Training programs and certificates (e.g. training for a specific technique)
	Time/pace	Factors related to time or work pace (e.g. rest time)
	Relations	Relations between stakeholders (e.g. relation between workers and management)
	Production	Type of production system (e.g. batch production)
Workstation	Tools	Types and features of tools (e.g. weight of tools)
	Space/search	Factors related to work space and layout (e.g. worker movement)
	Conditions	Work environment (e.g. illumination)
Individual	Professional	Professional factors of individuals (e.g. skills)
	Personal	Personal factors of individuals (e.g. age)

Table. 2.1. A description of identified Quality Risk Factors (Kolus, Well, Neumann, 2018).

Two types of human effects were identified in the analysis: workload and/or fatigue. Results showed that there is an association between Quality Risk Factor and workload, namely physical, cognitive, psychological, biomechanical, muscular, cardiovascular, emotional, and social (as reported in the studies).

Physical workload was the most frequently identified effect, followed by psychological and muscular workload. Thirty-four Risk Factors were identified as increasing physical workload in (of which 14 belong to product design, 10 to workstation design, 9 to process design and 1 to individual factors). Results indicated that physical workload in manufacturing was associated with load, difficulty, task characteristics, tools and space about 70% of the time. The increase in muscular workload was associated with load, task characteristics, tools, space/reach and management 100% of the time. In addition, biomechanical and cardiovascular workloads were solely associated with product-related Risk Factors (i.e., load and task characteristics), while social workload was associated with

process-related Risk Factors. Psychological workload was associated with 17 Risk Factors of which management, load, difficulty, task characteristics and tools accounted for 69%.

Results also showed that there is an association between Quality Risk Factor and fatigue. The increased risk of fatigue in manufacturing was accounted for by 46 Risk Factors of which 57% were not associated with a specific type of fatigue. Visual fatigue was associated with 11, among which task difficulty, inappropriate time/pace and tools constituted 82%. Muscle fatigue was equally associated with load, tools and space. In addition, results indicated that poor instructions and work procedures might increase risks of physical and mental fatigue. It is worth mentioning that a linkage between workload, a fatigue precursor, and poor quality was identified. High physical and psychological workloads were associated with poor quality in about 26% and 12% of the studies, respectively. *(Kolus, Wells, Neumann, 2018)*

Delving further into the reported quality failures there is evidence that while "*Human Error*" is the defining mode of failure there is correlation between the occurrences of a failure and key groupings of Product – Process – Workstation – Individual. The study, based on the reports of numerous other studies found that *the majority of the reported factors impacting quality were related to process design (37%) followed by product design (27%). Similarly, factors causing work errors were ranked as factors related to product design (36%) followed by process design (32%). (Kolus, Wells, Neumann, 2018)*

2.4 Human Error: Categorical and Quantitative measures.

Much research focuses on the underlying causes of human error, as discussed above. A second strand of research focuses on the understanding of these different types of human errors, with a view to categorisation and quantifying. Significant work by Nakajo T, Kume H. (1985) and expanded on by Sondermann JP. (2013) continues to form the basic taxonomies for human error understanding. However, before beginning to work with the breakdown of human errors it is important for research to agree on a methodology for assessments.

The German standard VDI 4006: Human reliability - Methods for quantitative assessment of human reliability offers a consistent approach.

Böllhoff et al. (2016) reference the VDI standard for human error probability as the: *"Capability of human beings to complete a task under given conditions within a defined period of time and within the acceptance limits", whereas an error is a "human action which exceeds the defined acceptance limits". Accordingly, the human error probability (HEP) and human reliability probability (HRP) are indicators for the relative occurrence of errors and respectively faultless actions and defined as:*

$$HEP = \frac{number\ of\ observed\ errors}{number\ of\ the\ possibilities\ for\ an\ error} = \frac{n}{N}$$

$$HRP = 1 - HEP$$

As with any formulaic discussion the quality and veracity of the inputs determine the outputs. Therefor in any study due regard to data clarity and integrity must be measured. *One major issue with the quantitative evaluation of human error is the availability of reliable data. They can for example be determined via field study, experiment, statistics, and*

estimation by experts or interviews. Generally, data which has been derived from measurements should be preferred over subjective estimations. Böllhoff et al. (2016)

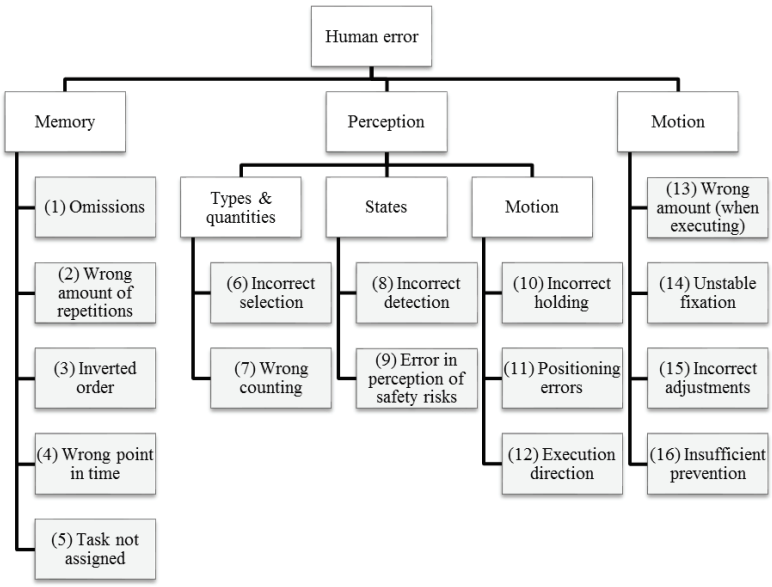


Fig. 2.3. Classification of human error according to Nakajo T, Kume H. (1985), Sondermann JP. (2013)

Using the taxonomy chart above the key findings for this project is that the identified problems in the current process are present in each of the core classifications of Memory, Perception and Motion. Thus similarities may be present in the researched solution proposals and the solutions developed for this project. Of specific interest are both the use of Poke-Yoke as a preventative measure and improved detection rates at the non-critical beginning of the process.

2.5 Human Error: Efforts to reduce occurrences.

A study by Sundin et al. (2004) explores the use of computer based simulations to understand the assembly process in the automotive manufacturing business. The aim of the study was to understand how product design and specifications, coupled with existing workplace ergonomics contributed to the final assembly times. This study found that poor ergonomics, reach, stretch and obscureness occurred due to product design and process design. *The conclusion is that a different participatory ergonomics approach, termed participatory ergonomics design, PED, has a potential for facilitating communication and co-operation.* Sundin et al. (2004)

However the use of computer modelling is secondary to the inclusive elements of the PED approach. The involvement of product and process engineers from the different manufacturing plants, as well as the involvement of experience production operators in mock-up simulations was influencing in the final product and process designs. *The approach has a potential to improve assembly productivity and ergonomics and offer a better understanding among product designers and production engineers in product development processes.* Sundin et al. (2004)

Participatory ergonomics in the workplace is not a new occurrence, but historically it was been restricted to end-users (operators) trying to improve their existing workspaces – after the workspaces and process have been designed and implemented – by definition a

retrospective involvement. *Nagamachi(1995) states that participatory ergonomics ''is the workers' active involvement in implementing ergonomics knowledge and procedures in their workplace''. According to Nagamachi, participatory ergonomics starts by organising a project team to solve ergonomic problems in workplaces.*

Wilson and Haines (1998) further say that the definition, at its most basic, consists of 'stakeholders' contributing to an ergonomics initiative or sharing ergonomics knowledge and methods. They also say that 'stakeholders' are a broader category than 'workers', including anyone affected by the process or consequent change.

However, not all persons involved are affected by the process or consequent change; they are instead affecting a change. (Wilson, J.R., Haines, H.M., 1998)

From the study conducted at the Volvo manufacturing plant, and specifically with the inputs from the end-users (Assembly operators) design changes were introduced. *Design changes decreased assembly times, work related physical stress among the workers and the amount of corrective rework otherwise necessary in several operations. Sundin et al. (2004)*

What these studies show is that where there is an active engagement with the end users, process or product improvements reduce the likelihood of the underlying causes of human error. Production process or product changes that result in less fatigue, stress and or ergonomic issues for operators result in greater quality and efficiency. The report also cites improvements in production efficiencies. *In the body plant only, materials handling and rework time were estimated by the company to show a reduction by 10–15%.*

Additionally the study found that *future assembly problems were detected early, deeply involving the design department in the participatory ergonomics process, leading to a more effective and ergonomic production system. Sundin et al. (2004)*

The recommendations of the study are demonstrated by the illustration below:

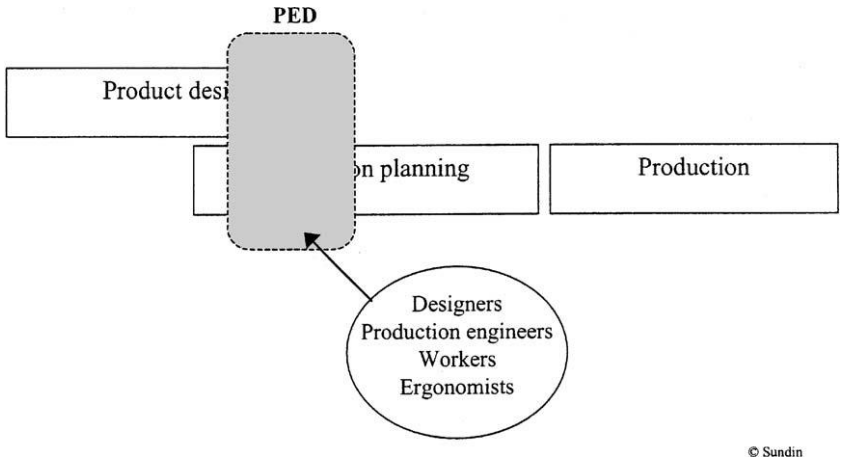


Fig. 2.4. Participatory ergonomics design, PED, as carried out in the case study described. Sundin et al. (2004)

A robust Participatory Ergonomics Process in the Pre-production phase can encapsulate any required changes to product design and production planning elements – before any detected problems are committed to production.

3.0 Literature Review Conclusion:

The conclusion from this review is that the initial questions posed at the beginning of this paper have been satisfied.

- A body of research exists in the areas of human error in production.
- Contributing factors for human error can be defined or categorised.
- The main effects or consequences of human error have been documented.
- Human error is evaluated and integrated to a manufacturing environment.

Furthermore the conclusion must be that analysis, understanding and accurate reporting of the process and its failures is an important first step in developing solutions to manage, reduce or eliminate the occurrence of incorrectly loaded raw material. Similarly developing engineering solutions to detect any errors that may occur is an attempt to contain the point of failure to a low-impact position in the process.

This approach fits well with the overall aim of the project.

Accurate reporting of the actual costs associated with the problems of incorrectly loaded material have highlighted the severity of the problem. Thus the impacts to quality have been examined.

Analysis of the existing process using activity studies, activity mappings and process maps has defined the areas where human errors can occur. Study found that multiple material movements are required to move raw material from warehouse to point of use – and a risk of error is present at each of these points. The solution, ordinarily, would be to reduce this to a single step, where material is booked directly from warehouse to point of use. However, cleanroom protocol prevents the unpacking of material in production, so a staging area and associated movements must be maintained. Therefore reducing the material being unpacked, by using an electronic KANBAN system is one of the proposals being considered. This analysis confirms that the current process as being a contributor to the root cause of the problem.

Equally, acceptance that errors may occur, and communicating this to the operators has encouraged engagement with the end-users, who in turn have suggested ideas to reduce the risks. The suggestions include non-technical solutions, such as scheduling changes to ensure visually similar materials aren't required sequentially, thus eliminating a potential point of failure. While a valid suggestion it may not be always possible to avoid the scenario thus a robust error detection has also been proposed. Again, the acceptance that the process lends itself to failure is acknowledged and the engagement with staff to propose solutions, albeit retrospectively, is an effort to reduce occurrence.

Finally, using an automated optical inspection system to verify each piece of raw material is a valid solution, the system is a safety net that directly interrupts the process only when a failure occurs. The designed system uses current technologies to supplement the existing human process – it is not a replacement for a human. This again correlates the understanding that as long as humans are involved there is a risk of human error, but technology can consistently detect failures while humans may suffer from fatigue.

4.0 Methodology:

The overall goal of this project is to reduce or eliminate scrap costs using a quality tools based approach to change the current process state to an improved future state. As examined in the Literature review an area of specific focus is how human error is as a result of a poorly designed/specified equipment process, poorly designed material, poorly executed work flow, or poorly trained or motivated personnel.

While human error is a cause of defects, the underlying causality is the critical driver to the actual generation of defects.

4.1 Research Philosophy: Choosing a philosophy.

As this project relates to a specific "real world" problem an overarching philosophy for the research is that the described problem has a measureable root cause and can be reduced or eliminated through analysis of the failure modes. The main research could be described as being positivist or scientific in nature, in the assumption that a data-driven method will lead to an understanding of the actual root cause.

However, as there is also a human-centric element to the research there is also an element of interpretivism to the research philosophy. Namely that the human behaviour must be studied in the as-is condition, to determine the levels of influence that behaviour has on the problem as a whole. Where human error is part of the problem there needs to be a method to define the influence on the problem, this influence may not be readily accessible with a data-centric approach.

A pragmatic approach is therefore the solution. Recognition that a data driven approach will not fully understand the problem and that interpretive influence from the human side is also critical to understanding and eliminating the problem. There must be recognition that no single viewpoint completely covers the problem. This approach can be demonstrated using the illustration below: (Figure 4.1.)

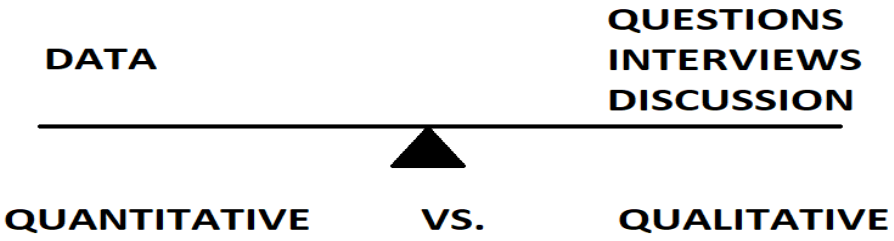


Fig. 4.1. Illustration of pragmatic balanced approach.

Quantitative data taken from the various measurement tools is balanced against the qualitative data from questionnaires, interviews, group sessions and activity work studies. There is an exchange mechanism between these areas, where quantitative data is used to provide a basis for the questions, interviews and meetings, and outputs and ideas from the human interactive aspects may lead to fresh inputs for additional data analyses. (*Figure 4.2.*)

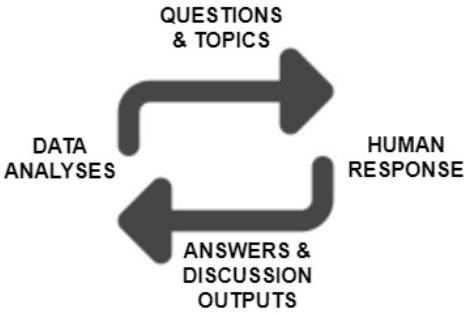


Fig. 4.2. Input Output cycle.

Only when all possible contributions to the problem are analysed can a complete understating exist. It is then more likely that a robust mechanism to completely eliminate the problem can be developed.

4.2 Research Approach: Deductive vs Inductive.

In much the same way as with the research philosophy there is no single approach to completely understand the problem. There is a clear requirement to utilise both deductive and inductive reasoning.

With so much data available an obvious starting point is data analysis. However, as a function of having so much data available, there is a necessity to pre-define a specific area to concentrate on, or develop a hypothesis to attempt to discover a root cause from the available data. In this case there needs to be some induced logic that can be used to initially limit the scope – to reduce the problem down to a smaller size.

For this particular problem the induced logic is that there isn't a systematic failure occurring within the process across ***all*** materials – as the problem isn't equally present on ***all*** products, yet there may-be a common failure present on ***some*** of the materials as evidenced by the problem only occurring on ***some*** products.

The initial induced hypothesis is therefore to determine if failure occurs across ***all*** or ***some*** of the products. As the top-level process is the same for all products, and by extension all materials are treated equally within this process, data-analyses can quickly identify if an ***all*** or ***some*** condition exists for further analyses

The initial data analysis is then more straight-forward.

- **How many unique materials are used by the process? (Quantitative data)**
- **How many of the unique materials has the failure occurred on? (Quantitative data)**

If the results are not equal, as in the problem has not been recorded on all materials, a reasonable determination is that the problem isn't a systematic failure, and that there is an as-yet-unknown underlying causality affecting only the materials identified from the initial data analysis. The initial data analysis is used to either support or disprove the initial hypothesis. Where the analysis result supports the hypothesis the outputs from this analysis, in the form of affected material numbers, can be recorded and used for subsequent detailed analyses to determine why only these particular materials are affected. (Table 4.1. Below)

Material	10053831	10125992	10126618	10128531	10128652	10132262
Occurrence	NO	NO	NO	NO	NO	NO
Material	10132266	12024194	12024701	12033249	12033484	12033511
Occurrence	NO	NO	NO	YES	YES	YES

Table 4.1. Defect occurrence analysis of all PCB types.

As the problem has now been reduced to a smaller data-set the next phase is to again prove or disprove an inductive hypothesis. Again, a large amount of data for this problem exists in the control documents, production reports, production plans and product data. There is a requirement to digest the problem down further.

The hypothesis being tested is if there are patterns present in the occurrences of the problem. Specifically, are there unknown properties within the affected materials that are contributing to the problem?

If so, these properties, once determined, must belong to a sub-set of currently unknown categorical data. Namely Process, Product, Planning, Logistics or Operational variables and parameters within the overall top-level process.

In short this is an exercise in filling in the blanks to remove as many of the unknowns from the current knowledge on actual causality.

The methodology for this is to poll the data using a set of specific queries to output a new data-set with greater details, using the results from the initial analysis as an input to restrict the range. Simply put, for each occurrence of the defect answer the questions and record the answers. (Figure 4.3. Below)

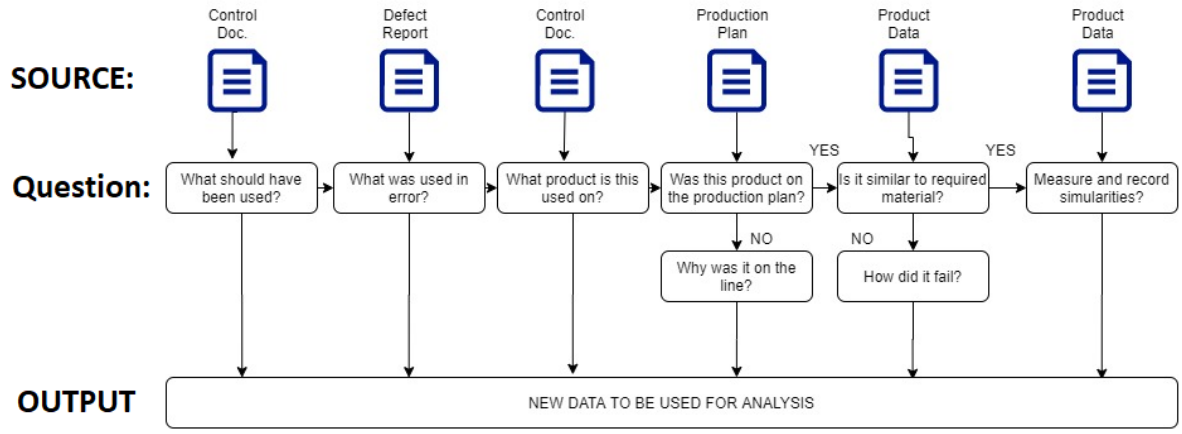


Fig. 4.3. Building blocks for query methodology.

Even at the out-set there is a further element of inductive logic to this; in using quantitative data in the form of records and product data to prove or disprove that patterns might exist. The induced logic is that if patterns exist there may then be an underlying causality that will present itself through further quantitative analysis.

The expectation is that this must be the case, otherwise the problem would manifest itself more regularly across the full portfolio of material and products. In essence the counter-hypothesis, that this is a systematic failure has already been discounted during the previous research step.

The overall research approach can then be described as a combination of deductive and inductive reasoning involving both quantitative and qualitative data, where hypotheses testing using data analyses is the primary (but not only) strategy to understand the problem.

This research approach aligns with the previously determined research philosophy.

4.3 Research Strategy:

Once the research philosophy and approaches have been determined it becomes necessary to identify strategies to gather the required inputs that fulfil the requirements of the chosen approaches.

For the purpose of this project there are 4 main categorises that are considered.

Data Collection, Data Analysis, Research Limitations & Ethical Considerations. (Fig. 4.4)

DATA COLLECTION	DATA ANALYSIS	RESEARCH LIMITATIONS	ETHICAL CONSIDERATIONS
Survey Methods	Quantitative Data Analysis	Absence of Data	Implications of "Blame"
Questionaires	Qualitative Data Analysis	Scope / Depth of Data	Existance of "Blame Culture"
Interviews			
Quantitative Data Collection Methods			
Correlation Analysis			
Regression Analysis			
Qualitative Data Collection Methods			
Case Studies			
Focus Groups			
Observations			
Futures Research.			
Experiments			
Action Research			

Fig.4.4 Project Considerations.

4.3.1 Designing the Survey Questionnaire and Group Meeting:

The questions were determined by several factors that were identified during the initial project analyses. These factors are as follows:

- Are the participants generally aware of the problem?
- Where participants are aware do they have a specific insight into a potential cause of the failure?
- Questions should be related with the main objective of the research i.e. how can we reduce or eliminate the occurrence of the problem?
- An open text box for comments was included in the questionnaire where participants were free to enter anything they wished.
- The questionnaire was kept deliberately short, to encourage completion.

The group meetings were chosen over individual interviews, mostly for operational reasons where it was easier to schedule a single session involving multiple participants. Prior to the meeting the simple questionnaire was circulated to all participants, the results were consolidated and presented at the meeting for discussion – no personal identifiable information was presented.

Details of the group formation and analysis of the outputs is discussed in section **5.3**.

4.3.2 Developing a Framework:

When the initial idea for this project came about it was as a result of my involvement in a defect / problem-solving report following an occurrence of the "wrong PCB loaded" event. Prior to this I had no awareness of the historical occurrences of these events and no ideas of the frequencies or costs involved, despite being the engineer with oversight for the laser etch process. During the team discussion to close out the report the main corrective action was to place additional inspections on the loading point of the raw material, with responsibility assigned to the operations group.

I suggested to the team that this was a simplistic viewpoint, and onerous on the operators who are already tasked with multiple other activities on a high-speed production line. At this point I hypothesised that in order to load "wrong" material that material must have been present at the point of loading to begin with, so a better solution was to ensure that only the "correct" material should be present for the scheduled build.

It was from this discussion that the general framework of this project took shape. This is essentially 3 parts.

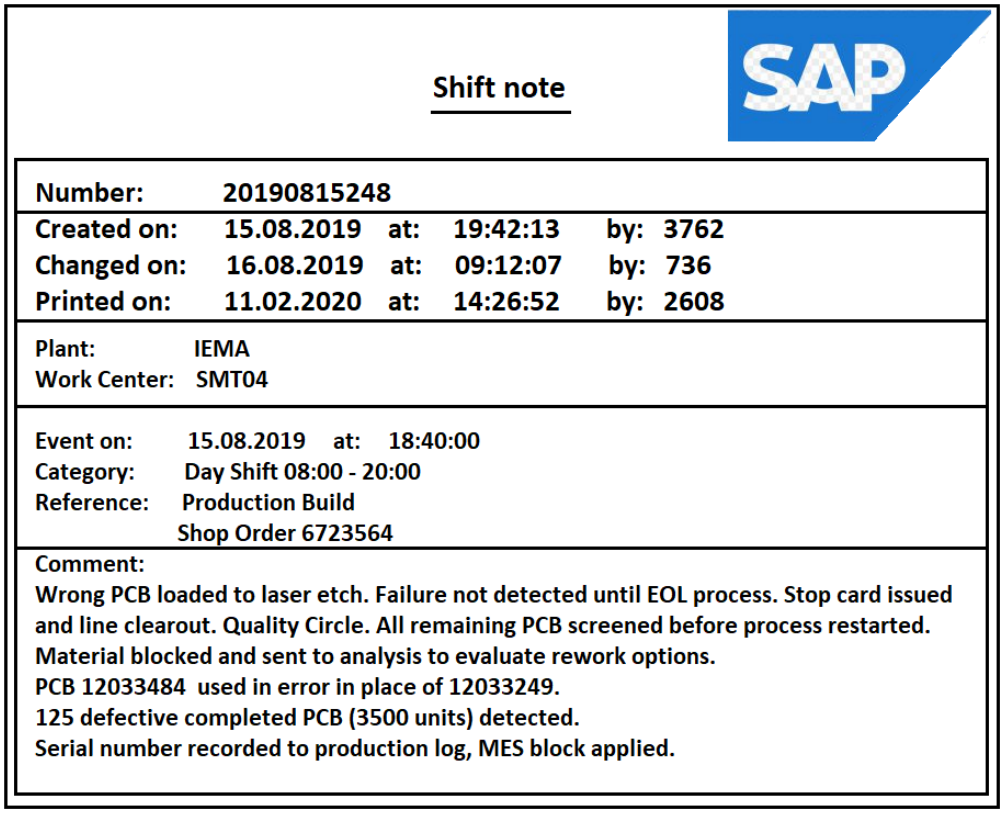
1. Removing the opportunities for loading the "wrong" material is a better solution than putting in additional manual inspections.
2. Where those opportunities can't be removed the production equipment should be capable of automatically detecting the incorrect material by detecting variation in the raw material.
3. Where this can't be currently achieved the engineering change mechanism should be used to redesign the raw material so that the "wrong" material can be detected by the current equipment.

The project method utilises the quality principle of DMAIC, (Define, Measure, Analyse, Improve, Control), to determine the key areas, and as such determine many aspects of the methods used.

- Define: Determine the actual failures occurring and their mode(s).
- Measure: Using previously recorded data, determine the rates of occurrence.
- Analyse: determine if there are common trends across multiple failure modes and or occurrences, with a view to identifying possible root-cause(s).
- Improve: Where a trend / pattern has been determined examine if practical solutions exist and can be implemented. Where possible implement an improvement action.
- Control: Where solutions can be implemented develop a control plan, where a solution is determined, but can't be practically implemented develop a control plan to manage the risks.

4.3.3 Defining the problem:

The top-level failure is reported on an in-house reporting tool. Where an error/problem/defect occurs the production (operation) staff update this record. Where an intervention by a member of the maintenance / engineering groups is involved this record is updated with the actual cause of failures and remedial actions where required. An example of an entry is below: (Figure 4.5)



Shift note

Number:	**20190815248**				
Created on:	**15.08.2019**	**at:**	**19:42:13**	**by:**	**3762**
Changed on:	**16.08.2019**	**at:**	**09:12:07**	**by:**	**736**
Printed on:	**11.02.2020**	**at:**	**14:26:52**	**by:**	**2608**

Plant: IEMA
Work Center: SMT04

Event on: 15.08.2019 at: 18:40:00
Category: Day Shift 08:00 - 20:00
Reference: Production Build
Shop Order 6723564

Comment:
Wrong PCB loaded to laser etch. Failure not detected until EOL process. Stop card issued and line clearout. Quality Circle. All remaining PCB screened before process restarted. Material blocked and sent to analysis to evaluate rework options.
PCB 12033484 used in error in place of 12033249.
125 defective completed PCB (3500 units) detected.
Serial number recorded to production log, MES block applied.

Fig. 4.5. Detail of Shift report entry.

Thus, this record forms a body of knowledge on failures, as well as a record of occurrences.

The categorisation of failure can be summarised as; “Wrong PCB loaded”.

Now that the top-level failure has been defined an initial examination was conducted into the variability within this category, with a view to expanding this topic so that production metrics could be linked, as required for the next “measurement” phase. The input data is taken from the raw production log, and cross referenced against the affected raw material number. The data is presented in the table 1 below, colourised to present raw material that had occurrence(s) of a failure (shaded) vs raw material that had no occurrence (unshaded). (Table 4.2)

Material	10053831	10125992	10126618	10128531	10128652	10132262
Occurrence	NO	NO	NO	NO	NO	NO
Material	10132266	12024194	12024701	12033249	12033484	12033511
Occurrence	NO	NO	NO	YES	YES	YES

Table 4.2. Defect occurrence analysis of all PCB types.

This data clearly demonstrates that 3 of 12 raw material numbers are involved. With this in mind the problem definition, and scope for additional investigation is more specific. Namely, why have these 3 material numbers an increased risk of being incorrectly used?

4.3.4 Measuring the problem & Statistical Treatment:

With the information gained from the initial analysis the starting point is how often the material numbers of interest were used in production and how often there was an occurrence of "Wrong PCB loaded". In the high speed manufacturing environment batch sizes would regularly be in the 1000's of individual PCB, thus for this measurement the number we are interested is the quantity of batches produced in a specified time period rather than the quantity of individual PCB used to produce those batches.

While this may seem counter-intuitive the logic behind this method is that we are primarily interested in the occurrence patterns, rather than the impacts of those occurrences. Likewise, where there is an occurrence we are less interested, from a human error perspective, on the quantity of incorrect wrong material than on the actual occurrence itself.

As with the table above we are only interested in the data for materials 12033249, 12033484 & 12033511, where occurrences of "Wrong PCB loaded" have been recorded. This data is gathered by cross referencing the product name from the shift report data with the raw material number from the bill of materials (BOM) and joining this result set to the material movement history from SAP.

This analysis of historical performance is taken as a baseline measurement of how the process is performing. Using the formula for calculating the effect of Human error gathered during the literature review it is possible to put a value on the problem. (Figure 4.6.)

Böllhoff et al. (2016) reference the VDI standard for human error probability as the: *"Capability of human beings to complete a task under given conditions within a defined period of time and within the acceptance limits", whereas an error is a "human action which exceeds the defined acceptance limits". Accordingly, the human error probability (HEP) and human reliability probability (HRP) are indicators for the relative occurrence of errors and respectively faultless actions and defined as:*

$$HEP = \frac{number\ of\ observed\ errors}{number\ of\ the\ possibilities\ for\ an\ error} = \frac{n}{N}$$

$$HRP = 1 - HEP$$

Fig. 4.6. HEP definition and calculation steps.

From the production logs for the previous 20 weeks there were 142 production builds where any of the 3 suspected materials were required. Using this as input to the formula we can see that there is a 4.9% risk of an error occurring, this will be further discussed in the results. Now that the baseline is known any efforts to resolve the problem can therefore be measured against the initial value, to measure the effectiveness.

4.3.5 Analysing the problem:

With the information available from the electronic production records, SAP history, and the inputs from the questionnaire and interviews the next phase is analysis. The quantitative data can be logically analysed, and the qualitative inputs can be categorised and weighted to assign a "value" to them. These inputs will form the final overall view of the problem. The results of this analysis and the subsequent "Improve" and "Control" elements will be presented in the results in Chapter 5.

4.4 Time Horizon:

As the project relates specifically to a randomly occurring event the study examines similar events over an extended time frame. Thus while each of the occurrences is independent, and could be seen as a cross sectional study at a specific time, the project proper is longitudinal in nature, in order to capture the event patterns, with a view to eliminating the underlying causes.

5.0 Analysis of the problem (Identifying probable root causes):

The findings of this project are discussed in the following sections, beginning with the results of the data analysis, followed by the finding of the interviews and questionnaires. The final section brings both quantitative and qualitative inputs together to demonstrate that there was a connection between the independent inputs that only became evident when a formal project was conducted. This forms the basis for the improvements, the results of which are discussed in the section **6.0**.

5.1 Quantitative Analysis of production data:

As discussed previously the problem of "Wrong PCB Loaded" does not occur on all the raw material on the production line. It is limited to 3 specific blank PCB panels. The production logs (Shift reports) were referenced for number of occurrences of the failure. The details of the initial data analyses is below. (Table 5.1)

Material	12033249	12033484	12033511
Occurrences	4	2	1

Table 5.1. Defect occurrence on affected PCB Types.

The next stage cross referenced these 7 individual occurrences against the production logs, production plans and product matrix to add detail to the table below. (Table 5.2.)

#	Expect	Actual	Product	On Plan?	Similar Size?	PCB X	PCB Y	Fid1 X/Y	Fid2	Visually Similar?
1	12033249	12033484	RLS "B"	YES	YES	278	215	273/209.9	4/5.1	Indiscernible
2	12033249	12033484	RLS "B"	YES	YES	278	215	273/209.9	4/5.1	Indiscernible
3	12033249	12033484	RLS "B"	YES	YES	278	215	273/209.9	4/5.1	Indiscernible
4	12033249	12033484	RLS "B"	YES	YES	278	215	273/209.9	4/5.1	Indiscernible
5	12033484	12033249	RLS "A"	YES	YES	278	215	273/209.9	4/5.1	Indiscernible
6	12033484	12033249	RLS "A"	YES	YES	278	215	273/209.9	4/5.1	Indiscernible
7	12033511	12033484	RLS "B"	YES	YES	278	215	273/209.9	4/5.1	Different Etch Position

Table 5.2. Expanded details from data analysis.

The result of this led to the following findings.

- PCB 12033484 (RLS "B") was used in error for each of the occurrences where PCB12033249 (RLS "A") should have been used.
- PCB 12033249 (RLS "A") was used in error for each of the occurrences where PCB 12033484 (RLS "B") should have been used.
- PCB 12033484 (RLS "B") was used in error for the single occurrence where PCB 12033511 (RLS "C") should have been used.

As discussed in **4.3.5** the measurement and statistical treatments of the problem can be used to develop an understanding of potential root causes. Exploring the data from the shift reports and transaction logs we can see a clear picture developing, namely that PCB types "A" and "B" contribute to the bulk of the problem. (Fig 5.1)

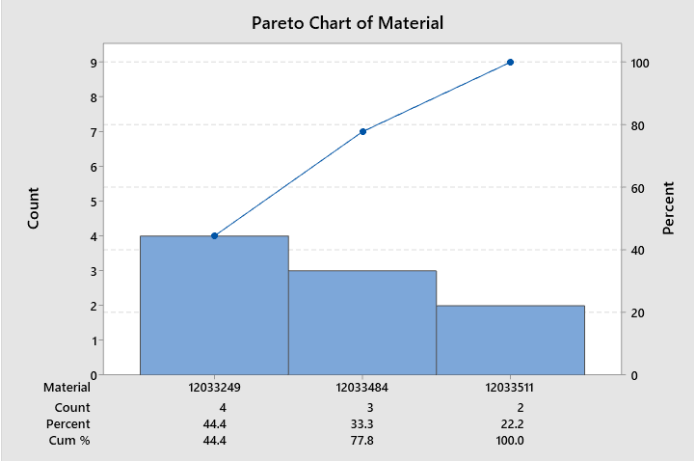


Fig 5.1. Defect analysis graph.

To determine the risk assessment for each of the 3 PCB types the individual error factor (HEP) is calculated, again the source for the input data is the production logs and transaction details. In this instance the number of possibilities for error (PE) is the number of builds planned for each individual PCB type while the observed error (OE) is the total that a wrong PCB was used. As PCB type "C" 12033511 was never used incorrectly its OE is 0. (Table 5.3)

Material	Possibilities for error (PE)	Observed Errors (OE)	HEP (%)
12033249 (A)	79	4	5.1%
12033484 (B)	58	3	5.2%
12033511 (C)	5	0	0.0%
Total	142	7	4.9%

Table 5.3. HEP Score – Baseline.

This information clearly demonstrates that the risk is very similar when PCB "A" and "B" are involved, but not present when "C" is involved. This then points to a suspicion that a possible influencer over error probability may be any differences or similarities between the different raw materials. We can then look for details as to why there is an increases in occurrences between PCB types "A" and "B", but not type "C". Reviewing the analysis of measurement data, taken from the PCB specifications we find the below.

- All 3 PCB as exactly the same in size (X, Y) and have the same alignment fiducial positions.
- The only distinguishing feature that visually stands out is the difference in etch position between 12033511 (PCB "C") and both 12033484 (PCB "A") & 12033484 (PCB "B"). This visual difference could be sufficient to explain why PCB "C" has not been used in error.

In real terms PCB type "A" and "B" are so visually similar that the risk of an error involving either is significantly higher, and as the data shows, statistically similar in terms of probability.

However, this isn't the only contributing factor. The incidence rates match where the "wrong" PCB type is scheduled for a build on the production plan and the same time as the "right" PCB type.

- In 7/7 (100%) occurrences the incorrectly loaded PCB was physically present on the production line, as it was required for a subsequent build.

This would lend support to the initial observation as outlined in **4.3.2**, namely removal of the risk of loading a wrong material by not having the wrong material present at the point of loading to begin with. While this observation may be valid there needs to be a support in statistical terms that would demonstrate if it is feasible to suggest this as an improvement, as it would have a significant impact on production if this were the only valid outcome.

Further data analyses to look for trends is possible by once again referencing the error occurrences against the build plans and transaction records and recalculating the HEP values on a week-by-week basis, for 20 weeks of historical data. (Table 5.4 below.)

Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Total
Builds (PE)	6	4	11	7	7	10	6	7	6	11	0	5	3	12	12	12	0	6	11	6	142
Errors (OE)	0	0	1	1	0	1	0	0	0	1	0	0	0	1	0	1	0	0	1	0	7
HEP %	0.0%	0.0%	9.1%	14.3%	0.0%	10.0%	0.0%	0.0%	0.0%	9.1%	0.0%	0.0%	0.0%	8.3%	0.0%	8.3%	0.0%	0.0%	9.1%	0.0%	4.9%

Table 5.4. Weekly HEP Score – Baseline.

This shows that the error occurrence and HEP score is directly linked to build sizes. Almost all errors occur where the number of different products (builds) is 10 or more, there are two notable exceptions, where a build size is 7 and an error occurred and a build size of 12 (Week15) where no error occurred. (Table 5.5 below.)

Week	3	4	6	10	14	16	19
Builds (PE)	11	7	10	11	12	12	11
Errors (OE)	1	1	1	1	1	1	1
HEP %	9.1%	14.3%	10.0%	9.1%	8.3%	8.3%	9.1%

Table 5.5. HEP Score / Build sizes.

While this data is certainly relevant there is an additional requirement for analysis of the actual raw material requirements week-by-week. The question being posed is if there is any correlation between the error occurrence and a build schedule that involves different raw material numbers, specifically PCB types "A" and "B". (Table 5.6)

Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
12033249 (A)	6	0	7	4	5	6	0	6	4	6	0	4	0	6	7	7	0	4	7	4
12033484 (B)	0	3	4	2	2	3	6	0	2	4	0	0	3	5	5	4	0	1	4	1
12033511 (C)	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1
Total	6	4	11	7	7	10	6	7	6	11	0	5	3	12	12	12	0	6	11	6
Errors	0	0	1	1	0	1	0	0	0	1	0	0	0	1	0	1	0	0	1	0

Table 5.6. Correlation of mixed schedules to HEP Score.

From the table above the following conclusions can now be formed.

*note there were 2 weeks where no builds occurred so total are expressed as "n" of 18.

- Each error occurrence corresponds with a schedule where PCB "A" and "B" were present on the line. (7 of 18)(Grey)

- When either PCB “A” or “B” are exclusively used there was no error (6 of 18) (Green)
- In 5 of 18 weeks, there were no errors but PCB “A” and “B” were in use – scheduling is now the next point to investigate. (Yellow)

Production scheduling is dependent on 3 main factors.

1. Customer Orders.
2. Material Availability.
3. Equipment Availability.

Analysing the data shows the following:

- Where an error occurred there were customer orders, material and equipment was available, so all builds were scheduled to run continuously. (Grey)
- Where PCB types were exclusive there were no orders for the absent PCB type, yet material and equipment were available. The material issued to the line was only for the orders required. (Green)
- For weeks 5,9 and 18 there were material supply problems which meant the builds were split with a number of days between type “A” and “B”. (Yellow)
- The remaining weeks, 15 and 20, there were no material or equipment issues, however the build data shows that the builds occurred days apart. This was due to late orders after the initial builds were completed. (Yellow)

5.2 Conclusion of Quantitative Analysis of production data:

The conclusion of the quantitative data analysis can therefore be condensed into the following core points.

1. PCB types “A” and “B” are so similar as to have a high probability of getting mixed up.
2. Schedules where types “A” and “B” are consecutive have an increased probability of error if material is present on the line.
3. There is no current detection method to reliable identify Type “A” and “B”.

The recommendation for improvements must therefore address these identified risks.

1. Where possible the production schedule should not have PCB types “A” and “B” as consecutive builds – to ensure that the material isn’t on the line.
2. Utilise the engineering change mechanism to change a fiducial position, or add a visual aid to correctly identify (detect) the different PCB types so that each PCB type is different.
3. Investigate if an opportunity exists to use the current automated vision technology to detect any visual differences, currently or implemented under engineering change.

5.3 Qualitative Analysis from Questionnaire and Meeting:

For the qualitative analysis, a group meeting was conducted with production operators (6), technical support staff (2), operation planners (1) and PCB designers (1). The meeting gave insights into the practical aspects of the potential causes of human error, and occasionally an insight into where improvements may (or may not) be realised.

Various types of interview methods were considered in order to collect the data. For operational reasons I have chosen to use a group session, where the general topic was introduced in advance of the group meeting to all participants, and they were asked to complete a simple questionnaire. Thus the meeting itself was problem-centric, where the quantitative statistical data was presented during the meeting. In essence the statistical data was used to trigger a discussion and/or to add insight to a hypotheses.

In most cases the additional supporting data such as technical details or PCB and process design, and production history was readily available from the existing electronic sources, so where a specific comment or question arose the data could be discussed / analysed in real-time.

Each participant was informed of the specific problem, “wrong PCB loaded”, and their response to the question sets were recorded. These inputs were then correlated into a single document and presented to the larger group for discussion during the group meeting. The output from this group discussion then became a driver for developing solutions. The simple questionnaire is shown below, (Figure 5.2).

Q1	Are you aware of the wrong PCB issue on RLS products?	YES	NO
Q2	If you answered "YES" to Q1, do you have any suggestions why the problem is occuring? (If YES Enter details in the area below)	YES	NO
Q3	For Q2, if you had a suggestion did you previously discuss this with your Supervisor / Lead?	YES	NO
Q4	If YES, was your discussion acted upon? (Enter details below for either answer)	YES	NO
Q5	Now that you have been informed that there is a problem do you have any suggestions why the problem is occuring? (Ignore if you answered above)	YES	NO

Fig. 5.2. Sample Questionnaire.

The questionnaire was distributed to all of the production operators (12) and technical support staff (4), however as the production facility operates on a shift pattern the meeting couldn’t be scheduled to include all respondents, and the responses to the questions were recorded and presented to the reduced group.

No member of a management / supervisory team was present at the meeting, as they are not directly involved in any aspect of the process, this also had the effect of the meeting being less formal.

5.3.1 Analysis of Questionnaire:

The distribution and completion rates of the questionnaire is as below: (Table 5.7.)

Group	Operators	Technician	Planners	Design	Total
OUT	12	4	2	1	19
IN	11	4	1	1	17
%	92%	100%	50%	100%	89%

Table 5.7 Questionnaire completion.

The lack of response was because of illness in the case of the operator and one member of the planning group has no input into the production process in question so wasn't released for involvement by his manager. The results of the YES/NO questions is below. (Table 5.8)

Group	Operators	Technician	Planners	Design	Total
Q1 YES	11	4	0	0	15
%	100%	100%	0	0	88%
Q2 YES	7	4			11
%	64%	100%			73%
Q3 YES	3	1			4
%	43%	25%			36%
Q4 YES	3	1			4
%	100%	100%			100%
Q5 YES			1	1	2
%			100%	100%	100%

Table 5.8. Analysis of Questionnaire results.

This clearly shows that the staff who are directly involved in the production process, operators and technicians, are all aware of the problem (Q1), and more importantly almost 75% of this group have suggestions as why the problem occurs (Q2).

Interestingly of the number who have suggestions as to root causes only 36% escalated to their supervisors (Q3), this would be a concern. Reassuringly in all cases where an escalation occurred the inputs were acted on (Q4), this suggest that the existing escalation process does function – when utilised, an aim should be to increase the willingness to escalate, by reporting that actions are taken.

Another significant take-away from the responses is that the planner and designer were not initially aware of the problem (Q1), but can offer suggestions once the issue was highlighted (Q5), even before the statistical data was presented at the meeting.

For the open text fields, particularly for Q2 and Q5; suggestions on why the problem is occurring, the responses were very similar, see fig X.X below for summary of response themes, categorised into technical / non-technical groupings. (Table 5.9.)

Group	Summary	Theme	Tech/Non-Tech
Operator	Batch Sizes too big, too much material on line	Planning	Non-Technical
Operator	Mixed Builds planned on same schedule, different raw material present at same time.	Planning	Non-Technical
Operator	Boards are too similar, we can't always tell them apart.	Product Design	Technical
Operator	Boards are too similar, we can't check all in time due to being busy.	Process Design	Technical
Operator	Why can't the machine check them, hasn't it a camera for fiducials, can this be used?	Process Design	Technical
Technician	Machine can't detect differences as PCB are the same, can we get the PCB redesigned?	Product Design	Technical
Technician	Different raw material present at same time, can we use just in time to order the correct material?	Process Design	Technical
Planner	All the boards look the same to me, I can see if we can split the build to separate based on raw material?	Planning	Non-Technical
Planner	We can see about setting the raw material up on SAP to book directly to the line under the build shop order.	Process Design	Technical
Designer	I can raise an ECO to put a distinguising mark on the PCB waste area, if the machine could use this?	Product Design	Technical

Table 5.9. Meeting Outputs.

There was a general agreement between these results and the results of the quantitative data analysis. As with the conclusions outlined in **5.2** the feedback from the questionnaires can be summarised as follows:

1. The operators are too busy to adequately inspect all raw material.
2. The raw material PCB are so similar as to present a real risk.
3. Scheduling mixed builds is seen as a problem, there is an understanding that this increases the risks.
4. There is no current detection method to reliable identify the PCBs.

These condensed points were then used during the meeting, to prompt discussion.

5.3.2 Group Meeting:

Once all of the various data was presented there followed a robust discussion on what steps could be taken to resolve the identified risk.

An interesting contribution came from the PCB designer, he hadn't been aware of the problem as it was never escalated to him. Once he received the invite, and was asked to complete the questionnaire he did his own analysis on the PCB designs and identified the similarities between the different materials, and correctly identified this as a risk. His suggestion to raise and ECO was an attempt to rectify this – however he lacked the technical knowledge on the process capabilities, specifically the machine camera system, so was unsure of what would work. He also highlighted that our existing DFM (Design for Manufacturing) process doesn't check for this.

The operators and the planners were interested mostly in the ability to schedule builds so as to remove the risk, and if a just-in-time ordering system was possible. Similarly the planner had not been directly aware of the problem, but had been aware of a series of scrap

events that required him to plan in additional builds, which in turn were responsible for material supply issues.

The technical and engineering representatives concluded that the machine was not capable of detecting the differences in the current PCB designs but would be capable of detecting either fiducial positon changes or a defining marking on the waste area, subject to being in the field of view of the camera, the details of which were provided to the designer.

The summary of the meeting and the questionnaire results discussion can be expressed as below:

1. The production schedule should not have similar PCBs as consecutive builds – to ensure that the material isn't on the line.
2. Get rid of the bulk storage of raw material and allow the Operators to order using just-in-time system.
3. Utilise the engineering change mechanism to change a fiducial position, or add a visual aid to correctly identify (detect) the different PCB types so that each PCB type is different. (Preferably using the machine camera system)
4. Investigate if an opportunity exists to use the current automated vision technology to detect any visual differences implemented under engineering change. (Related to #3 above)

5.4 Conclusion of the Problem Analysis (Inputs for Improvement):

Both quantitative and qualitative analysis point to the similar failures within the overall production system. There are essentially 4 probable root causes and 4 improvement steps required to reduce or eliminate the risks.

However as the ECO mechanism and changes to production schedules and the development of the JIT system all take time there are temporary actions required to address. These temporary actions and the permanent improvements planned are shown below. (Table 5.10.)

Root Cause	**Temporary Action**	**Resp**
Scheduling of similar raw material.	Split builds (Short term Trial)	Planning
PCB too similar to detect differences.	Use offline laser etch to add a feature to PCB.	Mfg Eng. (ME)
Machine can't detect PCB differences.	Program camera to detect feature (test of above)	Mfg Eng. (ME)
Root Cause	**Improvement**	**Resp**
Scheduling of similar raw material	Split builds	Planning
Too much raw material on line	Implement JIT	Process Eng.
PCB too similar to detect differences	Move fiducial and/or add feature.	Design
Machine can't detect PCB differences	Program camera to detect feature.	Mfg Eng. (ME)

Table 5.10. Root Cause – Corrective Actions.

The next section will report on the effectiveness of the solutions implemented, and offer further information on why some proposed improvements weren't implemented.

6.0 Project Results (Analysis of Improvements):

The improvements identified were distributed to the local management team, along with the assigned actions. As the ECO process, and implementation of an electronic JIT system would be high cost activities the proposal was to conduct a lower cost in-house trial to evaluate viability. Similarly management, specifically key sale account managers, expressed concerns about changes to the current scheduling methods.

Consent was received to implement the temporary actions as an initial trial, pending the results of these trials the decision would then be made on the more costly permanent improvement options. No action was taken on the production scheduling (planning) of the day-to-day builds)

1. Utilise an offline laser machine to pre-etch a distinguishing feature onto the PCB waste area – a different position is used for each of the 3 PCB types.
2. Control of the raw material for #1 above by a manual JIT system, all material is blocked in stores, only the correct material is manually transacted and a full traceability record on batch details, each packet of (25) PCB to have external barcode scanned to ensure correct material number in use, prior to loading to the machine (Verified by quality supervision) batch sizes at this point limited to 250 PCB (10 Packs).
3. Boards etched at #1 were repackaged and issued with a new internal barcode before being transacted back into non-blocked stores locations, from where they could be issued directly to the production line, using the existing material ordering system.
4. The newly etched distinguishing feature for the each PCB type was programmed for each of the Laser etch programs (Each PCB type has a unique program) – failure to detect the additional mark results in an immediate process stop, and a warning dialog with visual and audible alarm. The system will also update the machine log with the results of the pass/fail evaluation and record a time stamp. Verification and release of this process was completed by quality engineering.

Table 6.1 (below) shows the action taken and the root cause area it aims to address.

Action	Improvement	Resp
Etch distinguishing mark (offline).	Defines different PCB types. (determins if ECO change is required)	Mfg Eng. (ME)
Manual JIT system / Reduce Batch size.	Evaluate JIT and improve control and traceability.	Planning / Quality
Only allow pre-etched board to line.	Evaluates JIT an improves control of Raw material.	Plannig / Logistics
Machine programmed to detect PCB differences.	Immediate process stop when "wrong" material detected.	Mfg Eng. (ME)

Table 6.1. Summary of Actions.

The actions above were implemented in early October 2019. The initial programming of the offline etch machine took one day, quality release of this process took a further day.

The programming of the newly etched feature took a number of days, particularly optimising the vision (camera) parameters to reliably detect all standards of mark (due to process variation of raw material standard and leaser etch variability). Once programmed a validation process under the control of quality engineering took place. The process involved testing 100 of each of the PCB types under their own program to ensure 100% acceptance, followed by a series of trials where the “wrong” PCB was randomly introduced in a

controlled process to verify that the new vision programme would detect all non-conformances. The results were 100% detection across all variables.

The amended process was then signed off by Manufacturing and Quality engineering. Associated control plans and work instructions were updated to reflect the changes and communicated via the existing distributions to all personal.

In regular production the operators completed their loading tasks without modification, the raw material was dispatched to the production line in the same manner as prior to the trials. The only difference being the material was pre-etched.

Using the same data analysis approach as outlined previously in **5.1** the number of builds and errors was analysed. The error factor was also calculated. The table below illustrates the initial state and the current state after 20weeks of production. (Table 6.2)

Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Total
Initial (PE)	6	4	11	7	7	10	6	7	6	11	0	5	3	12	12	12	0	6	11	6	142
Errors (OE)	0	0	1	1	0	1	0	0	0	1	0	0	0	1	0	1	0	0	1	0	7
HEP %	0.0%	0.0%	9.1%	14.3%	0.0%	10.0%	0.0%	0.0%	0.0%	9.1%	0.0%	0.0%	0.0%	8.3%	0.0%	8.3%	0.0%	0.0%	9.1%	0.0%	4.9%
Trial (PE)	7	8	10	8	9	9	5	9	8	6	5	0	0	9	9	6	7	6	5	8	134
Errors (OE)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HEP %	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Table 6.2. Weekly HEP Score – Comparison to baseline.

There is a clear reduction in the number of errors from 7/20 in the initial state to zero occurrences during the trial period. However as previously discussed the build sizes and raw material variance were also deemed to be contributors to the problem.

Analysis of the build details are presented in the table 6.3 (below). As previously discussed, emphasis is on weeks where PCB type “A” and “B” and scheduled consecutively.

Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
12033249 (A)	4	5	7	4	5	6	4	4	4	3	3	0	0	4	5	3	4	5	2	4
12033484 (B)	2	3	2	4	3	3	0	5	3	3	2	0	0	5	3	3	2	1	2	4
12033511 (C)	1	0	1	0	1	0	1	0	1	0	0	0	0	0	1	0	1	0	1	0
Total	7	8	10	8	9	9	5	9	8	6	5	0	0	9	9	6	7	6	5	8
Errors	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 6.3. Reduction in defect on mixed schedules.

There were no builds in week 12 & 13 (Holiday period), and only in week 7 was there an exclusive build using PCB type “A”. Additional analysis of the build schedules found that there were no significant material or order issues and all build were scheduled and completed consecutively.

All of the data above is taken from the same sources as the initial analysis, namely production logs, material transactions and production schedules.

As a significant improvement aspect of this project is the implementation of a robust automated detection mechanism in the event of a human error occurring it is important that we can also explore this function. The programming of the laser etch machine to check for the unique distinguishing mark also include an error log. This log was analysis to look for a specific failure text “BAD BOARD DETECTION MODEL NOT FOUND” this would signify that the camera system detected a failure, responded by stopping the process thereby preventing at the point of occurrence before any defect was generated. The logs for the trial period were revised, analysis results are below: (Table 6.4.)

Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
12033249 (A)	0	0	1	0	1	1	0	0	0	0	0	0	0	1	1	0	0	0	0	0
12033484 (B)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12033511 (C)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Detection	0	0	1	0	1	1	0	0	0	0	0	0	0	1	1	0	0	0	0	0
Build size	7	8	10	8	9	9	5	9	8	6	5	0	0	9	9	6	7	6	5	8

Table 6.4. HEP from detection log of camera system.

Worryingly, over the course of the trial there were 5 occurrences where a potential defect was detected. While the occurrence was prevented from becoming an actual defect the risk of human error was still present. All 5 occurrences coincide with the larger build sizes (sizes of 9 & 10) where the PCB types “A” and “B” are present on the line. Recalculating the week-by-week HP score for the new process we can then evaluate if additional efforts to improve the production system process are required, particularly if a line based JIT system and / or changes to the scheduling methodologies would be required. The revised HEP values are presented in table 6.5 below, along with a comparison to the previous (baseline) value.

Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Total	Mean
Initial (PE)	6	4	11	7	7	10	6	7	6	11	0	5	3	12	12	12	0	6	11	6	142	7.1
Errors (OE)	0	0	1	1	0	1	0	0	0	1	0	0	0	1	0	1	0	0	1	0	7	0.35
HEP % (Base)	0.0%	0.0%	9.1%	14.3%	0.0%	10.0%	0.0%	0.0%	0.0%	9.1%	0.0%	0.0%	0.0%	8.3%	0.0%	8.3%	0.0%	0.0%	9.1%	0.0%	4.9%	3.4%
Build size (PE)	7	8	10	8	9	9	5	9	8	6	5	0	0	9	9	6	7	6	5	8	134	6.7
Detection (OE)	0	0	1	0	1	1	0	0	0	0	0	0	0	1	1	0	0	0	0	0	5	0.25
HEP% (Trial)	0.0%	0.0%	10.0%	0.0%	11.1%	11.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	11.1%	11.1%	0.0%	0.0%	0.0%	0.0%	0.0%	3.7%	2.7%

Table 6.5. Comparison of current to baseline HEP.

While there is an improvement from the initial HEP of 4.9% to 3.7% the underlying issue of human error is still plainly present. The changes to the detection process have clearly resolved the risk of the human error becoming an actual defect, but have done nothing to address the underlying causality. Without changes to how the raw material is handled on the production line, specifically how mixed builds are planned we will not be able to further reduce the risk of human error.

Following the trial period the results were once again distributed internally, specifically highlighting the detection rates of the camera system and the ongoing risk of human error. The key recommendation (findings) put forward for management approval are as follows.

1. The use of a unique distinguishing feature in association with a reliable camera detection system clearly prevented defects from occurring. The use of an off-line solution is only temporarily possible and has increased workload in some areas. The ECO mechanism should be used to add a feature to the raw material by the PCB supplier. Discussion with the PCB manufacturer has already occurred (lead by design). We can add a 3rd fiducial to any free space on the waste area for zero-cost. As it is on the waste area no PPAP or qualification samples are required, customers should be informed of the change as a continuous improvement. ***(Status – Agreed, target implementation Q2 2020)***
2. Removal of the large on-line storage bins to reduce number of raw material stored prior to builds and switch to a JIT method. Ideally the material should come to the floor in the original packaging with a verifiable barcode. A hand scanner should be used to confirm material to requirements – fully integrated with the existing ERP/SAP systems. Has

already been discussed with the production systems manager (MES). Timeline would be a problem due to current roadmap, estimate of cost is in the 10s of thousands of euro. ***(Status – Refused, cost payback is a concern, especially as the proposed ECO changes would prevent scrap costs. Also housekeeping (5S) concerns about the handling of the waste packaging if material is de-trashed on the production line)***

3. Schedule all builds of the same raw material type together, exclusively. If necessary split weekly orders between PCB types “A” and “B” to different production periods, i.e. start / end week, before / after planned maintenance events. If possible schedule alternate bi-weekly builds. ***(Status – Agreed,, target implementation Q2 2020, concerns that may not always be possible due to fluctuations in demand and / or material supply, however strong commitment given to plan accordingly to reduce instances where mixed builds are planned concurrently.)***

7.0 Conclusion:

The project aim, while concerned with human error, has fundamentally been about reducing scrap costs. In this case the project can be deemed to have been successful. From the trial period and continuing to date (April 2020) there have been no further occurrences of incorrectly built parts at the end of line, thus current scrap / rework cost for this specific problem have dropped to zero. Analysis of the machine logs since the end of the trial period have shown further reductions in the number and frequency of detections, due mostly to the effort by the planning department to schedule builds in a manner that lessen the risk of mixed schedules. I would also suggest that the awareness of the operators to the problem, and the steps they can take, time permitting, to reduce the risks are also contributing. There is anecdotal evidence to suggest that the logistics team are transacting a lesser quantity of raw material more frequently to the online storage bins, rather than the bulk deliveries that previously occurred. While not directly instructed to modify the material movements the awareness has moved to ancillary support groups as well. It would appear that everyone is making additional efforts to reduce the risks, once these risks have been communicated and understood.

From the initial introduction to this project the specific areas of concern were:

- Human Error – causes, measurements and quality tools to understand occurrences.
- Human Error – changes to product, process and systems design to reduce occurrence.

In both cases the project has provided clarity to the problem, correctly identifying, defining and taking improvement actions where possible. The use of a logical, scientific, data based approach and a team based qualitative format was the ideal vehicle for determining the actual root causes and exploring solutions that worked. The acceptance early in the project that the similarities in the PCB design, and the inability of humans and machine to detect the differences were fundamental weaknesses, resulted in the implementation of the necessary PCB design changes through the ECO mechanism and the process improvements to detect these changes using a camera solution – which is effectively a digital POKE-YOKE.

The combination of quantitative and qualitative methods meant the time from project beginning to implementing improvements was reduced. The use of verifiable data also made the presentation to senior management more successful, there was no ambiguity in the effects of the problem or the explanations of likely causes. The familiarity of management with the concepts for the follow-up meeting was also a positive, where agreements were quickly given.

The conclusion must be that analysis, understanding and accurate reporting of the process and its failures is an important first step in developing solutions to manage, reduce or eliminate the occurrence of incorrectly loaded raw material. Similarly developing engineering solutions to detect any errors that may occur is an attempt to contain the point of failure to a low-impact position in the process.

7.1 Further Actions (Next Steps):

The ECO change is complete and production is underway, expected delivery of the modified PCB are expected in late Q2, these will be introduced as soon as all remaining stocks are consumed.

The lessons learned have been added to the existing PCB design guidelines and to the design for manufacturing checks, Mentor Graphics and Valor (software packages), all new PCB designs will now be assessed for physical / visual similarities and if required corrected in pre-series.

A risk assessment is also underway to analyse all current (series) PCB for the problems identified. Where necessary similar actions will be undertaken, where not possible specific work instructions will be issued.

All current line etch machines have been evaluated for compatibility with the camera requirements, machines which are not compatible have specific work instructions advising of the process limitations.

The requirement for a built in robust camera detection system has been added to the key functionality requirements for our approved vendor list for equipment purchases.

Perhaps the biggest change is that the line operators are going to be more involved in the pre-production phases of new product introductions and involvement in the improvement process. This is an acknowledgement that their familiarity with the line processes and PCB designs has been previously overlooked as a contribution.

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