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Dissertation : How Industry 4.0 can compliment a TPM maintenance Strategy

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Research Methods and Professional Development

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I Executive Summary

This project looks at the benefits of Total Productive Maintenance (TPM) and Condition-based maintenance (CBM) combined with Industry 4.0 aspects such as Data analytics and IOT dashboards. It is centred around an organisation, Company X, and details the implementation of these maintenance methodologies and the improvements that they deliver. The company is still in its infancy and after a period of immense growth, a rise in engineering resource has presented the opportunity to concentrate on continuous improvement of legacy processes.

Research into various maintenance methodologies and their utilisation within different sectors, would establish a base knowledge to create a specific maintenance structure designed for Company X. Through the adoption of the lean principles metric Overall equipment efficiency (OEE) the project improvements could be sufficiently tracked over time.

Project planning was delivered through a maintenance strategy highlighting an equipment criticality requirement, that would help develop the preventative maintenance and coincidingly deliver a structured inventory store. The TPM principles were then implemented by streamlining the PM structure and developing autonomous maintenance through production ownership.

Predictive maintenance was included through the use of IOT sensors and data modelling, and created an opportunity for data analytics and IOT dashboards to be introduced.

Through utilisation of analytics and the dashboards continuous improvement has delivered feedback to create further improvements to preventative maintenance. The conclusions drawn are that new I4.0 aspects will continue improve production efficiency through predictive and responsive maintenance. To implement such features will require a high initial financial injection with a large diverse project team. One question remains, as efficiencies are continually met and organisations strive for smart factories, how will this affect the size of the engineering/maintenance teams?

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1.0 Introduction

The advancements in innovative manufacturing technology have entered a new era of Industry 4.0 which involves innovations such as the Internet of things IOT, cloud computing, artificial intelligence AI, Digital Twin etc. Within the scope of cloud computing is big data and analytics, which is the use of advanced analytic techniques for predicting and enhancing business processes (Sharma & Pandey, 2019). One such department with an interest in big data would be maintenance, where an emphasis on data can establish predictive maintenance programs, which reduce downtime and save on maintenance costs. They can also extend the life of their equipment, reduce unnecessary preventive maintenance tasks, and optimise spare part inventory (Christiansen, 2020).

There are a number of maintenance methodologies adopted by companies, from complete structures such as Total Productive Maintenance (TPM) and Condition-Based Maintenance (CBM) to just basic preventative maintenance (PM), all are implemented to ensure the health and performance of their assets (Wu, 2020). Big data introduction within a maintenance environment could help with asset performance and health, through utilisation of monitoring sensor data to model the performance of equipment. Therefore, a combination could allow the data to improve the TPM protocols for individual equipment, predict failures before breakdown occurs thus enabling a more planned and exclusive approach (Christiansen, 2020).

For companies utilising a basic PM approach the adoption and integration of protocols such as TPM or CBM is an incremental innovation and the foundations of progress. These foundations can then be built upon by the adoption of Industry 4.0 technologies to show vast improvements in machine overall equipment effectiveness (OEE). OEE is a worldwide recognised metric for comparing the manufacturing performance with the maximum possible performance of equipment (ESmaeel et al., 2017).

This project will research and compare a number of maintenance techniques to establish within an organisation, Company X, delivering incremental innovation and a robust foundation for maintenance protocols. This will be built upon by utilising data analysis and I4.0 condition-based monitoring sensors to predict the failures of certain equipment. Progression throughout the project will be compared by the utilisation of OEE calculations and plotting the progression in performance against time. This progression will be extracted from data dashboards that will be developed within the project



2.0 Background

Through extensive insights into manufacturing and maintenance this report reviews the introduction of different TPM and CBM strategies within a start-up company, Company X, that has seen immense growth. The company is heavily investing in capacity increases that hinders the budgets for maintenance improvements, and limits the resource to implement them.

3.0 Aim

The Aim of the project is to explore the different types of maintenance methodologies, and research companies adopting simplistic versions and others implementing full Total Productive Maintenance (TPM). Investigations into the benefits of lean thinking and how it can directly affect the effectiveness of the maintenance strategy and production output. A comparison of differing maintenance strategies from different sectors will be detailed, with aim of improving the maintenance strategy within a company called Company X, a fast-growing company that manufactures hair removal IPL's. A tailored maintenance strategy will be implemented together with IOT sensors for condition monitoring, equipment data models and OEE dashboards to show the effect they have on OEE.

4.0 Objectives

The objectives for the project include:

1. To research the different maintenance protocols.
2. To explore how these protocols are utilised within different sectors.
3. To deliver a suitable maintenance strategy for a chosen company, Company X, including:
 - a) Equipment criticality identification and spares
 - b) PM revisions and autonomous maintenance
 - c) IOT installations for PdM through condition monitoring
4. Explore Big data collection and its benefits through OEE dashboards
5. Analysis of project Improvements



5.0 Justification

For a company to succeed there has to be progression, improvements to processes and equipment are essential to allow the company to thrive within competitive markets. Maintaining a company's assets to a high standard can ensure that equipment functions as expected for safety aspects; can ensure throughput yield is held at a positive level with minimal waste for manufacturing processes; and aid in the delivery of efficient services. Maintenance strategies can be the difference between a successful and non-successful company, thus the justification of said project.

6.0 Literature Review

This literature review will encompass a researched based look into maintenance strategies, how they are utilised within different manufacturing sectors, will explore OEE and Industry 4.0 innovations such as data analytics and OEE dashboards.

6.1 Maintenance protocols/techniques

According to the (European regulation EN 13306, 2020), maintenance is defined as “the combination of all technical, administrative and managerial actions during the life cycle of an item, intended to retain or restore it to a state in which it can perform its required function”. (Wu, 2020) describes six maintenance types that maybe adopted to help ensure the efficiency of machinery ensuring production is continuous.

6.1.1 Preventative maintenance (PM)

These are actions that are undertaken at preselected intervals, through structured protocols to minimise the wear and degradation of equipment and infrastructure systems (Sullivan, 2004). The main attributes of PM would be the inspection, adjustment, calibration, lubrication, cleaning, replacement, and rebuilding of equipment, partnered with a robust spares inventory system. This is a simplistic form of maintenance adopted by many small companies, that require a systematic approach to maintenance with minimal time and setup costs. Chen (1997) argues that predicting the optimal level of PM activities is difficult and that human meticulousness will play a major part in its effectiveness.

6.1.2 Condition-based Maintenance (CBM)

CBM is a maintenance strategy that monitors the real-time condition of an asset to determine what maintenance needs to be performed. Unlike preventive maintenance, which uses calendar-based maintenance to determine when to schedule and perform maintenance, condition-based



maintenance dictates that maintenance should only be done when these real-time indicators show irregularities or signs of decreasing performance (Brown, 2003). These indicators can be from sensors or spot check readings that compare analysed data against predetermined limits enabling the rectification of impending failures before they occur. An asset criticality report is generally a criterion adopted with CBM to rank equipment that are most likely to fail and the impact the failure will have on production. CBM can be a costly maintenance, however, in sectors where failures can be catastrophic, such as the oil industry, power industry and food industry etc. it can be advantageous (ahmed & Kamaruddin, 2012).

6.1.2 Predictive Maintenance (PdM)

PdM incorporates CBM activities that can monitor the condition of equipment and combines with predictive models that can be developed over time in a CMMS or from the Original Equipment Manufacturer (OEM) data sheets. PdM is reliant on the IoT where sensors are connected to a central system that is setup to analyse the information through algorithms that predict failures before they happen. Once setup, this system could optimise a maintenance system, however, would incur high upfront costs, time and the requirement of specialised equipment (Lee et al, 2019). The motor manufacturing sector incorporates this strategy as well as others, having being established over long periods and strategically incrementing their systems (Jain,2014).

6.1.3 Corrective Maintenance (CM)

CM is a maintenance task performed to restore a non- or under-performing asset to an optimum or operational condition. There are scheduled corrective maintenance, that is needed, but not required to be performed immediately and unscheduled corrective maintenance/reactive maintenance that is required due to a critical failure with immediate action necessary (Deighton, 2016). Scheduled CM will be the result of PM, PdM or CBM analysis that have highlighted a requirement for corrective action, which will be planned for the most beneficial opportunity, generally when production is not running. Reactive CM is the restoration/repair of failed equipment and return it to a useable state, unfortunately, this can cause serious production and safety issues.

6.1.4 Reliability Centred Maintenance (RCM)

RCM has one main aim to reduce the maintenance cost, by focusing on the most important functions of the systems and avoiding or removing maintenance actions that are not strictly necessary. It is based on the assumption that the inherent reliability of the equipment is a function of the design and built quality (Waeyenbergh and Pintelon, 2002). It integrates Preventive Maintenance (PM), Predictive Maintenance (PdM), Corrective, and Proactive Maintenance to

increase the probability that equipment will function as required over its design life-cycle with a minimum amount of downtime and maintenance. According to Moubray (1997), RCM is the maintenance performed to ensure that physical assets continue to do what their users want them to do. An RCM analysis basically provides answers to the following seven questions (Rausand, 1998):

1. What are the functions and associated performance standards of the equipment in its present operating context?
2. In what ways does it fail to fulfil its functions?
3. What is the cause of each functional failure?
4. What happens when each failure occurs?
5. In what way does each failure matter?
6. What can be done to prevent each failure?
7. What should be done if a suitable preventive task cannot be found?

6.1.5 Total Productivity Maintenance (TPM)

TPM is a maintenance system defined by Nakajima (1988) in Japan, which covers the entire life of equipment in every division including planning, manufacturing, and maintenance. It describes a synergistic relationship among all organisational functions, but particularly between production and maintenance, for continuous improvement of product quality, operational efficiency, capacity assurance and safety (Yamashina, 1995). TPM initiatives, as suggested and promoted by the Japan Institute of Plant Maintenance (JIPM), involve an eight-pillar implementation plan which results in substantial increase in labour productivity, reduction in maintenance costs and reduced production stoppages and downtimes. TPM includes the following eight pillars:

1. autonomous maintenance
2. focused maintenance
3. planned maintenance
4. quality maintenance
5. education and training
6. office TPM;
7. development management
8. safety, health and environment

6.2 Reliability Bath Tub Curve

There are evident failures that occur randomly in the machine's life cycle, and there are predictable equipment wear-out failures. The bathtub curve shown in Figure 6, represents the failure pattern seen in many products. The vertical axis is the failure rate at each point in time and the horizontal axis is the test time or life cycle of the product. The bathtub curve is divided into three regions: early failure, useful life, and wear out (Kosky & Wise, 2021) .

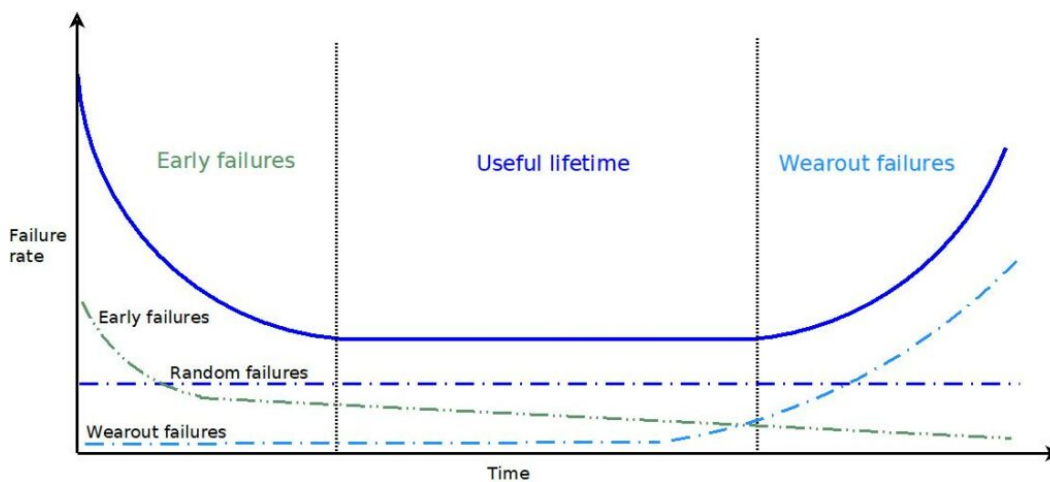


Figure 1: Failure rate bathtub curve (Kosky & Wise, 2021)

Early failure: This is the early failure (or break-in) stage. During this period failures typically occur because products were not designed properly or manufacturing flaws occurred. Failure rates at the beginning of the early failure stage are high, but then they decrease with time as the early failures are removed.

Useful life: This is the centre stage of the bathtub curve and is characterized by a constant failure rate. This stage is the most significant stage for reliability prediction and evaluation activities.

Wear-out stage: This is the final stage where the failure rate increases as the products begin to wear out and break down. When the failure rate becomes high after a long period of use, repair or replacement of parts should be performed.

6.3 Data Analytics in manufacturing

According to (Indrawati & Ridwansyah, 2015) manufacturers have been able to reduce waste and variability in their production processes and dramatically improve product quality and yield, by implementing lean and Six Sigma programs. However, according to (Hanna et al., 2021) in certain manufacturing environments, swings in variability are common issues, sometimes even after lean techniques have been applied. Given the sheer number and complexity of production activities that influence yield, manufacturers need a more granular approach to diagnosing and correcting process flaws. Advanced analytics provides just such an approach. Advanced analytics refers to the application of statistics and other mathematical tools to business data in order to assess and improve practices. In manufacturing, according to (Auschitzky et al., 2021) operations managers can use advanced analytics to take a deep dive into historical process data, identify patterns and relationships among discrete process steps and inputs, and then optimize the factors that prove to have the greatest effect on yield. Many global manufacturers in a range of industries and geographies now have an abundance of real-time shop-floor data and the capability to conduct such sophisticated statistical assessments. They are taking previously isolated data sets, aggregating them, and analysing them to reveal important insights.

Analytics, according to (Auschitzky et al., 2021) can help with transforming the data that is available into valuable information for executives so that better decisions can be made. They can help analyse large amounts of data quickly and display it in a formulated manner to help achieve specific organisational goals. It encourages a culture of efficiency and teamwork by allowing the managers to share the insights from the analytics results to the employees. Consistent with (Dal et al., 2000) the gaps and improvement areas within a company become evident and actions can be taken to increase the overall efficiency of the workplace thereby increasing productivity. The packages can be tailored to the user's needs ensuring that only relevant information is presented which can enhance the experience by detecting and correcting errors or avoiding non-value-added tasks.

6.4 Overall Equipment Effectiveness

(Dal et al, 2000) suggests OEE enables organisations to benchmark and monitor their progress with simple and easy to understand metrics with a purpose to increase the manufacturing performance. The OEE calculation is based on a composite of the six big losses of your equipment broken down into three main areas; Availability, performance and quality. It is a very simple calculation in reality;


$$\text{OEE} = \text{Availability\%} \times \text{Performance\%} \times \text{Quality\%}$$

OEE (Overall Equipment effectiveness) is the main performance measure that drives action within Total Productive Maintenance (TPM) and is used by the teams to focus their continuous improvement activities as well as identifying those areas that require resource (Singh et al., 2013). Research, undertaken by (Esmaeel et al, 2017) measurements of OEE at the start of TPM initiatives is normally less than 40% in most industries, however, A well-managed TPM programme can elevate OEE to over 85% as a world-class standard within a period of two to three years.

6.5 OEE Dashboards

Dashboards can display OEE data on a real-time, daily, quarterly, or another cadence. This lets you see if there are any persistent problem areas, and can help you track whether or not your improvements are making a difference. When you combine time data with machine type, machine OEE by type, or by program, you can get a detailed view of production (Tulip, 2021). OEE dashboard services from companies such as Tulip, can be a costly investment, however, the benefits they bring can deliver a ROI in minimal time depending on the company. One pertinent fact would be that predefined OEE dashboards will have had a considerable amount of research and development time allotted to them to ensure maximum efficiency and ease of deployment. This cannot be said for the in house developed design which is proposed, however, it will be undeniably relevant and can be adapted to incorporate additional data when required.

7.0 Maintenance protocols with differing sectors

7.1 Automotive Sector

In the automotive industry, quality is one of the most significant arguments for management. In order to maintain a long-term achievement of quality, it is necessary to retain the capability of machines (processes), their reliability and performance (Fonseca and Dominguez, 2017), (Pinto, H et al., 2016). TPM concept was first defined in Japan in the 1970's by the Japan Institute of Plant Maintenance JIPM and concentrated on process quality, reliability, profit, minimising costs, the environment and safety protocols. One such company that has adopted TPM is Ford Motor Co. with the introduction in the early days realising a 15% to 25% increase in equipment operation and equipment running at 95% uptime within the first 5 years (Ford Motor co., 2018). Some Japanese companies have reported improvements in equipment availability up 50% and failures down 90%, process defects down 90%, customer complaints down 75%, maintenance costs down 30%, and maintenance inventory down 50% (Windle, 1993). These results can only be effective through the mastering of basic principles (Pacaiova & Izarikova, 2018):

- Achievement of maximum equipment effectiveness (OEE - Overall Equipment Effectiveness);
- creation of complex system of preventive maintenance based on constant improvement;
- participation of all: constructors, technologists, operators and maintenance workers, safety technicians;
- involvement of each employee from the top (top-management) up to the lowest management level- complex activity support (management support)
- implementation of preventive maintenance for small groups – autonomous maintenance.

Ford Motor Co. utilises OEE matrix to ensure that equipment effectiveness is improving through data analysis into Availability, Performance and Quality, which highlights issues/losses that require attention. (Salonitis & Omogbai, 2017), described the implementation of the 5S as an integral part of TPM ensuring the organisation and culture mainly within the field of OHS management, quality and environment. (Ramdass, 2015), elaborated into the importance in identifying hazards, source of defects (risk), and to select appropriate procedures of how to check and maintain them on a long-term acceptable level. 5S is derived from Japanese words Seiri, Seiton, Seiso, Seiketsu and Shitsuke (Sort, Set, Shine, Standardise, Self-discipline) which ensures no losses are apparent within the process by standardizing the most effective and efficient practices.



The Automotive sector is highly critical of quality and thus the continuous improvement of its processes through standardization, OEE comparison to world class rankings and participation at all levels has ensured the fundamental principles of TPM haven't changed for over 40plus years.

Innovation within the TPM maintenance strategy within the Automotive sector in companies such as Ford is through the utilization of Industry 4.0 technologies such as big data analysis, advanced robotics, IOT, RFID technologies, 3D printing etc.

7.2 Hair Removal Industry

The Hair Removal Industry is extremely competitive, requiring continuous incremental innovation to stay ahead of the competition and ensure market share. Company X, for the purpose of the project, a thriving Welsh company in the hair removal market is such a company, where new product introduction NPI is strained to extremities. This concentration on ever changing machinery and software from rapidly changing product ranges, has negative effects on the maintenance structure and its delivery. Through new installations, commissioning and validation, maintenance protocols can become overshadowed and instead of a planned schedule it can become mostly reactive. Dependency within the engineering department to deliver continuous projects, removes their availability to conduct DMAIC six sigma improvements and thorough root cause analysis RCA that would be prevalent within settled automotive companies such as Ford.

PM is essential in such companies, adopted as part of the Quality Management system QMS, however, the deployment and adoption is only as effective as the personnel that carry out the tasks. This requires a more positive and well-planned maintenance scheduling, one that encourages precision and criticality, so that each task makes a difference to the equipment. At a basic level, preventive maintenance (PM) scheduling is simplistic protocol that figures out a task to be completed, a time and a place is set, and then the assignment of someone to perform the work. Once that time comes, the assignee does the work, and the scheduled event is either completed (one time) or recurs at some specified interval (Senra, Lopes, & Oliveira, 2017). According to (Pinedo, 2009) due dates, deadlines and periodicity are important parameters on preventive maintenance tasks. These parameters should be respected to guarantee the correct functioning of production lines. The objective most related with maintenance task delays and due dates, are the minimisation of maximum lateness, minimisation of number of overdue tasks and minimisation of total tardiness (Leung, 2004). Scheduling the maintenance tasks over multiple production lines can aid in the minimisation of overdue tasks by spreading the downtime that less effects production. Consideration into manpower, spare part inventory and periods under



maintenance is essential, together with how cost effective it actually is to complete the maintenance tasks (Ebrahimipour et al, 2013).

7.3 The Aviation industry

Reliability centred maintenance (RCM) started in the aviation industry, which according to (John, 2014) is due to the numerous parts and components that comprise aviation equipment, their heavy use, and the risks and potentially catastrophic consequences of aviation equipment failures. Over time, organisations across industries have implemented the minimum criteria set out for RCM methods in technical standard SAE JA1011 — Evaluation Criteria for Reliability-Centred Maintenance (RCM) Processes.

(Kennedy, 2006) described the key to RCM within the aviation industry, is to assess each part on an individual basis and through a series of questions, to decide which is the best way to maintain it. Equipment will be assessed to understand what its key functions are, parameters it can work within to ensure safety and its limitations. Identification into its failure modes and how they influence the entire system of the aircraft, this will be key to see how it fails, how often and what key events can affect the failure. This can be highly pertinent in high use components and if environmental or human interaction can escalate such a failure.

By understanding the failure modes, occurrence rates and failure acceleration factors the industry can understand the consequences of such failures, whether it be total system failure, decrease in speed, or maybe lighting will fail. This is all critical to ensure that prevention or at least diminishing the consequences of failure can be achieved, where preventative maintenance is completed at set intervals before failure to replace said equipment (John, 2014). RCM involves looking at assets in terms of criticality, where utilising inductive analytical methods such as Failure mode and effects criticality analysis could play an important involvement. It is a continuous process which should be periodically re-evaluated through data analytics to ensure equipment reliability is up to date. This strategy is costly and requires dedicated man power to ensure firstly to establish the criticality of all equipment and to maintain the system ensuring it is relevant (Sajaradj et al., 2019).

8.0 Selecting a suitable maintenance strategy

To select a successful maintenance strategy according to (Deighton, 2016), a firm understanding of maintenance management principles together with an in-depth knowledge of the company processes and performance are essential. Dhingra & Velmurugan, 2015, concurred and added unfortunately, there is no exacting formula for the selection process and many strategies will be developed from a mixture of differing philosophies that best suit the company and their requirements.

As previously discussed, there are many strategies available that have been developed and optimised towards maintaining company assets, eliminating the root cause of failures altogether, and improving equipment design to minimise maintenance requirements. The definitive goal should always be to improve equipment reliability through continuous improvement while reducing ownership costs (Wu, 2020). This is pertinent when considering the cost of adopting a maintenance strategy against the performance improvements that it could deliver. An effective strategy is one that balances the resources required to implement and maintain while ensuring the equipment and company performance are maximised. It also requires a degree of flexibility where the dynamics of the structure can adapt to changing circumstances and continually tailor to the company's needs (Dhingra & Velmurugan, 2015).

A critical part of selecting an appropriate strategy, according to (Dhingra & Velmurugan, 2015) will require a detailed assessment on the current business by answering some fundamental questions. These questions will be directed at the business in which the project is set.

- What are the current production targets?

Currently the manufacturing facility incorporates 13 production lines, which produce five variants of IPL all with similar output targets and incorporating similar equipment.

IPL Variant	Output Target/week (2 shifts)	Average weekly output
Variant 1	24000 parts/week	22,358
Variant 2	3000 parts/week	2680
Variant 3	6000 parts/week	5068
Variant 4	3000 parts/week	3002
Variant 5	6000 parts/week	4697

Table 1: Targets and Actual output/ week for each variant (Company X, 2021)

These figures are accurate for all parts made in straight time, the utilisation of working break times and weekends allows the lines to hit their weekly targets, apart from Variant 5 which is the newest product and suffering poor deployment.

- What is the overall equipment effectiveness OEE of the equipment?

OEE is calculated for each product and the corresponding manufacturing equipment, and is taken as an average of the last three months.

IPL Variant	Availability	Performance	Quality	Total OEE
Variant 1	89%	76%	95%	64%
Variant 2	96%	82%	92%	72%
Variant 3	92%	72%	89%	60%
Variant 4	98%	84%	96%	79%
Variant 5	96%	68%	75%	49%

Table 2: OEE ratings per variant (Company X, 2021)

- What are the company shutdown targets?

At present there are minimal shutdown targets set, this is due to resource utilisation on new product introduction projects and ensuring the ever-increasing market demand is met through increased capacity requirements.

- Is there a maintenance budget? If so, what is it?

No maintenance budget has been set at present.

The preliminary information shows some clarity on the current situation and allows for some defined objectives to be formulated into a maintenance plan. For this it was crucial that these were aligned with the objectives of the company to ensure that each was concise and realistic in terms of implementation. Stakeholders within the company were gathered to discuss the overall requirements of the maintenance plan, which was translated into a workflow, Figure 1.

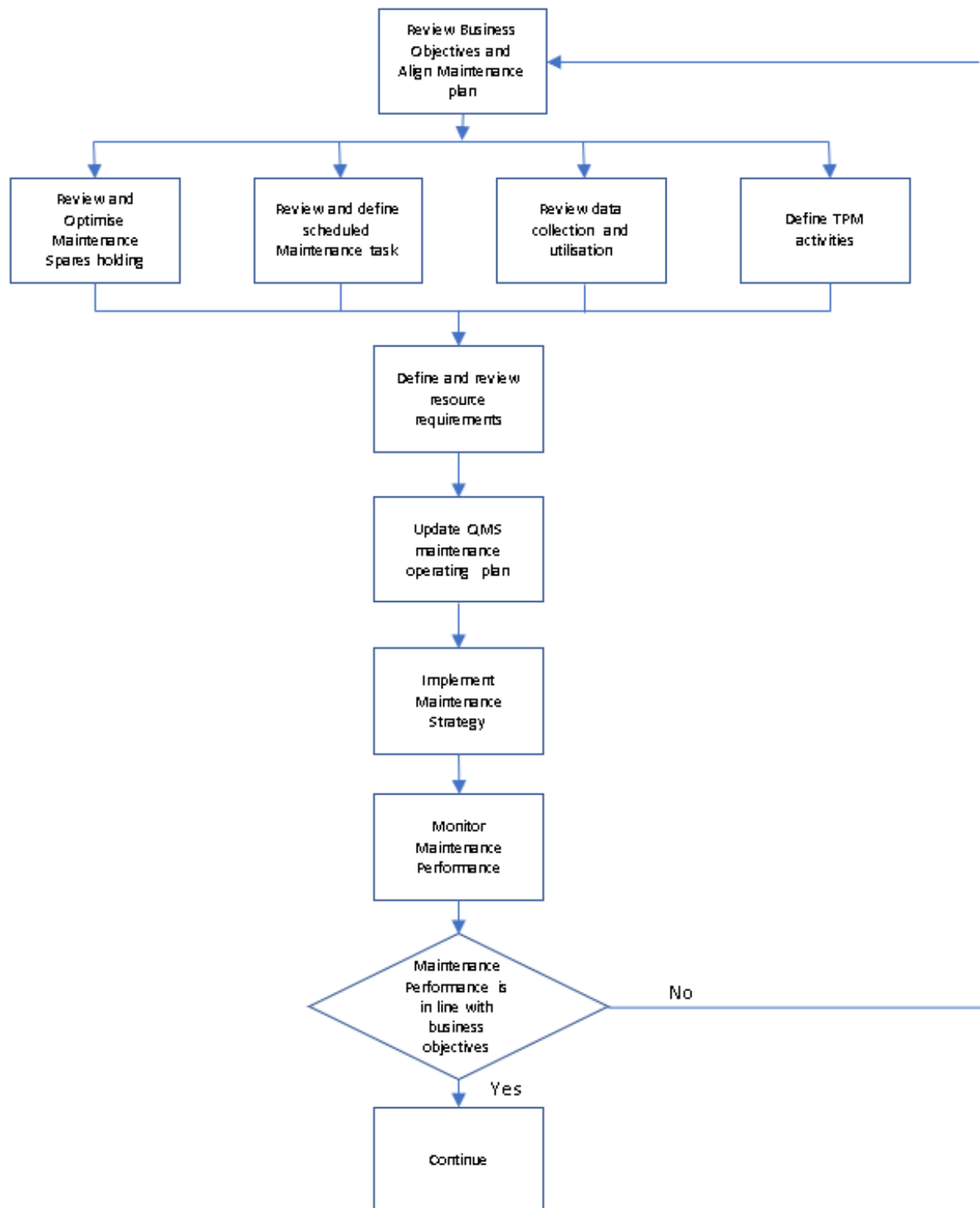


Figure 2: Proposed Maintenance strategy workflow (Company X,2021)

8.1 Machine Criticality

As company X is relatively new and has no maintenance budget or Shutdown plan set, a criticality assessment is to be developed to help prioritise resources effectively. Lipol & Haq 2011, describe failure modes and effects analysis (FMEA) as a reliability evaluation technique to determine the effect of system and equipment failures. This qualitative technique helps identify failure potential in a design or process i.e., to foresee failure before it actually happens. A FMECA is an analytical quantitative technique which ranks failure modes according to their probability and consequences. A FMEA or FMECA can be conducted on either a component or a functional level. A component FMEA/FMECA only covers hardware aspects but a functional FMEA/FMECA can cover all aspects of a system (Bertolini, 2004). For either approach the general principle remains the same.

This qualitative technique helps identify failure potential in a design or process i.e., to foresee failure before it actually happens. This is done defining the system which is under consideration to ensure system boundaries are established and then by following a procedure which helps to identify design features or process operations that could fail. The procedure according to (Lipol & Haq, 2011), requires the following essential questions to be asked:

1. How can each component fail?
2. What might cause these modes of failure?
3. What could the effects be if these failures did occur?
4. How serious are these failure modes?
5. How is each failure mode detected?
6. What are the safeguards in place to protect against accidents resulting from the failure mode?

For the purpose of the project a functional FMECA was completed within in a cross functional team of both Engineers and maintenance Technicians to capture a more accurate assessment. The Results of the FMECA has prompted the review and optimisation of the maintenance spares holding, which is shown in the strategy plan Figure 1. The shortfalls in maintenance spares have become obviously apparent after completing the FMECA, together with the lack of organised holdings for all machine spares. The speed of growth in which the company has had to overcome, has meant that critical spares have been neglected, and with no inventory structure, finding spares is extremely difficult.

8.2 Critical Spares Inventory management

Through utilisation of the FMECA a detailed list of critical spares was derived to ensure plant operations are not affected from the unavailability of certain parts. These replacement items are selected from a broader range of machine components after careful consideration of the components that are indispensable to the smooth manufacturing processes. A failure of the corresponding factory-installed machinery components could completely stop production activities, resulting in costly equipment downtime. Having readily available critical spare parts in storage, minimises the negative effects of lengthy equipment inactivity as maintenance technicians have immediate access to replacement items and can quickly fix faulty machinery.

In creating the parts list this only constitutes to one part of the solution, there requires a means of data collection of said parts, to ensure over time, the correct parts are still relevant and also the creation of a stable restocking strategy. Budget will have significant effect on how robust the inventory management is maintained, with fully real time inventory solutions costing thousands and more cost-effective solutions i.e., Microsoft Excel being a free option. For this project Microsoft Excel will be used as a short-term solution for budgetary reasons.

According to (Baskarada, 2012) there are numerous disadvantages to using Excel for inventory purposes, however, ensuring some critical best practice rules are implemented could limit unnecessary errors. These will include the adoption of auditing on a monthly basis, where stock take will take place to ensure stock quantities are upheld. At this point a consolidation of the monthly data should ensure that critical items are being restocked and no short comings occur that could result in line stoppages. As Excel is not a real-time inventory solution, updating the document immediately when items are removed from or added to the stores, should help ensure the list is kept up to date. (ROSENBERG, 2021) explains that traditional offline Excel documents are severely limited because only one person can use the sheet at once. (Pupavec and Baburic, 2011) concur however, add that using Excel in the Cloud (OneDrive), ensures that you can invite multiple people to the sheet and edit it at once to improve self-auditing, input data from multiple sources, and speed up processes. It also comes with the added benefit of automatic backups and syncing across all of the chosen devices.

A preview of the drafted excel inventory solution is shown in Figure 2, it has a range of critical spares added with descriptions, part numbers, and supplier details with hyperlink for ease of ordering. A number of cupboards were reutilised for the Stores, with some additional shelving, component trays and each one colour coordinated for ease of use.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	INVENTORY STORES LIST (CRITICAL SPARES)														
2	OPERATION	MOUNTING LOCATION	PART DESCRIPTION	MANUFACTURER	SUPPLIER	PART NUMBER	HYPERLINK	CUPBOARD/RACK	LOCATION	QUANTITY IN STOCK	REORDER QUANTITY	MAX. LEVEL STOCK	MIN. LEVEL STOCK	REORDER POINT	LEAD TIME
3	Assembly Station	Stage 1	Electric ESD driver brushless 0.05-0.5Nm 700-1000rpm c/wPSU	Kaisertech/RS	Kaisertech/RS	270-BS3000E		C1	A1	2	1	2	1	<=1	3 days
4															
5	Assembly Station	Solderjig	Tensor Pinion for JBC AL-2A	JBC	Kaisertech	415-0002535	com/pdf/EXPLC	C1	A2	4	3	6	3	<=3	5 days
6	Assembly Station	Solderjig	Clutch Set for JBC AL-2A	JBC	Kaisertech	415-0016755	com/pdf/EXPLC	C1	A3	3	2	3	1	<=1	3 days
7	Assembly Station	Solderjig	Spring Set for JBC AL-2A	JBC	Kaisertech	415-0017534	com/pdf/EXPLC	C1	A4	1	2	3	1	<=1	3 days
8	Autoline	Test machine	24V DC Coil Non-Latching Relay 10A 2 Pole	Hongfa Europe	RS	176-2867	1/web/p/non-la	C1	A7	4	2	5	3	<=3	2 weeks
9	GEN 4	Test machine	24V DC Coil Non-Latching Relay 6A 3-Pole	Omron	RS	/ G7SA-3A3B	m/web/p/non-la	C1	A8	3	1	4	3	<=3	2-3weeks
10	HCM	Test machine	240V 8 Pin Relay Socket	Schneider	RS	884-1345	com/web/p/rela	C1	A9	2	2	3	1	<=1	5 days

Figure 3: Inventory Store List (Company X, 2021)

The stocked quantity has a colour key set for visual aid in determining when items require ordering, GREEN for healthy stock, AMBER for minimum stocked level reached and RED reorder point reached, place item order. The reorder quantity is directly next to the stock level together with the stock limits and lead times for delivery.

The budget for developing and introducing a working critical spare store was agreed at £500 with all stakeholders, this was broken down into the following areas:

- Storage = £348.95 (included one extra cupboard, 6 shelves and equipment drawers for storage)
- Visual factory = £34.05 (signage and labelling)
- Training = ~£2.30 (The work instruction was developed by the project owner in their spare time, this was the cost of paper and ink)
- Software development = £0.00 (This was developed by the project owner in their own time)

The total spent on the critical spares store came to total **£385.30**.

All engineering and maintenance personnel were fully trained to be conversant with the new inventory stores, with an audit planned for the last Friday of the month, in which consolidation of the data would be scrutinised to ensure stock levels are maintained.

8.3 Review and Define Maintenance Protocols

8.3.1 Preventative Maintenance

Preventative maintenance as described in section 6.1, is a maintenance protocol that schedules tasks to ensure and prolong the lifespan of equipment. This can be developed utilising both the OEM machine manual which should include sections on maintenance requirements; from data analysis of equipment history; and from recent innovations such as real-time sensor data captured through IOT (Dhingra & Velmurugan, 2015).

At present the maintenance scheduled tasks were duplicated from legacy machinery to enable fast deployment due to limited resources. They are scheduled via a developed excel spreadsheet, figure 4, that shows when equipment is due for weekly, monthly or quarterly maintenance tasks. PM tasks at present, are 30 minutes weekly 50 minutes monthly per machine. Figure 3, an Ishikawa diagram, was used to illustrate some of the reasons why PM tasks need to be revisited to improve efficiency. These include; limited resources and time for PM development resulting in underdeveloped and inefficient processes; no account taken for new machinery, are there tasks that need to be

completed in the first year etc.; and there is a lack of training for the machines so knowledge is limited ideas are scarce. However, it also indicates part of the solution where a considerable amount of the machines are identical, hence training would be quick once developed, the machines have minimal moving parts so perhaps quick maintenance could be limited to visual only. Furthermore, the machines are relatively new so effective maintenance will provide longevity for the equipment.

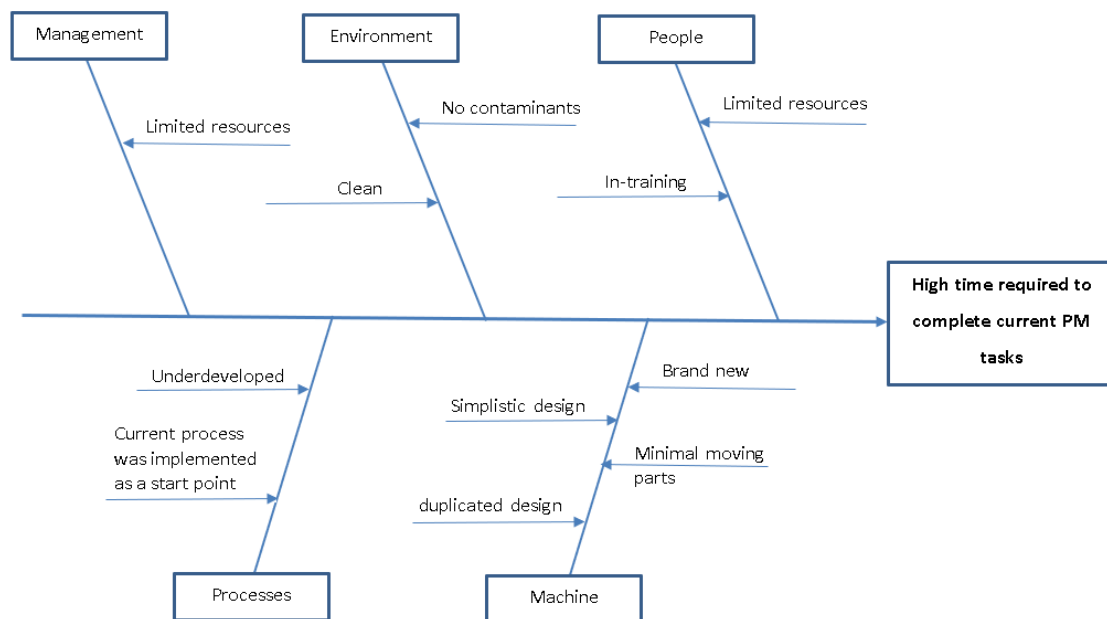


Figure 4 Ishikawa diagram - High time required to complete current PM tasks

The new defined strategy must incorporate the following preventive maintenance objectives:

- Reduction of equipment failures—number and length of a failure, reduction of equipment start-ups;
- Reduction of costs—scrap, components;
- Reduction in time wasted on needless PM and actual time completing tasks;
- Removal of PM through implementation of IOT technology.
- Removal of paperwork through IT introduction

Historical data was analysed to highlight prevalent machine stoppages and cross referenced with existing PM tasks to highlight each tasks criticality, relevance and required interval between PM schedules.

Equipment Details								Maintenance Register						
Site	Equipment ID	Make	Model	Serial Number	Equipment Owner	Operating Procedure	Equipment Status	Maintenance Required	Frequency	Date of Last Maintenance	Date of Next Maintenance	Internal External	Contract or	Procedure
T	Glow 2 Automated	EBS Automation	EBS-E-D-28-03	EBS4430-118	RT	Glow 2 Instruction Manual	Current	Y	Weekly	29-Nov-2021	06-Dec-2021	INT	N/A	Glow 2 Weekly Maintenance
								Y	Monthly	29-Nov-2021	29-Dec-2021	INT	N/A	Glow 2 Monthly Maintenance
								Y	Quarterly	20-Nov-2021	20-Feb-2022	INT	N/A	Glow 2 Quarterly Maintenance
T	Glow 2 Line 1 Manual	Tribotics Automation	IPC Panel	IPC0101	RT	GEN 4 Manual	Current	Y	Monthly	01-Nov-2021	01-Dec-2021	INT	N/A	Glow 2 Manual Line weekly Maintenance
			Test machine 1	TM0601			Current	Y	Weekly	29-Nov-2021	06-Dec-2021	INT	N/A	
								Y	Monthly	01-Nov-2021	01-Dec-2021	INT	N/A	
			Test machine 2	TM0602			Current	Y	Weekly	29-Nov-2021	06-Dec-2021	INT	N/A	
								Y	Monthly	22-Nov-2021	22-Dec-2021	INT	N/A	
			Test machine 3	TM0603			Current	Y	Weekly	29-Nov-2021	06-Dec-2021	INT	N/A	
								Y	Monthly	22-Nov-2021	22-Dec-2021	INT	N/A	
			Test machine 4	TM0604			Current	Y	Weekly	28-Nov-2021	05-Dec-2021	INT	N/A	
								Y	Monthly	22-Nov-2021	22-Dec-2021	INT	N/A	
			Laser Etch Glow	LE0201			Current	Y	Weekly	28-Nov-2021	05-Dec-2021	INT	N/A	
								Y	Monthly	22-Nov-2021	22-Dec-2021	INT	N/A	
T	Glow 2 Line 2 Manual	Tribotics Automation	IPC Panel	IPC0202	RT	GEN 4 Manual	Current	Y	Monthly	22-Nov-2021	22-Dec-2021	INT	N/A	Glow 2 Manual Line weekly Maintenance
			Test machine 1	TM0701			Current	Y	Weekly	22-Nov-2021	29-Nov-2021	INT	N/A	
								Y	Monthly	22-Nov-2021	22-Dec-2021	INT	N/A	
			Test machine 2	TM0702			Current	Y	Weekly	22-Nov-2021	29-Nov-2021	INT	N/A	
								Y	Monthly	22-Nov-2021	22-Dec-2021	INT	N/A	
			Test machine 3	TM0703			Current	Y	Weekly	22-Nov-2021	29-Nov-2021	INT	N/A	
								Y	Monthly	22-Nov-2021	22-Dec-2021	INT	N/A	
			Test machine 4	TM0704			Current	Y	Weekly	22-Nov-2021	29-Nov-2021	INT	N/A	
								Y	Monthly	22-Nov-2021	22-Dec-2021	INT	N/A	
			Laser Etch Glow	LE0301			Current	Y	Weekly	22-Nov-2021	29-Nov-2021	INT	N/A	
								Y	Monthly	22-Nov-2021	22-Dec-2021	INT	N/A	

Figure 5: Maintenance Schedule (Company X, 2021)

8.3.2 Autonomous maintenance

(Kennedy, 2006) describes autonomous maintenance as a time-driven preventive maintenance which is performed in the same repeating cycles, aiming at performing simple, standardised work procedures while looking for abnormalities that might affect future operation of the equipment and lead to a failure. This TPM methodology, according to (Adesta et al., 2018) counts on various frequencies for equipment downtimes and preventive maintenance. Standard frequencies could include daily, weekly, monthly or annually based on the priority of the equipment with regards to production or its load. Research by (Hashim, 2012), states that this results in a more effective process as it does not require the same number of people to execute preventive maintenance. Therefore, the workforce can be effectively assigned to preventive maintenance based on priority. The factors mentioned above results in the equipment classification according to the priority, which will receive the frequency of preventive maintenance.

The existing tasks were updated to incorporate operators, giving them ownership over equipment and providing training to complete medial cleaning and inspection tasks. Proposed improved maintenance solution according to priority and target improvements:

- A+—extra high priority—AM prevention on a daily basis (D-Daily)
Operator ownership of tasks, that are completed in parallel with COVID cleaning, no loss of production, maximum gains to be achieved through reduced downtime
- A—high priority—AM prevention (W-Weekly) Technician ownership
Streamlined PM tasks, highlighted through RCA of historical data, to be completed in break times, maximum gains to be achieved through reduced downtime.
- B—medium priority—AM prevention on a monthly basis (M-monthly) Technician ownership
Streamlined PM tasks, value adding activities, scheduled for the weekend to maximise machine uptime during the week.
- C—low priority—AM prevention on a half-year basis (A-annually). Technician ownership
Intense PM tasks involving strip downs and overhaul, time consuming activities, scheduled for shutdown to allow extended timescales

Figure 5, shows the responsibilities and ownership to both operators and technicians, and also the feedback loop created for continuous improvement. This loop is to be established through monthly review meetings and within the documented maintenance sheets to ensure a controlled process delivery is achieved

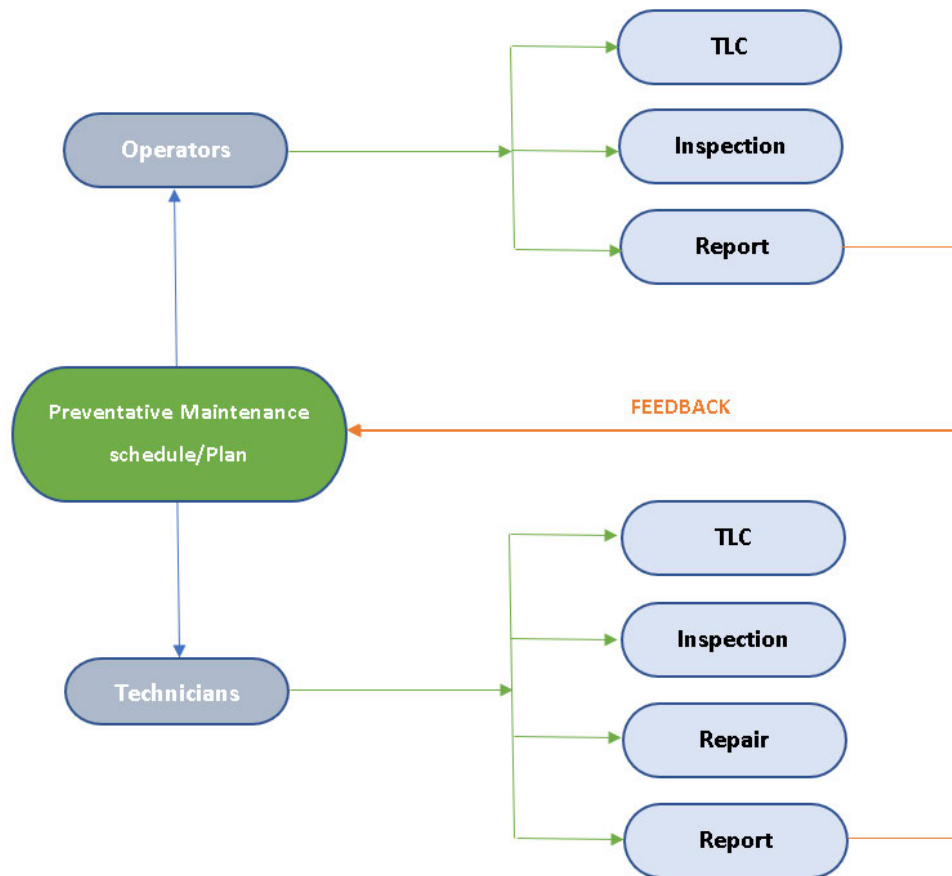


Figure 6: Maintenance control and improvement plan (Company X, 2021)

8.3.3 Introduction of IOT for Predictive Maintenance

To create a leaner more efficient PM structure, the introduction of IOT sensors and data modelling would deliver a predictive approach to maintenance. As the majority of the machinery are duplicates of each other, most will have the same components with the same life cycle and failure rate hence replicating the data modelling would be efficient. Historically we have seen motors that have failed from both early failure and wear-out failure, each resulting in line downtime and reduced production scores. Theoretically the PM tasks that have taken time to complete should have detected the failing motor, unfortunately they didn't. The proposed improved system would remove motor inspection from the PM and replace it with an IOT sensor to monitor the motor health. The main parameters of induction motors that could be measured are: -

- Voltage (individual phase)
- Current being drawn by motor.
- Over current in individual phases, such as imbalances due to single phasing faults.
- Phase Winding temperature based on measurement using thermistors.
- Vibration Monitoring, indicating bearing failure.
- Motor speed (inc. comparison of actual to Synchronous field speed calculated speed).

The root cause of the main wear failures was all from the main gearbox bearing, thus the current would rise due to added friction in the system. If this rise in current was monitored, possibly with the use of a current transformer (CT), figure 6, which is wired into the PLC, in real-time and limits were set to manage normal running conditions, any deviations from the norm could alert maintenance/engineering to a change in the system. This would allow for a more predictive maintenance system one where parts life cycle can be modelled and by using the real time data a prediction of part failure can be identified.



Figure 6: Current Transformer (RS components, 2021)

8.4 Data Collection and Utilisation

In the case of a new company such a company X, Historical data has only been captured over a few years, so could be construed to be in its infancy, however, even small data sets could reveal some interesting yield improvements. In the medical industry, records, explicitly data, is to be kept for 11 years to appease regulatory protocols, allowing the utilisation of big data analysis. The challenge is to migrate from the present day, where data is manually entered into inhouse developed OEE tracking Excel spreadsheets, towards an automated data collected era. Figures 7-8, shows a typical production tracking spreadsheet that helps collate the daily achievements, establish OEE metrics and report equipment, process or department issues. There are many flaws in the sheet, one most apparent is the human element, in which throughput, rejects and downtime are all manually input, which inadvertently incur errors. Stock checks are a prevalent factor, as to are part shortages due to miscounts and the assigning of incorrect stock quantities to production orders.

A short study was concluded on the wasted time taken to manually collate all the production information; the results were:

Number of people manually collating data/day = 35 (line leads, supervisors, engineers, managers)

Total hours wasted per day = 59 hours per day

Total hours wasted per week = 295 hours per week

A breakdown of the hours is shown in table 3:

	hrs/day	days/week	people	total
line lead	3	5	8	120
repair op	2	5	8	80
tsm	1	5	3	15
manager	1	5	1	5
engineers	1	5	15	75
				295

Table 3: Hours wasted through data recording (Company X, 2021)

Production Log/OEE tracker

Bare Manual 3		Product Information			Output			Total	Planned Downtime (Minutes)				Un-Planned Downtime (Minutes)					OEE			
		W/O	Model	Quantity	Mornings	Afternoons	Nights		Production	Engineering	Warehouse	Quality	Production	Engineering	Warehouse	Quality	Total	Availability	Performance	Quality	Total
	Sunday							0									0				0.0%
	Monday	5371	SSB-4J-BL	2000	0	240	0	240	59	0	0	0	0	240	0	0	299	78%	63%	97%	47.7%
	Tuesday	5371	SSB-4J-BL	2000	390	400	0	790	120	0	0	0	0	50	0	0	170	86%	105%	93%	84.5%
	Wednesday	5371	SSB-4J-BL	2000	385	400	0	785	120	0	0	0	0	0	0	0	120	88%	98%	95%	81.4%
	Thursday	5371/5372	J-BLK/SSB-3	2000/1750	371	410	0	781	129	0	0	0	0	15	0	0	144	86%	105%	95%	85.6%
	Friday	5372	SSB-3J	1750	390	385	0	775	120	0	0	0	0	0	0	0	120	88%	103%	94%	84.7%
Saturday							0									0				0.0%	
MicroBare Manual 4		Product Information			Output			Total	Planned Downtime (Minutes)				Un-Planned Downtime (Minutes)					OEE			
		W/O	Model	Quantity	Mornings	Afternoons	Nights		Production	Engineering	Warehouse	Quality	Production	Engineering	Warehouse	Quality	Total	Availability	Performance	Quality	Total
	Sunday							0									0				0.0%
	Monday							0									0				0.0%
	Tuesday							0									0				0.0%
	Wednesday							0									0				0.0%
	Thursday							0									0				0.0%
	Friday							0									0				0.0%
Saturday							0									0				0.0%	
MicroBare Manual 5		Product Information			Output			Total	Planned Downtime (Minutes)				Un-Planned Downtime (Minutes)					OEE			
		W/O	Model	Quantity	Mornings	Afternoons	Nights		Production	Engineering	Warehouse	Quality	Production	Engineering	Warehouse	Quality	Total	Availability	Performance	Quality	Total
	Sunday							0									0				0.0%
	Monday							0									0				0.0%
	Tuesday							0									0				0.0%
	Wednesday							0									0				0.0%
	Thursday							0									0				0.0%
	Friday							0									0				0.0%
Saturday							0									0				0.0%	
Bare Manual		Product Information			Output			Total	Planned Downtime (Minutes)				Un-Planned Downtime (Minutes)					OEE			
		W/O	Model	Quantity	Mornings	Afternoons	Nights		Production	Engineering	Warehouse	Quality	Production	Engineering	Warehouse	Quality	Total	Availability	Performance	Quality	Total
	Sunday							0									0				0.0%
	Monday							0									0				0.0%
	Tuesday							0									0				0.0%
	Wednesday							0									0				0.0%
	Thursday							0									0				0.0%
	Friday							0									0				0.0%
Saturday							0									0				0.0%	

Figure 7: Production Log/OEE tracker (Company X,2021)

Production Log/OEE tracker continued..

BARE														
Bare Manual 3		Product Information			Output				Production	Engineering	Warehouse	Quality		
		W/O	Model	Quantity	Mornings	Afternoons	Nights	Total						
	Sunday							0.0%						
	Monday	5371	SSB-4J-BL	2000	0	240	0	47.7%					PM- morning shift didn't run so starting up from scratch, test machines not turned on and also 3 ops off	PM...all testers switched off at start of shift,tester 1&2 back up and running @ 16:00, tester 3 & 4 down due to broken adaptors inside the machine (240 mins)
	Tuesday	5371	SSB-4J-BL	2000	390	400	0	84.5%					AM...High amount of Pre-shot fails	pm... driver mechanism on stage 3 broke, had to change driver
	Wednesday	5371	SSB-4J-BL	2000	385	400	0	81.4%					PM... High number of pre shot fails	
	Thursday	5371/5372	J-BLK/SSB-3	2000/1750	371	410	0	85.6%					AM...Change over to WD5373	AM...Issue with testers 2 & 4 with comms pin and tripping out the machine (30)
	Friday	5372	SSB-3J	1750	390	385	0	84.7%						
	Saturday							0.0%						
MicroBare Manual 4		Product Information			Output				Production	Engineering	Warehouse	Quality		
		W/O	Model	Quantity	Mornings	Afternoons	Nights	Total						
	Sunday							0.0%						
	Monday							0.0%						
	Tuesday							0.0%						
	Wednesday							0.0%						
	Thursday							0.0%						
	Friday							0.0%						
	Saturday							0.0%						
MicroBare Manual 5		Product Information			Output				Production	Engineering	Warehouse	Quality		
		W/O	Model	Quantity	Mornings	Afternoons	Nights	Total						
	Sunday							0.0%						
	Monday							0.0%						
	Tuesday							0.0%						
	Wednesday							0.0%						
	Thursday							0.0%						
	Friday							0.0%						
	Saturday							0.0%						
Bare Manual		Product Information			Output				Production	Engineering	Warehouse	Quality		
		W/O	Model	Quantity	Mornings	Afternoons	Nights	Total						
	Sunday							0.0%						
	Monday							0.0%						
	Tuesday							0.0%						
	Wednesday							0.0%						
	Thursday							0.0%						
	Friday							0.0%						
	Saturday							0.0%						

Figure 8: Production Log/OEE tracker continued. (Company X,2021)

The misconception would be that there is no big data collection, however, there is a considerable amount, it is the lack of resource or budgets to utilise it. OEE dashboards and KPI metrics visually displayed on front end data analysis software can be costly investment and the ROI is not immediate. By nature, the analytics models improve accuracy over time and require dedication to implement the solution. Since the business users do not see results immediately, they sometimes lose interest which results in loss of trust and the models fail. (Cochran et al, 2016) describes when an organisation decides to implement data analytics methods, there needs to be a feedback loop and mechanism in place to understand what is working and what is not, and corrective actions are required to fix things that are broken. Without this closed loop system, senior management may decide that analytics is not working or much valuable and may abandon the entire exercise.

The outcome was to employ a software engineer that has knowledge of both SQL database and front-end data analysis dashboards, so as to develop in house and push the innovation barriers within the company. This would allow the company to tailor its needs through a dedicated employee, directing his priorities towards necessary improvements that would change the company and propel it forward. The cost of employing a dedicated Software engineer would pay for itself within 12 months, having cancelled a contract with an outside company to oversee the IT/SQL database. The role would be to oversee the SQL database, while developing Bigdata analytics for the site, that could track part flow through the whole company and displaying it on a front-end dashboard.

8.5 Improvements in OEE through Data Collection and Analysis

Previously in Table 2, the OEE was calculated by area or variant, this included a number of assembly and packing stations, however, this part will concentrate only on the machine areas. Each machine OEE was calculated over a three-month period to indicate which were performing under the world class average of 85%. The graphical bar chart, figure 9, shows all machines from the ten lines in descending order.

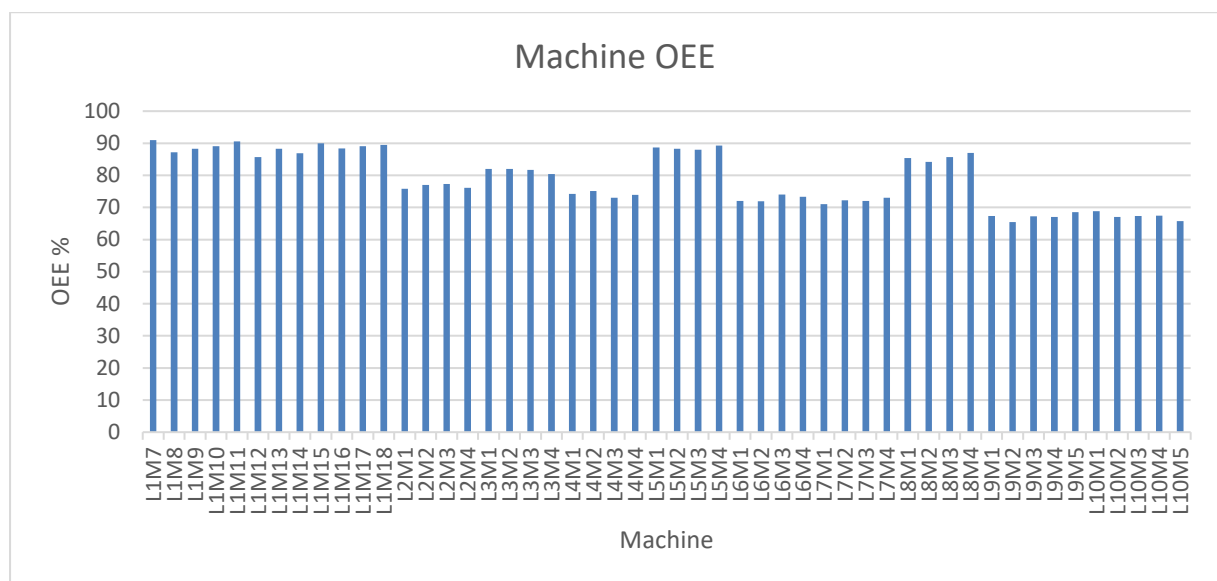


Figure 9: Machine OEE % (Company X, 2021)

Seven out of the ten lines showed significant lower machine OEE and were targeted for improvement, through both data analysis and Root cause Analysis RCA including the 5 why approach. Data collection by this point was underway, the backend database was being sectioned to allow for dashboards to be developed, see figure 11, and the creation of visual reject analysis was being presented within Kaizen projects. Action plans were being drawn up and CI projects were being assigned to improve the efficiency of the affected machines. The monthly progressive augmentation of Line 6 machine 1 for example is highlighted within table 4, which shows some of the work carried out on the machine and figure 10, the improvement trend of OEE.

Line	Machine	Issue	Planned action	Target date
6	1	Premature spring failures	Implement scheduled strain gauge testing into maintenance plan to detect possible failures, upgrade springs.	13/06/2021
6	1	Dust contamination resulting in calibration failures	Introduce autonomous maintenance at start of shift to clean tiles	04/05/2021
6	1	Machine Starved	Process improvements to previous assembly stage to remove bottleneck and feed machine	22/08/2021
6	1	High changeover time between derivatives	Introduced line barriers to allow previous works order to complete, while introducing new variant to the start of line	30/09/2021
6	1	High pin changes	Adjusted machine fixture to align pins with devices	15/07/2021

Table 4: Machine 6 improvements (Company X, 2021)

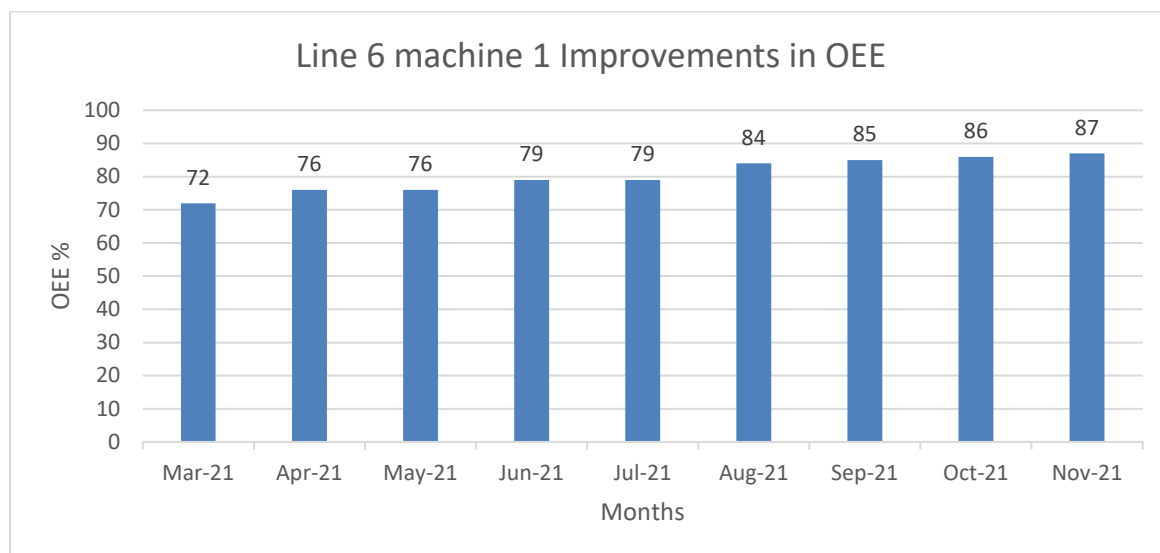


Figure 10: Line 6 machine 1 Improvements in OEE (Company X, 2021)

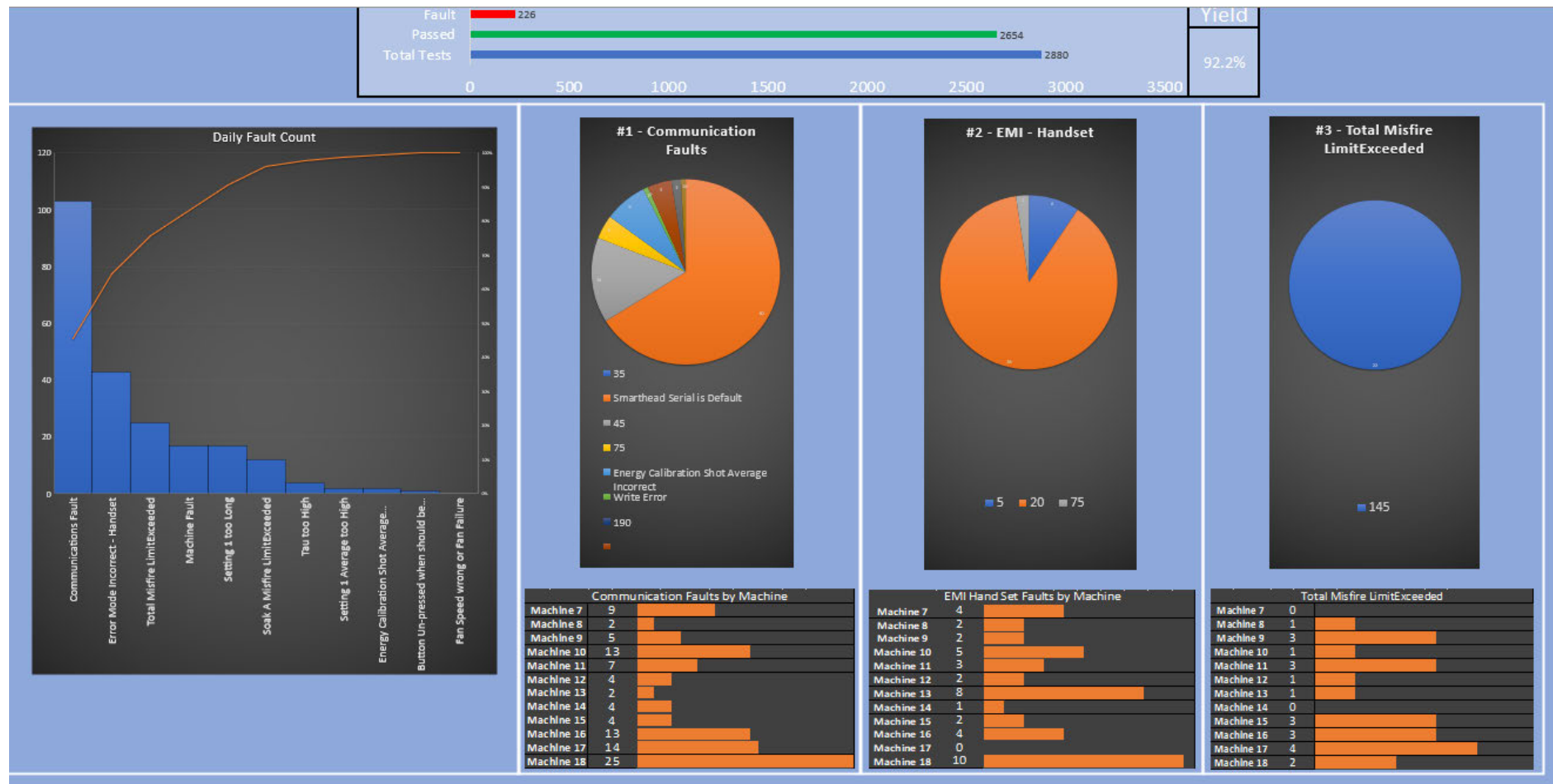


Figure 11: Reject Analysis Dashboard (Company X, 2021)

8.6 OEE Dashboard integration

The development of the front-end dashboards and the success of line 6 machine 1 ignited an analytical debate within the senior engineers. An abundance of questions arose, which required clarification to ensure the engineering department would benefit from the correct data collection.

- What data was relevant?
- How to efficiently portray the data to get the most impact?
- How many different screens would be required?
- What colour code should be adopted?
- Should the data be graphical or numeric, or both?
- How do we ensure the data was correct?
- How much is too much or is there too much data?
- Who would choose what data was relevant?

It became apparent that this decision was of such magnitude it would require a collective cross-functional group that could utilise the data for continuous improvements. Data hubs were formed, where brainstorming into all the above questions could be extrapolated from many people to decide the most diverse direction for success. The hubs were set up of no more than 4 people, consist of one senior to orchestrate and record the outcomes of the brainstorming discussions. Each group would present their ideas with clear reasoning behind their decisions, which intentionally developed further ideas and agreements on moving forward.

Figure 12 is the outcome of said hubs, from dashboard design to the colours of the graphical representations, all combining in a collective decision for the company. It was decided:

1. There should be a clear indication of Yield, where total tests, passes and rejects were clearly shown (this was mainly for top level management)
2. There would be a pareto bar graph of the daily fault count with cause (this would be for engineering, 80/20 rule applied 80% of failures would come from 20% of faults)
3. Derived from the pareto chart will be the top 3 failure modes broken down into individual machine failures (this will be for engineering and maintenance)
4. There will be a breakdown of the top 3 failure modes by machine (this will be mainly for maintenance)

Once a design was chosen, to ensure its feasibility and effectiveness it was developed to analyse the data from one area only, instead of the whole factory. This would allow a more controlled approach and test the dashboard to ensure it met the demands of different departments.

The requirement for change would be true from the first trials of the dashboard, where, after the first day it was pertinent to save the previous days data for reference. This ensured that each day the dashboard was relevant and live to the user, with a reference to past days easily retrievable. At the end of the week this request evolved further into a weekly overview, Figure 12, that could be used to benchmark weekly performance of areas and machines.

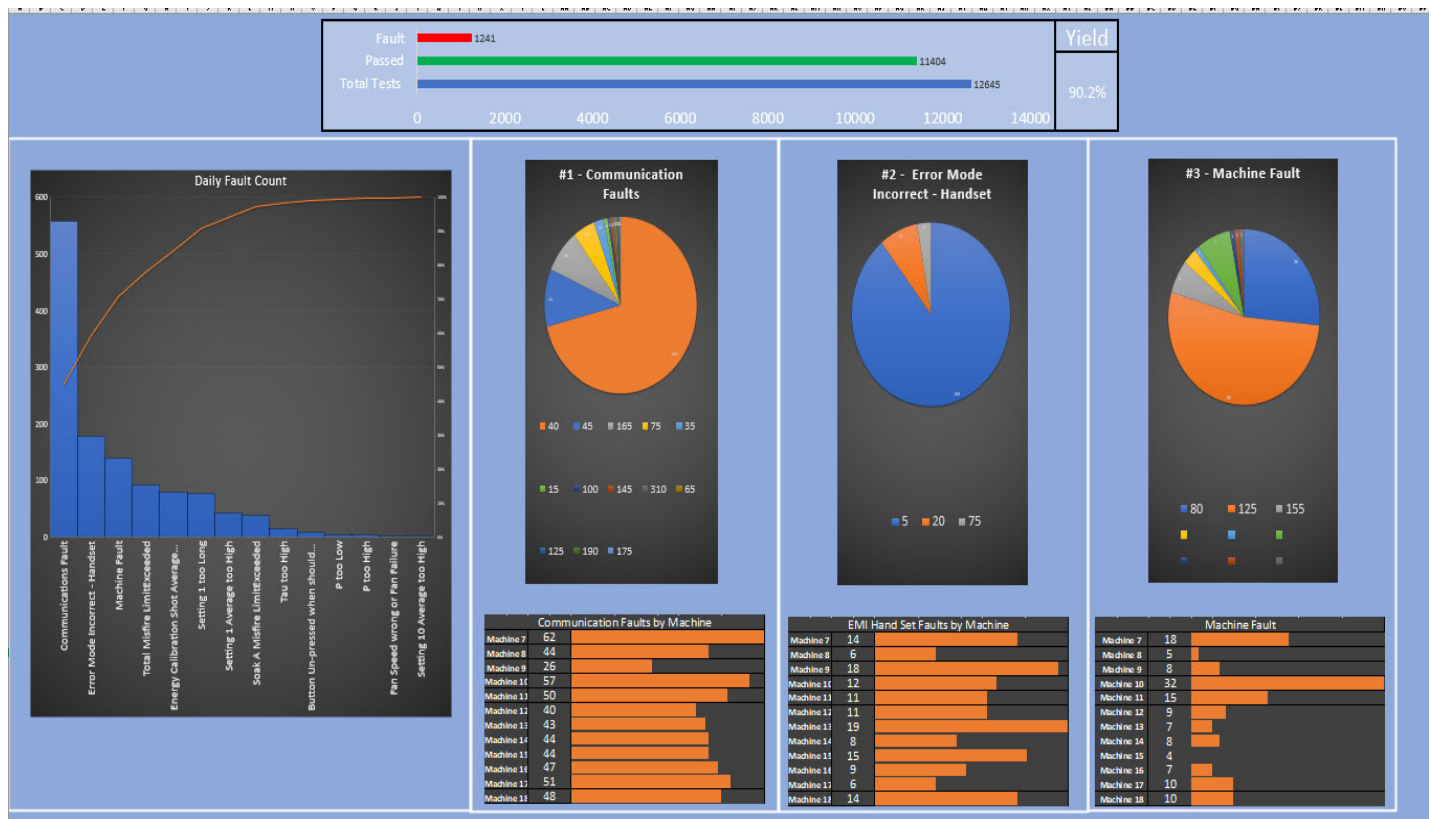


Figure12: Saved weekly review dashboard screen (Company X, 2021)

This high-level overview, figure 12, would clearly indicate problem areas, such as machine 10, which suffered 32 machine fault errors within the week, far more than any other machine. What the weekly data doesn't show, yet the daily does, is that 28 faults occurred on Tuesday and Wednesday, by Thursday it only recorded 1 machine fault due a fixture was replacement.



The one item that was agreed was missing was the addition of graphical trends of to be visually shown for evaluation and improvement action planning. These would be key in not only capturing failures that are continuously deteriorating, but those that have been actioned and removed from the reject count. The saved weekly dashboards were a means of comparing selective weekly data, however, figure 13, shows the performance of machines in terms total faults, yield and faults by machine. This screen will also be crucial to track any CI projects and their corresponding improvements, for supplier issues, quality concerns and operator performance comparisons between lines that directly affect performance and output.

Further developments would be critical to ensure the dashboards retain their relevancy, one which is prevalent and is currently being actioned, is to deliver the trend results as either a percentage of the production output or to incorporate into the trend graphs a production output line. This will visually indicate whether the fall or rise in trends has any direct correlation the production output.

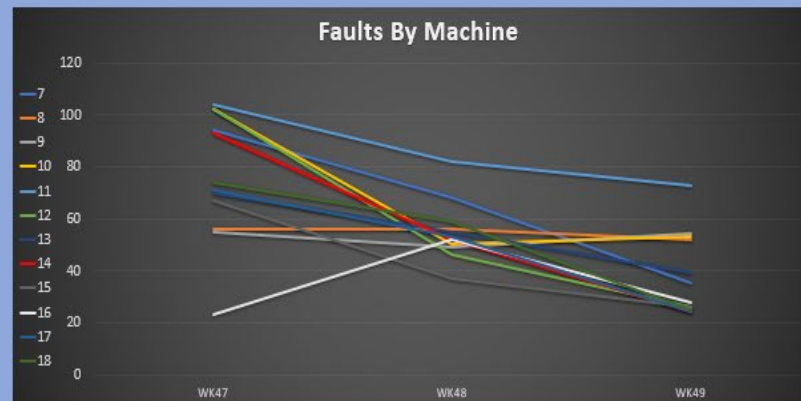
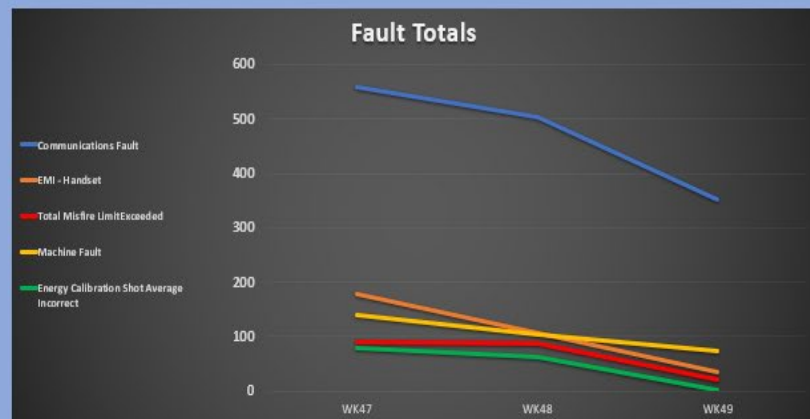


Figure 13: Trend dashboards design (Company X,2021)

8.7 Define and review resource requirements

Organisations typically plan their future needs for supplies, equipment, building capacity, and financing. They must also plan to ensure that their human resource needs are satisfied. Human Resource Planning (HRP) involves identifying staffing needs, forecasting available personnel, and determining what additions or replacements are required to maintain a staff of the desired quantity and quality to achieve the company's goals (George, 2019). Tiburca, 2017, agreed and added that a well established HRP can help in personal and professional development of employees. Furthermore, HRP could affect and boost the performance of project groups and the company as a whole.

The human resource was a critical factor throughout the project, with process/procedural failings highlighted from the onset. Capacity prioritisation by higher management was found to be the largest contributing factor, where processes were deployed as a temporary measure. Preventative maintenance on legacy equipment was deemed a secondary action to line instalments and machine commissioning. Additionally, a versatility matrix highlighted not only the need for additional resource but for a restructure of resource to fill in the knowledge gaps. Table 5, shows the personnel numbers at the start of the project compared to company at present, also including the additional staff at the new China facility. This now enables the company to operate at a functionable level, where the continued introduction of new variants/products is sustainable, together with continuous improvement and maintenance of legacy equipment.

1 st Quarter headcount 2021		4 th Quarter headcount 2021
1 x Engineering manager	UK	1 x Engineering manager
1 x Equipment engineer	UK	1 x Senior Manufacturing Engineer
2 x Process engineer	UK	2 x Manufacturing Engineers
1 x NPI engineer	UK	1 x Senior Process Engineer
1 x Manufacturing engineer	UK	4 x Process Engineers
1 x Controls engineer	UK	1 x Senior NPI Engineer
2 x Maintenance Technicians	UK	1 x validation Engineer
	UK	1 x Controls Engineer
	UK	1 x Facilities Engineer
	UK	4 x Maintenance Technicians
	UK	2 x Apprentice Engineers
	UK	1 x Software Engineer
	China	1 x Manufacturing Engineer
	China	1 x Process Engineer
	China	2 x Maintenance Technicians

Table 5: Company Headcount 2021



8.8 Update QMS maintenance operating plan

Neyestani & Juanzon, 2017, describe the Quality Manufacturing system QMS as a set of rules that document procedures, policies, processes and records, provided by an organisation on how they will achieve their business strategy. The system is created to ensure customer focus, a systematic approach to process delivery, evidence-based decision making and management. ISO 9001 is an international requirement standard which is recognised worldwide and provides framework and guidance to enable customer expectations and regulatory requirements.

Direct correlation between implementing a successful ISO 9001 QMS and an improvement in quality performance has been documented through many studies including (Neyestani, 2016), (Kuo et al, 2009) & (Sun & Cheng, 2002). One conflicting study was found (Martinez-Costa et al., 2008), where they stated that adopting ISO9001 had no real effect on internal processes, however, in contradiction, concluded that ISO 9001 certified companies performed better than non-certified.

The QMS within Company X, was updated to include the new aspects of the maintenance plan, figure 1 including annual reviews to ensure TPM relevance and incorporate any required improvements. It would be the aim that in the next review a budget will allow the introduction of a CMMS system that can integrate with the OEE dashboards and can be detailed within the QMS.

9.0 Analysis of improvements

9.1 Creation of critical spares stores with inventory list

The organisation and development of a working stores has improved the mean time to repair (MTTR) of equipment progressively throughout its introduction time. Figure 14, shows the improvement in MTTR through the course of the project. It is relevant to note that other contributing factors such as machine reliability will have a direct effect on these results, however, there has notably been a decrease in wasted time searching for spares.

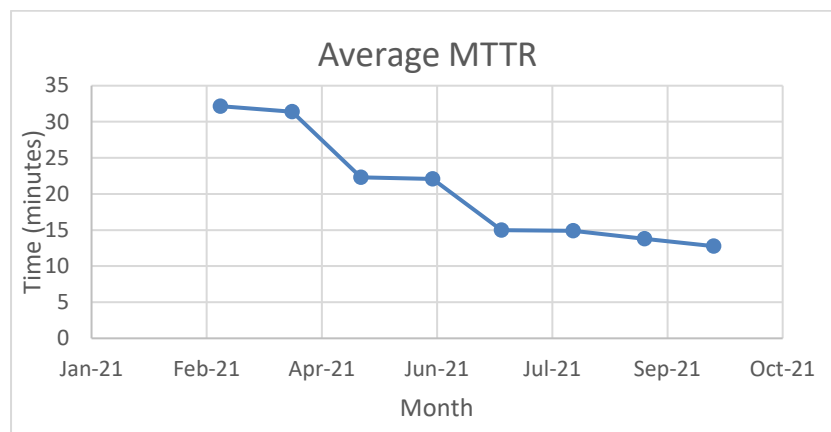


Figure 14: MTTR improvements (Company X, 2021)

9.2 Introduction of Improved PM and Autonomous Maintenance

Operator involvement and ownership is an essential part of TPM and has directly impacted the mean time between failures (MTBF) of the equipment, figure 15. The introduction of cleaning and inspections prevented downtime of machines through stabilised calibration readings, which can be affected from contamination. Furthermore, daily checks have brought about CI improvements to deliver a more robust machine cycle.

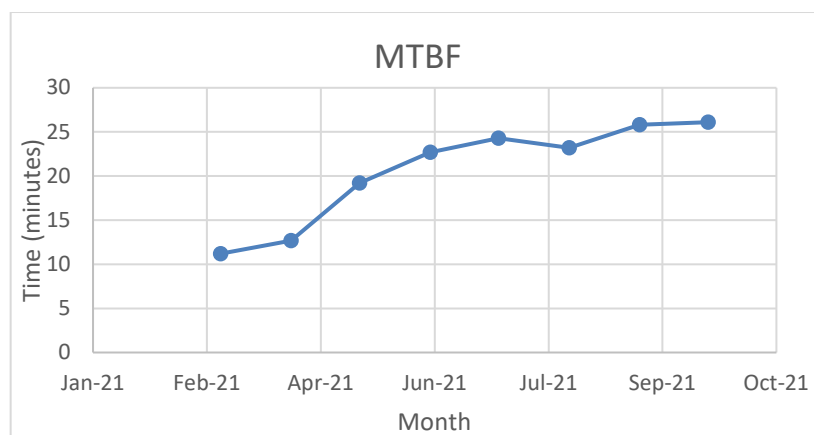


Figure 15: MTBF Improvement (Company X, 2021)

9.3 Reduction in Wasted Time Through Automated Data Collation and Analysis

Section 7.4 highlighted an approximate total time of 295 hours per week allocated to wasteful data recording and analysis through all departments within Company X. Through dashboard delivery and data retrieval from the database, which auto populates the OEE sheets instead of manual input, this wasted time has been drastically cut and repurposed into line improvements, training and project delivery. Figure 16 shows the approximate improvement in time allotted to data recording.

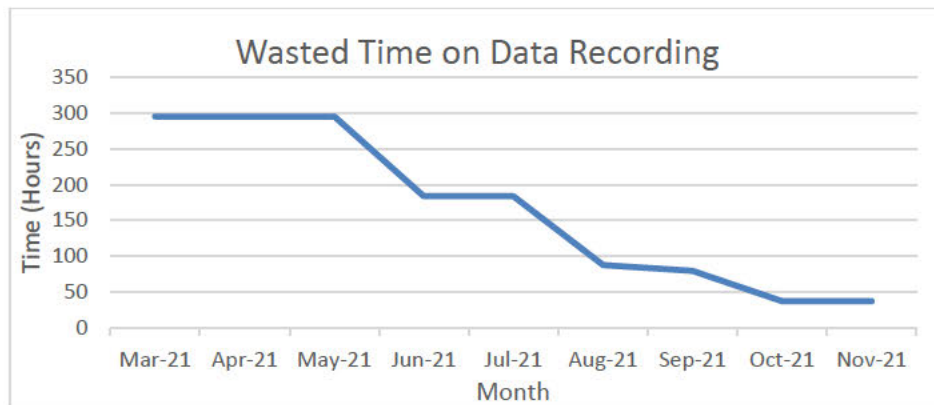


Figure 16: Wasted Time on Data Recording (Company X, 2021)

9.4 Improvements in Machine OEE

Figure 17, shows the improvement in machine OEE and the addition of two extra China lines. The graph shows the point at which OEE is at the end of the project and is contributed by improvements in TPM scheduled maintenance. PM were scrutinised and NVA tasks were removed and VA items remained, IOT current transformers were installed to monitor motor efficiency and CI actions were implemented from autonomous maintenance.

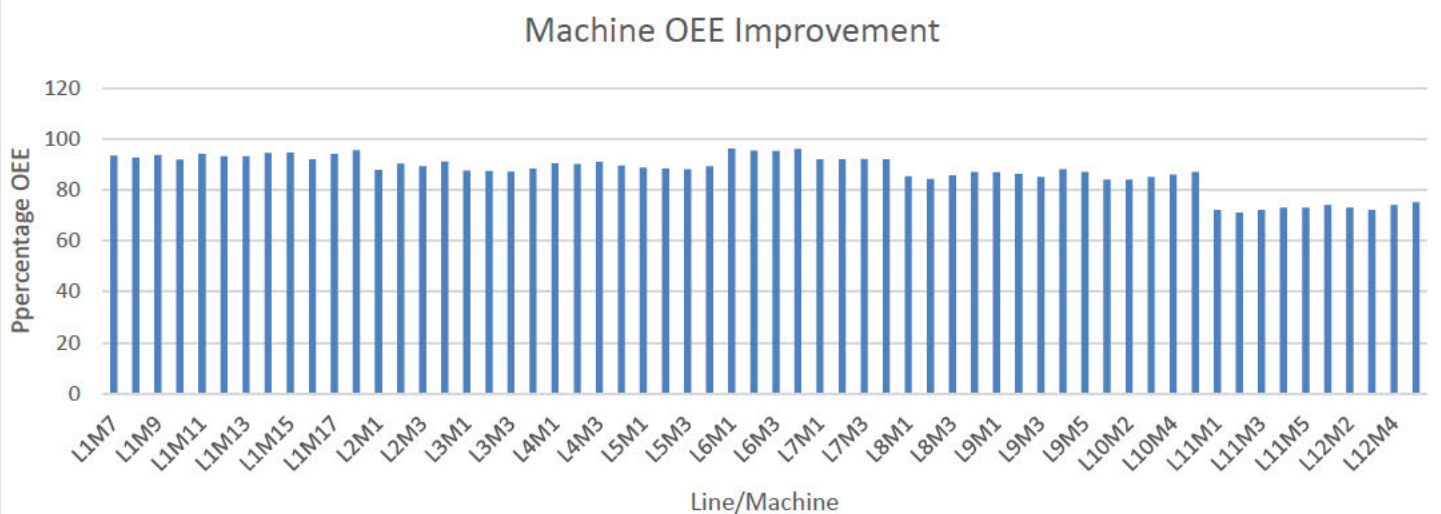


Figure 17: Machine OEE Improvements (Company X, 2021)

9.5 Improvements in TPM and OEE through data analysis and dashboard Introduction

The true extent of how effective the dashboards and data analysis have direct correlation with the improvements in MTTR, MTBF, Automating data collection and machine OEE. It continues to identify failure trends that can be minimised by adding preventative measures into TPM tasks. For example, it has proven a particular consumable life cycle is averaged at approx. 11 days, not 15 as predicted, TPM tasks have been updated to schedule pin changes every 10 days, which has improved machine failures by 7%.

9.6 Project Improvements on Output and OEE

At the start of the project some relevant output data was collated as a reference point to compare all improvements, Table 6 shows not only an improvement in output but for some a rise in weekly targets.

IPL Variant	Output Target/week (2 shifts)	Average weekly output
Variant 1	25000 parts/week	25,115
Variant 2	3500 parts/week	3502
Variant 3	6200 parts/week	6241
Variant 4	3500 parts/week	3530
Variant 5	6000 parts/week	5985

Table 6: Updated Targets and Output/week for each variant (Company X,2021)

The OEE was again calculated this time through use of the automatic populated sheets and after all improvements have been implemented. The results show that two variants are running at world class OEE of over 85%, two are just below at 83%, and the new variant 5 has achieved an improvement in OEE of 26%. It is relevant to note that variant 5 has had 75% of its capacity transferred to the China facility and even with a troubled start is still showing a vast improvement primarily due data extraction.

IPL Variant	Availability	Performance	Quality	Total OEE
Variant 1	97%	90%	96%	83%
Variant 2	98%	89%	95%	83%
Variant 3	96%	96%	95%	88%
Variant 4	98%	91%	96%	86%
Variant 5	97%	84%	89%	76%

Table 7: Updated plant OEE by variant (Company X, 2021)

10.0 Conclusions

Conclusions for the project are established in context of the aims and objectives set out in the primary chapter of the project.

Research the different Maintenance Protocols, OEE, Dashboards and Data Analytics

Concise research was documented about the different maintenance protocols that are adopted by organisations to help maintain and protect the performance of its assets. These would range from simple PM tasks, to an extensive TPM methodology that brings a sensor of ownership towards equipment and provides training on simple maintenance techniques. This knowledge would prove to be invaluable as the project developed and allowed a diverse appreciation of what was required for company X. Through deployment of the OEE metrics the trends of improvement would be captured throughout the project, with emphasis on the utilisation of OEE dashboards for both live feedback and for history backups. Data Analytics would enable managers to analyse legacy data to establish process and equipment improvements throughout the company.

Explore how these protocols are utilised within different sectors.

The exploration into the different maintenance protocols that are adopted in a range of organisations and the reasoning behind these choices, provided an in-depth insight into the criticality and improvements the correct strategy can achieve. The comparison between the different industries indicated the large gap between smaller businesses and more established companies. A study by Kyocera found that within competitive markets, smaller companies within the UK are struggling to adapt to digitisation (Spadafora , 2019). This could be said of Company X, it is only through an acceleration in resource procurement and a slowdown in the market due to Covid, that continuous improvement has been established effectively. TPM in companies such as Ford, has been established and finessed over many years with a vast amount of resource and RCM within aerospace was born out of a necessity for safety critical maintenance. It could be concluded that a blend of both methodologies together with the innovative data analytics and dashboards, could deliver halfway house between no and the smart factories of the future.

To deliver a suitable maintenance strategy for a chosen company, Company X, including:

a) Equipment criticality identification and spares

The FMECA would serve two purposes both to highlight critical components within the machines so PM or PdM actions can be adopted, and secondly to ensure that the correct critical spares are available on site. It would be developed much like an FMEA with failure modes, potential failures,



potential causes and current controls. The severity, Occurrence and Detection will all be evaluated and which will deliver not only a Risk Priority Number RPN but a Criticality score. This could be used to drive improvements to eliminate or diminish the criticality, and also to ensure controls are in place should a failure occur. The equipment FMECA for Company X turned into an enormous document that continuously developed, adding all machinery and their respective failure modes.

It drove the development of the inventory stores, a source document that would enable the creation of stocked quantity amounts, reorder points, maximum and minimum stock levels. In conclusion the development of the stores has been a resounding success, creating a quick access point to critical equipment to ensure all failures are dealt with efficiently and improving the MTTR.

b) PM revisions and autonomous maintenance

Revising the PM system through TPM and autonomous maintenance has changed the working aspects surrounding the machines for both operators and tradesmen. Ownership of the machine has given a sense of pride to the operator and driven continuous improvement, where competition for efficient working has become evident. A main attribute, is the release of resource to establish the change and ensure cross-functional development of relevant maintenance responsibilities that deliver efficient maintenance. Due to the nature of the machines and their requirement to calibrate the product, simple cleaning activities were seen to be the most beneficial in achieving improvements to machine MTBF.

c) IOT installations for PdM through condition monitoring

Though in its infancy within Company X, the introduction of IOT sensors is a milestone of innovation that will create change and development on the production floor. Condition monitoring and data modelling are an intricate part of I4.0 and the benefits could play an important role in improving the prediction of equipment failures. That said, its negative drawback is the initial investment, from purchasing of equipment such as the current transformers, additional PLC interface cards, cost of controls engineering time to install and setup and finally IT time to deliver a data model that can visually track the health and deliver warnings if an imminent failure were to occur. For an established company, the introduction of industry 4.0 would appear to require an incremental innovative development, through a revised business case and further funding. The benefits adding the current transformers will inevitably allow for a predictive means of planning in CM around production time. The conclusion would be though, to benefit fully from I4.0 tech and data modelling a full system should be covered not only small parts of equipment.



Implement and Define Big data collection and the benefits through OEE dashboards

This part of the project would typically feedback into all other areas, ensuring constant continuous improvement is visually highlighted and tracked. The development of data analytics and the dashboards was utilised to streamline the PM tasks by adding and removing NVA and NA activities respectively. By cross referencing the data critical equipment with failure rate, a correlation could be found to help evaluate stock count and replenishment criteria. Additionally, the live data model for the drive motors, would eventually feed into the planned maintenance. Through trend analysis of the motor health, this will not only show the motor characteristics, but any change in the mechanics that it is attached to, such as gears, chains, bearings, linkages and belt wear. Any deviation from the normal trend could be an imminent failure and can be acted upon accordingly.

The adoption of OEE within the dashboards has encouraged CI activities in engineering, quality and also in production, with easy access and simple dashboard layout becoming the driving force for change. This component of the project could inevitably be conceived to be more than just a tool for improvements, though a catalyst for delivering change on an ethics level.

Analysis of project improvements

The analysis of improvement shown in part 10.0, have changed Company X, in terms of OEE, into a world class leading company. The innovative additions that were deployed within the project, were critical to its success and more importantly were delivered from in house resources. In conclusion, the continuation of said improvements can only develop Company X further towards a company of the future, a Smart factory.

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