Case Study: Evaluation and Optimization of a Reconfigurable System for Automated Assembly of Deformable Products

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Abstract

Nowadays many commercial products have a certain degree of deformability which brings a set of challenges to the industrial automation scenario. An industry that is affected significantly by this is the medical product sector. In the case study presented here, a manufacturing company that operates in this sector produces a high quantity of flexible intravenous sets. The automatic assembly line used for the production was originally designed for a single product, however in response to market demands the company has modified the line to manufacture a number of product variants. This has resulted in a drop in operational efficiency of the line. This work presents a thorough investigation of this problem as a case study in the application of formal evaluation, optimization and design tools to a complex automation problem. After an analysis involving engineering tools such as operational equipment efficiency metrics and 5-why analysis, the transfer and holding of coiled tubes were identified as problem areas. Through the appropriate use of design tools and investigation in Total Productive Maintenance pillars, a number of potential design and maintenance improvements were identified. The eventual adoption of these measures are projected to lead to 55% reduction of the current lost revenue.

1. Introduction

Traditionally the study of automation and robotics considered the manipulation of rigid objects. This assumption simplified the whole problem and was therefore accepted during the development of the technology. In recent years the community began to do “something about the assumption concerning the object being rigid” [1]. Deformable objects have been classified as linear objects, thin/sheet objects and lump/three dimensional objects [2]. These geometrical categories are further classified according to the material and industrial application, each requiring different specialized manipulation.

One approach of handling deformable objects is to model them so as to acquire knowledge of their behavior in real life. Different methods have been developed to give a mathematical representation of such flexible objects and of their behavior during manipulation [3]. These include energy-based models for deformable linear objects (e.g. [4]), and discrete element approaches (e.g. [5], [6]). Other approaches avoid the use of a detailed model, and incorporate tactile and visual approaches and suitable control methods (e.g. [7], [8]) to control both grasping and manipulation of deformable material [9].

Industrial applications of linear deformable materials are rarely found in literature. In fact the above cited study found that only 11% of ninety-six published papers on non-rigid materials focused on linear deformable materials [2]. Industrial cases have included simulation of non-rigid material (e.g [5]) and the development of specific robotic solutions to handle flexible material ([10], [11]). It has been found that very limited information has been published on the assembly of medical devices. The medical devices industry is usually supported by automation specialists who custom build assembly machines depending on the approved proprietary product and production needs. The research in such areas is rarely published to avoid competitors from duplicating the technology.

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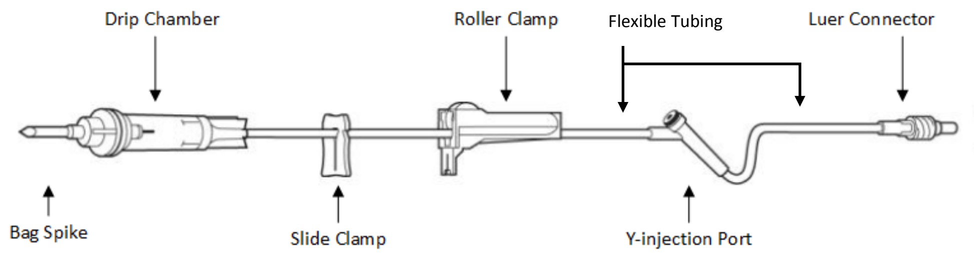


Figure 1: Basic layout and components of IV Set

This work involves the automated assembly of the intravenous (IV) set assembly shown in Figure 1, which includes flexible tubing as two of its subcomponents. The assembly work is carried out on a cam-based automated machine denoted *set automation 1* (SA1), consisting of twenty stations that assemble the various, automatically-fed, subcomponents of the product. The machine was originally developed for production of a single variant, however over the last fifteen years the engineers and technicians of the company have adapted the machine and adjusted its settings to be able to assemble thirteen variants of the product. This has resulted in a drop in the operational efficiency of the machine, which has also been seen to exacerbate over the years.

The industrial objective of this study is to evaluate critically the performance of the assembly process, with particular emphasis on the identification of those stations that have the greatest influence on the operational efficiency, and then to design solutions to the identified problems. The first stage of the study consisted in attaining in-depth familiarization with the product and with the whole production line but most particularly with each specific station. The second stage involved an analysis of the efficiency of the machine. Through a deep investigation of all the available past performance data and their component metrics, the effect of different product codes and different stations could be determined, leading to the identification of the problem stations. A root cause analysis was then held on the relevant problem areas. The third stage involved the categorization of the findings into design and maintenance inefficiencies, and the design of solutions to these problems. A formal approach was taken to the development of all solutions. Design improvements were based on the full design process and used the appropriate methods to successfully generate a new design. A full design synthesis, concept generation and evaluation, embodiment and detailed design were carried out for all selected functional improvements. With respect to maintenance, a set of recommendations was put forward after comparing the designed maintenance system with current practices as well as cross-comparing to the pillars of Total Productive Maintenance (TPM).

The academic significance and objective of this work involves the comprehensive investigation and solution development for a case study where the heuristic conversion of a fixed automation system into one that is reconfigurable has resulted in a degradation of performance. The study demonstrates the complementary and sequential approaches of (i) an in-depth understanding of the assembly process; (ii) the detailed analyses of quantitative performance data collected over an extended period; (iii) the collection and interpretation of qualitative data from manufacturing personnel; and (iv) the systematic development of both *design* and *maintenance* improvements to the automation system, in order to address a complex assembly problem involving a deformable product. The study identifies the major problem areas related to the process under investigation, traces these to their root causes, and follows through to solution development. The research methodology that was taken combines the quantitative approach (analysis of numerical data) and the qualitative approach (problem identification and solution evaluation through interviews with technical personnel). The results serve as a springboard for a wider future study on the general application of reconfigurable automation solutions to the assembly of deformable products.

2. METHODS OF ANALYSIS

2.1. OVERALL EQUIPMENT EFFICIENCY AND ITS KEY METRICS

Overall equipment efficiency (OEE) was developed by Nakajima [12] to capture all the major machine losses within a mathematical structure. OEE is calculated via Equation (1).

$$\text{OEE} = \text{Availability x Performance x Quality} \quad (1)$$

Availability captures the ratio of actual operation time to the loading time. (Note: the loading time is the time when the machine is in productive use.) The operation time consists of all the loading time apart from unplanned stoppages and setups or adjustment time. *Performance* is a calculation of the speed efficiency. It is calculated by multiplying the ideal cycle time by the number of actual assembled products and then dividing by the whole operating time. *Quality* is the direct ratio of the number of defect free products to the total number of products produced during

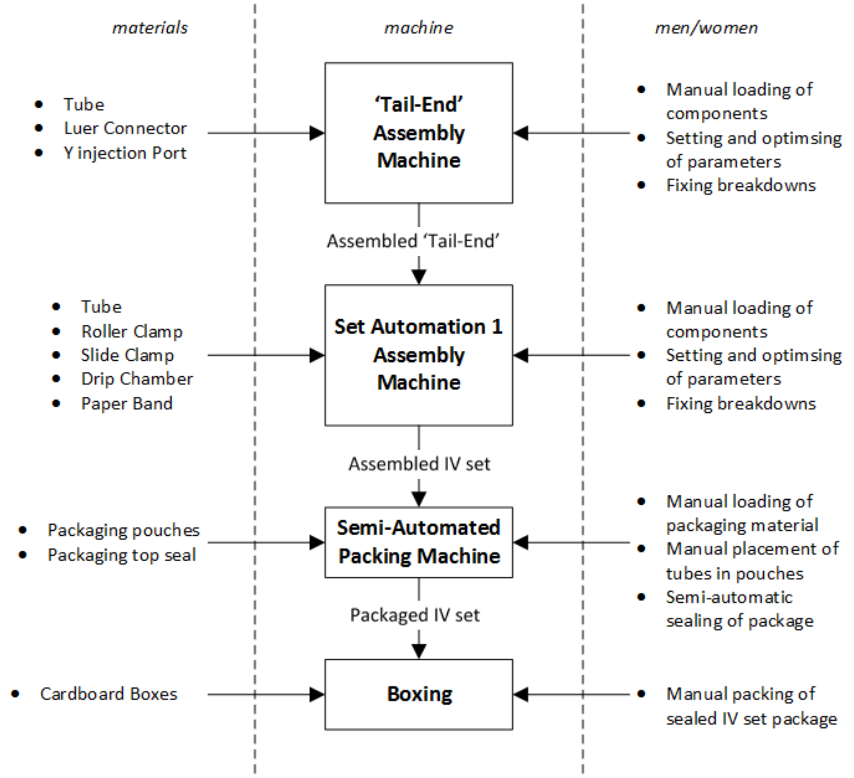


Figure 2: Sequence of IV set assembly

the operating time.

2.2. PARETO AND ROOT CAUSE ANALYSIS

These two tools were used substantially throughout the investigation stage of the study. The *Pareto* tool uses the 80:20 rule of thumb "to separate the vital few from the trivial many" [13]. The root cause analysis was then carried out using the *5-why* tool. This involved the continual use of the question 'why' to any cause that is identified in an issue until the primary cause is identified.

2.3. DESIGN METHODOLOGY

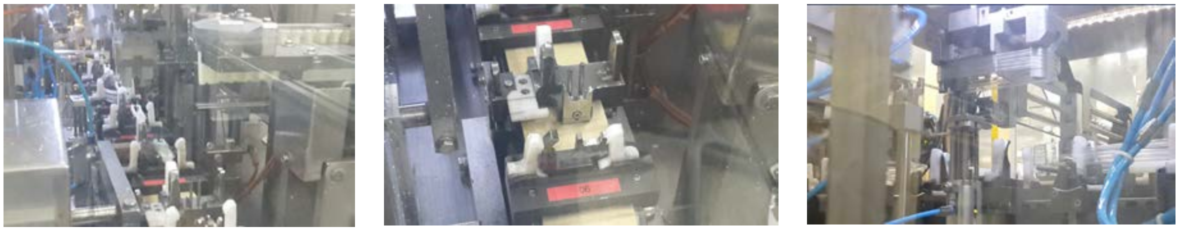
Throughout the design improvement stage the *Stuart Pugh* design methodology was used [14]. This involved the application of several design methods at four main key stages: Specification, Conceptual Design, Embodiment and Detailed Design.

2.4. TOTAL PRODUCTIVE MAINTENANCE

A proper understanding of the TPM Model as proposed by its founder Nakajima [12] and as proposed today by the Japan Institute of Plant Maintenance (JIPM) was needed. The study utilized the first six equipment-focused pillars of the JIPM Model (e.g. [15]): autonomous maintenance; individual improvement; planned maintenance; quality maintenance; education and training; and safety, health and environment.

3. THE ASSEMBLY PROCESS

The overall sequence for the IV set assembly is shown in Figure 2. The components used within the assembly are placed manually within automatic feeding systems that feed directly to the appropriate stations of SA1. The 'tail-end' assembly machine is considered a separate automated machine that assembles the bottom part of the IV set, referred to as the tail-end. Detailed views of SA1 are shown in Figure 3. The cam can be found under the assembly level of the



(a) (b) (c)

Figure 3: (a) General view of SA1; (b) Empty nest at start of sequence; (c) Coiled tube just before being lowered into nest

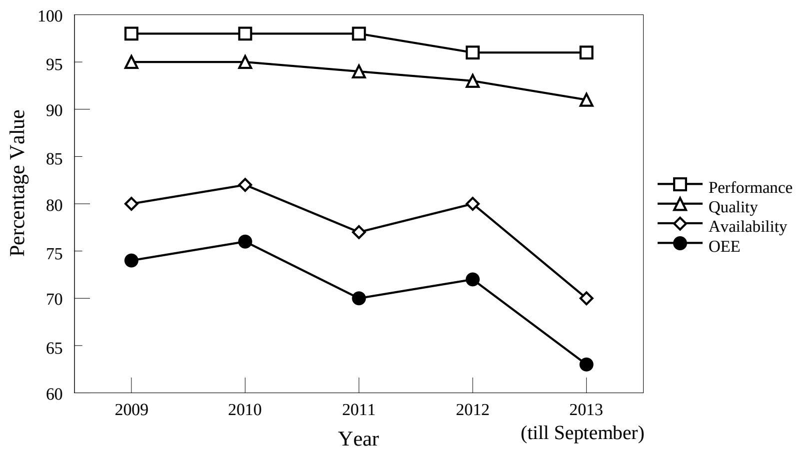


Figure 4: OEE metric trendlines for all sets

machine and it is operated via a single electric motor. As it turns, it provides the required movement to the linkage system of each station. At the end of each linkage one finds a number of different, PLC-controlled, pneumatic actuators that are required for the various subsidiary motions (e.g. holding and releasing the subcomponents). A digital rotary encoder located on the main camshaft keeps the PLC synchronized with the movement of the cam-linkage system. Additionally SA1 uses electrical servomotors to provide the necessary fast rotary motion at the coiling and unloading stations. All of these actuating mechanisms are complimented with an array of feedbacks such as micro switches and proximity sensors that ensure that an alarm goes off if the expected and timely feedback is not received. Other sensors, such as a visual camera, ensure that the product being assembled is according to product specifications. If such sensors detect a reject, the unloading station puts that specific product in the rejects bin instead of the packing conveyer.

4. Analysis and Trends

4.1. Overall Equipment Efficiency Analysis

Results showed that the OEE for Set A (which contributes to 60% of total production) was 62% while the other combined sets had an OEE of 53%. This confirmed that different sets contribute differently to OEE data. Furthermore, investigations into past OEE showed that during 2013 there was a 10% drop as shown in Figure 4. This can be mainly attributed to the *availability* metric although there has also been a worrying gradual decrease in quality, where rejects have doubled in five years.

It was found that the *availability* value is not calculated properly as per literature. The value that is actually calculated is the asset utilisation for the *Total Effective Equipment Productivity (TEEP)* metric, and therefore does not exclude planned downtime from its calculation. However due to considerations and assumptions taken, the data points only included a few instances of planned stoppages that were incorrectly captured within the value. These consisted of the one hour cleaning times and could be omitted by increasing the value of the metric by 2%. In this way the reason for the drop in availability would be only due to breakdowns and alarms stoppages as required.

Performance values within the information portal are calculated by actual speed versus theoretical speed. The actual speed is set manually by the technician and remains constant due to the cam nature of the machine. This metric did not contribute to any useful information except that it seems that there is a correlation between slightly lower speeds and higher levels of quality.

The *quality* value for Set A is 91%, and has resulted in a double-fold increase in the number of rejects over five years. Identification of the largest contributors was required and this is documented in section 4.3.

4.2. Analysis of Alarms

From a total number of seventy-eight alarms, the highest contributing alarms were identified using a Pareto analysis. This identified two alarms as being the main culprits of alarm stoppages, with only sporadic instances of other alarms. The highest alarm contributor was the '*Stn_20_Alarm_Nest_Not_Empty*' at around 30%. This alarm is activated when the set is not removed by station 19 from the nest and remains stuck. This requires that the machine operator remove the set manually. Further investigation has shown that the quantitative duration of the alarm has been constant throughout the months. The other alarm '*Stn_Gnd_Alarm_Press_Too_Low*' had a high reading at the start of 2013 but was practically non-existent by September 2013. The reason for this could not be definitively proven but could be either due to tapered operation reduction in another assembly machine or to maintenance on the SA1 pressure tubes or pressure system.

4.3. Analysis of Rejects

A Pareto analysis was again held to identify the primary reject modes. The summary presented here only shows the top two rejects. The highest reject was *'Stn 05 Reject Coil Present'* with an average of 19±7% and a linear trend-line increase of 5.5%. The reason for this reject is due to tangling of the coiled tube which results in the presence of two or more tubes in the roller clamp or none at all. The second highest reject was *'Stn 13 Reject Cognex Dripchamber'* with an average of 17±9% and a linear trend-line decrease of 11%. This reject occurs when the camera captures and calculates that the insertion limits of the drip chamber have not been adhered to.

4.4. Analysis of Costs

A very conservative profit of 10 Euro cents on each set was used to calculate the current lost revenue. It resulted that while rejects lead to a monthly loss of about €10,000, lost production during alarm initiated stoppages lead to a monthly loss of over €26,000. This means that considering that 45% of alarm stoppages are due to the tangling of coil, and that most rejects had to do with the incorrect positioning and holding of coil, there is a potential saving of up to 55% of the current lost revenue by addressing coil handling alone.

4.5. Major Problem Areas and Root Cause Analysis

The investigation of the alarms, rejects and costs confirmed that the two main areas that contributed to the tangling of the coil were the transfer of the coiled tube from coiling head to nest; and the holding of the coiled tube on the nest throughout all assembly operations. Apart from this it could be concluded that the large product range contributed in very different ways to the OEE values. Changeovers are far from perfect and usually go beyond the initial setting time and take sometimes a day to fine-tune by trial and error.

A 5-why analysis was held on these identified problem areas and is shown in Figure 5. The primary causes were found to be (1) Maintenance issues (lack of synchronisation; incorrect setting of parameters); (2) Design issues (incorrect ungrasping mechanism; not enough contact points to hold coiled tube; supports do not allow for placement variability); and (3) Product control issues (different ageing of tubing leads to different properties).

5. Design Improvements

5.1. The Nest

<u>Design Synthesis</u>

As established during the analysis stage, one of the objectives was to improve the catchment and holding of IV sets throughout the whole assembly process. A *function tree* was therefore created for the nest. This clearly identified all the inputs and outputs without determining the internal mechanisms of the system. After this, a *Product Design Specification* was drawn up to better define the design problem: this classified each specification to be either a demand or wish. A *Quality Functional Deployment Chart* was also created to transfer all the customer needs and requirements into engineering specifications. This method confirmed that the nests should be only directly mechanised, should avoid mountable electrical or pneumatic actuators, and should be modular. It also led to a *house of quality*, which clearly portrayed the relationship between all engineering specifications.

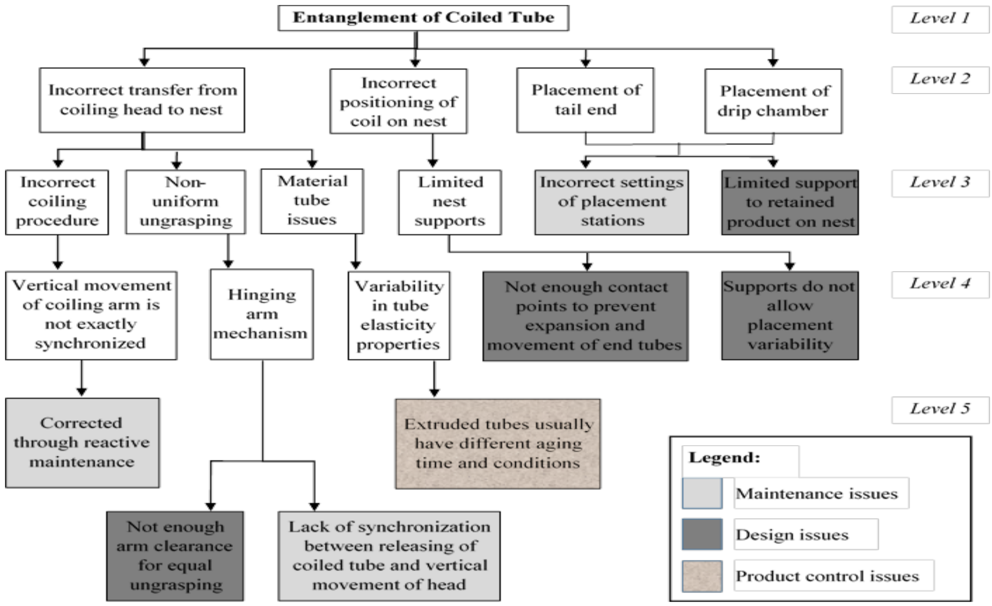


Figure 5: Summary of the 5-why analysis carried out on the problem areas

Generation, Evaluation and Embodiment of Concepts

A number of design tools were used to generate and evaluate possible design solutions. After a *brainstorming session*, the *morphological chart* neatly laid out all the possible means for each function. Each function was then sieved through the *Debono's Thinking Hats* [16] tool until a winning concept was selected, and then this was evaluated through the *SCAMPER* tool [17]. Each selected means for each function was then followed by the embodiment of the means. *Failure modes and effects analysis* was used to evaluate the existing and new designs.

Detailed Design

Through the use of reverse engineering of the existing components and the definition of the crucial dimension, the developed concept was then translated into an engineering computerised three dimensional model. The result of the upgraded model can be seen in Figure 6 (a). The upgrades consisted of the addition of two passive supports to the front and one to the back of the nest; incorporation of a new tab for added support; lengthening of the hinged support; improved securing of the pin support; modification of the roller clamp holder; and an end-tube support upgrade that allows attachment of more variants.

Design Review

The design review was conducted with the company engineers and received high appraisal for all the proposed upgrades. The most interesting novel solution was the use of an interference-fit end-tube support, which has the potential of avoiding costly gripper maintenance and tube cutting.

5.2. The Coiling Head

Design Synthesis, Concept Generation, Evaluation and Embodiment

The design methods and tools outlined in section 5.1 were applied for the ungrasping feature of the coiling head.

The concept generation and evaluation selected the 'horizontal movement of one arm' means. The embodiment stage studied in detail how this means could be achieved through a number of design configurations.

Detailed Design

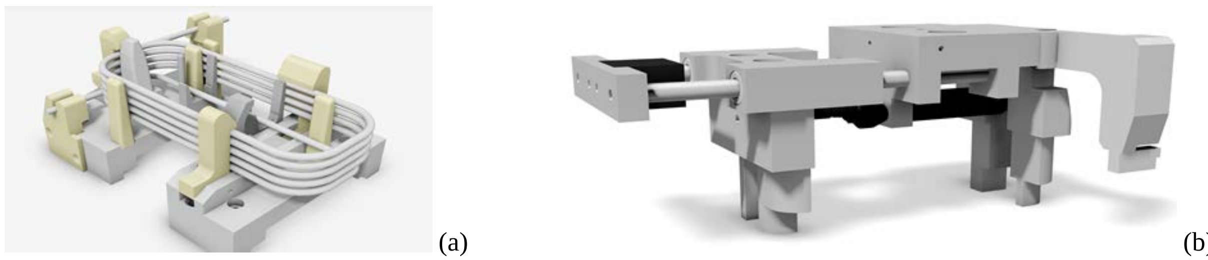


Figure 6: (a) 3D rendering of proposed nest; (b) 3D rendering of proposed coiling head

All of this resulted in a proposed design that suited all the customer needs and engineering requirements as shown in Figure 6 (b). The upgrades consist of rod rails that allow the movement of the back arm and that can be moved and secured to different positions; and a quick-change back end that allows very quick change to set different coiling lengths. The design allows the use of both 25mm and 40mm stroke pneumatic cylinder. While the 25mm stroke just covers the existing head variability, a 40mm stroke allows a wider range of product lengths. A static front arm replaces the hinging arm. It was found that the new design resulted in only an 8.5% increase in weight.

Design Review

The company engineers also commended the detailed design proposed. The only concern was that the hardened moving rod rails could pose a problem with grip screws. This led to a proposal to use a variable damper instead of having to set coiling length through the moving rods.

6. Maintenance Improvements

6.1. Overview of Actual Systems

A thorough study of the designed system, comparison with current practices and analysis of the current level of TPM implementation was held. The standard operating procedures (SOP) of the company capture the basis of the TPM philosophy, meaning that the SOP attempts to regularize and document all maintenance carried out while including all employees for maximum efficiency. Roles and tasks are clearly defined, and the start-up of SA1 follows a rigorous procedure that both machine operators and technicians are bound to follow. Importance is given to machine cleaning which is held daily during an allotted one-hour production stoppage. The product changeover is covered within the SOP and the main important tasks are listed in a checklist. Quality checks are also stringent after such changeovers or major stops to ensure that the highest quality is maintained. Another aspect covered by the SOP is preventive maintenance, where for SA1 the company takes a supplier-based approach and carries out tasks weekly, monthly, quarterly or yearly according to the specification laid out by the machine or component suppliers.

In order to investigate whether the actual practices matched those that were prescribed, an interview was carried out with a number of personnel responsible for SA1. Most of the interviews were held with the technicians due to their availability and also because they form the backbone of the maintenance system. Apart from the comparison of actual versus official procedures, a number of other undocumented variations emerged during the interviews. The first section of the interview looked into the employee's induction and training on SA1, and it resulted that the one month induction given to all technicians was augmented by ongoing "learning by doing" that continued to improve their skills. The second part of the interview discussed the troubleshooting of problems, and most technicians said that they use self-observation, information from machine operators, machine alarms as well as the SA1 screen to find an issue. Data is compiled on spreadsheets and discussed, interventions are recorded, and quality issues addressed through proper documentation. During discussions it emerged that the technicians solve most issues from their self-knowledge. The third section of the interview delved into the use of the proprietary information portal. All technicians said that they preferred to use the SA1's screen which offers a limited range of alarms and rejects data, while saying that the extensive data offered by the proprietary software is used by the management and engineers.

6.2 .Summary of Prioritised Recommendations

The first target should be to upgrade the present rejects and alarms trends analysis. The segregation of OEE data according to product code, proper calculation of availability and automatic plotting of alarms and reject trends would avoid the archaic manual system that is used presently for such analysis and eventual action. The second recommendation is to create a problem solving strategy and monitoring system. This would create a documenting logging system of all interventions as well as a standardised way of tackling a problem using appropriate tools. The third step is to create a detailed procedure manual for the exact sequence and steps during changeovers. The system should aim to set standard key parameters instead of taking a personal trial-and-error approach.

7. CONCLUSION

Through the systematic application of several analytical methods a complex system was dissected and primary root causes of problems identified. Once such issues were identified, other methods led to the development of a number of recommendations within both design and maintenance aspects of SA1. The improvement plan was received very positively by the company engineers and is planned for implementation. This improvement plan can result in the reduction of 55% of lost revenue and help develop a mentality that in the long run should lead to even more savings.

A number of avenues for future work are identified. Following the implementation of all of the proposals contained herein, a follow-up study can be carried out to determine the effects of the upgrades. Further study can be carried out to simulate the product within the assembly operations, based on an investigation and analysis of the mechanical properties of the plastic tubing used in the assembly. Such a study would allow the perfecting and testing of any design upgrades in a virtual environment and reduce the number of physical prototypes. In the industrial context, where time to upgrade and experiment with the machine is limited due to production needs, virtual simulation would be preferred. Finally, noting the number of deficiencies that are still present to properly achieving the TPM philosophy within the context of this case study, a new academic study could focus on the current implementation and challenges of TPM within a wider sample of manufacturing firms.

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