Faculdade de Engenharia da Universidade do Porto

Maintenance management of a production line
– a case study in a furniture industry

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Summary

This dissertation project was developed in the maintenance and production section of a factory belonging to the IKEA Industry and Swedwood group, located in the municipality of Paços de Ferreira, with large production rates. The enterprise is mainly specialized in the furniture sector, being one of the largest multinationals in the field, recognized by the consumer by their product, marketing and business model characteristics.

The main goal of IKEA´s Maintenance Department (MD) is to assure the necessary resources to ensure compliance of production plans in each production line (PL) and reduce the company's operational costs. Currently, the maintenance and production team objective is to improve the Overall Equipment Effectiveness (OEE), where the average value achieved in the previous fiscal year was 39.90%, through the method Total Productive Maintenance (TPM). The main purpose of this project is to develop a global action framework to obtain an OEE value above 60.00% in the selected PL, in the medium term.

The required processes to achieve this goal are: global analysis of the factors influencing the lines by the relevant and possible perspectives; implementation of new methodologies for detection and monitoring of equipment conditioning; elaboration of a maintenance plan (MP) based on the methodology Reliability Centered Maintenance (RCM) and use of the technique Failure Mode and Effect Analysis (FMEA) to optimize preventive maintenance (PM) actions. The plan also includes work orders based in predictive maintenance (PdM) activities; formulation of an Integer Programming (IP) applied to the obtained MP solutions to assisting in decision making; restructuring of data collection and organization; introduction to data mining through application of a relational model, enhancing a continuous improvement mentality.

Implementing such measures expects: optimize work orders respective to planned maintenance schedules; define PL´s top losses and discover undetected patterns; interpret information resulting in Standardized Work improvement, essential element to promote TPM; greater control of factors associated to PL, allowing to anticipate and react more effectively to future problems.

The study of disruptive monitoring systems is of great importance to the company´s future organizational structure and investment projects, leveraging IKEA with the resources needed to overcome the competitive market.

Gestão da manutenção de uma linha de produção - Um caso de estudo numa indústria de mobiliário

Resumo

Este projecto de dissertação foi desenvolvido na secção de manutenção e produção de uma fábrica pertencente ao IKEA Industry e grupo Swedwood, localizada no concelho de Paços de Ferreira, com elevados rácios de produção. A empresa especializa-se principalmente no sector mobiliário sendo uma das maiores multinacionais no campo, reconhecida pelo consumidor pelas características do produto, *marketing* e modelo de negócio.

O principal objectivo do departamento de manutenção é assegurar os recursos necessários para garantir a conformidade dos planos de produção em cada Production Line (PL) e reduzir os custos operacionais da empresa. A finalidade da equipa de produção e manutenção é melhorar o Overall Equipment Effectiveness (OEE), cujo valor médio alcançado em 2017 foi de 39,90%, através da metodologia Total Productive Maintenance (TPM). O propósito central deste projecto é desenvolver um quadro de actuação global que permita obter um OEE superior a 60,00% na PL selecionada, a médio prazo.

Os passos necessários para alcançar o objectivo são: análise global dos factores que influenciam a linha pelas relevantes e possíveis perspectivas; implementação de novas metodologias de detecção e monitorização das condições do equipamento; elaboração de um Maintenance Plan (MP) baseado na metodologia Reliability Centered Maintenance e utilização da técnica Failure Mode and Effect Analysis (FMEA), optimizando ações de manutenção preventiva. O plano também inclui ordens de trabalho baseadas em atividades de manutenção preditiva; Formulação de uma Programação Inteira (IP) nas soluções do MP assistindo na tomada de decisão; reestruturação de coleção e organização de dados; introdução ao *data mining* pela aplicação de um modelo relacional, incentivando uma mentalidade de melhoria contínua.

Implementar tais medidas prevê: optimizar ordens de trabalho respectivas a horários de manutenção planeada; definir maiores perdas na PL e evidenciar padrões indetectados; interpretação de informação conduzindo ao melhoramento de Standardized Work, elemento essencial na promoção de TPM; obter maior controlo dos factores respectivos à PL, permitindo antecipar e reagir mais eficazmente a problemas futuros.

O estudo de sistemas de monitorização disruptivos ganha relevo no futuro da estrutura organizacional da empresa e projectos de investimento, fornecendo ao IKEA os recursos necessários para superar o mercado competitivo.

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Contents

Acronyms

AM – Autonomous Maintenance
ARM – Association Rule Mining
BoF – Board on Frame
BoS – Board on Style
CbM – Condition based Monitoring
CL – Complete Line
CM – Corrective Maintenance
DV – Decision Variable
ERP – Enterprise Resource Program
EV – Expected Value
F&W – Foil and Wrap
FM – Failure Mode
FMEA – Failure Mode and Effects Analysis
FR – Failure Rate
IP – Integer Programming
ISD – Information Systems Department
KPI – Key Performance Indicator
L&P – Lack and Print
MD – Maintenance Department
MP – Maintenance Plan
MT – Maintenance Technician
OEE – Overall Equipment Effectiveness
PD – Production Department
PdM – Predictive Maintenance
PFF – Pigment Furniture Factory
PL – Production Line
PM – Preventive Maintenance
PO – Production Operator
PrM – Proactive Maintenance
PT&I – Predictive Testing & Inspection
RCM – Reliability Centered Maintenance
RM – Reactive Maintenance
SWO – Standardized Work Order
TPM – Total Productive Maintenance
WO – Work Order
MWT – Mean Waiting Time
MTTR – Mean Time to Repair
IID – Independent and Identically Distributed
ST – Statistical Test

1 Introduction

This thesis is developed in the scope of the Integrated Master in Industrial Engineering and Management at the Faculty of Engineering of the University of Porto.

This chapter describes the context in which the project is structured. It aims to explain: project framework; facility aspects and company current business state; project goals in more depth. It also displays a chronogram of activities and methods followed during the time period at the company. In the end of the chapter, a brief description of the next chapters is made.

1.1 Project Framework and Motivation

The execution of this thesis was made in an IKEA Industry factory initially starting in the Maintenance Department (MD) but culminating in the integration of several departments such as the Production Department (PD) and the Information Systems Department (ISD). The time frame in which this project was designed occurred between September, 2018 and January, 2019.

The maintenance field has become of particular interest due to the increasing costs and activities necessary to support line functioning. Particularly, large industries gradually need to invest in maintenance to reduce line stoppage and machine deterioration, prolonging manufacturing hours and increasing equipment life expectancy.

The maintenance area gains importance with the progressive development of new technologies to automate production lines (PL), obtaining higher production rates and quality. Therefore, research needs to be made to better understand and control the factors that condition line functioning and respective efficiency.

The initial suggested theme that caused the conception of this project was the study of *downtimes* in production lines (PL's) and elaboration of a Preventive Maintenance (PM) plan. Although, the opportunity to enlarge the PL identification problems arise and a complete study to it was performed. The PL chosen to be the study subject is the Complete Line (CL) due to its lower efficiency values compared to the remaining lines.

The CL achieved an average value of 65.49% and 67.52%, between January and July of 2018, for the availability and performance indicator, respectively. The stipulated benchmark for the availability is 90.90% revealing the discrepancy between expectations and reality. The compliance with the PM plan is also decreasing compared with the values depicted in a former study (Oliveira, 2016). The average compliance was 63.90% between September, 2015 and February, 2016 while for the same time interval in the fiscal year 2018 the average value was 2.70%, compared to a defined 90.00% benchmark. This fact clearly suggests a kickback in what is considered to be the best maintenance practices.

Therefore, the necessity to fully explore the maintenance and production framework emerged to propose a concise and effective PM plan based in historical failure data and the necessary dataset pivoting to explore different perspectives in important line influencers. It also gives opportunity to the implementation proposal of new methodologies that involve emerging technologies, both at technical and management level, such as Predictive Testing & Inspection (PT&I) tools and Data Mining models.

1.2 The IKEA company and factory situation

IKEA is a multinational group originally Swedish, characterized by its "ready-to-assemble" furniture, kitchen and home tools. The company is also known for its modernist's designs and the products are often associated with eco-friendly simplicity. Currently, IKEA detains more than 40 facilities globally in three continents, manufacturing 11% of the available products.

IKEA is going through a stage of global expansion since 1963, operating in 52 different countries. Figure 1 demonstrates the location of the new IKEA stores in 2018 around the world.

Figure 1 – New IKEA stores location in 2018 (source: https://www.ikea.com)

The increasing growth of IKEA clearly shows the business phase in which the company is, as displayed in Figure 2. In this phase sales accelerate and the cash flow becomes positive. Although the firm is also known for its investments in cost control and operational details, the company will only mainly prioritize cost reduction in the maturity stage, when the market is saturated, and increase in profits obtained by cost reduction.

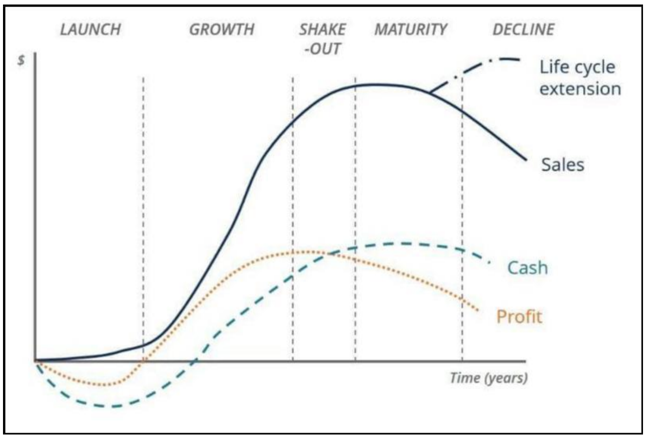


Figure 2 – Business life cycle of a company (source: corporatefinanceinstitute.com)

The IKEA Industry facility located in Paços de Ferreira, is divided in two factories manufacturing different types of product: the Board on Frame (BoF) and Pigment Furniture Factory (PFF). Both factories store their products in a central warehouse. The PFF factory is considered independent and is excluded from the study subject in this project.

1.3 Project goals

The main objective of this thesis is to increase both availability and performance efficiency indicators in a specific PL: the Complete Line (CL). It also intends to reduce the main costs and promote better organization related to maintenance. It suggests partial restructuration of maintenance activities and forward steps to consider in the future.

In an initial phase, a global analysis of the factors conditioning line efficiency will be made through different perspectives, to detect and correct potential major flaws. The data will be processed to generate new attributes and better understand the top losses of the Production Unit. A Pareto chart will be created to perceive the main failure causes in the CL. The data collected from automated monitoring will also be subject to an Association Rule Mining (ARM) detecting potential connections between line inefficiency, line stages and other line aspects.

The TPM method will be studied in the system to evaluate the “6 Big Losses”, which integrate the Overall Equipment Efficiency (OEE). Then, a RCM approach will be made to create a cost-effective maintenance strategy to address dominant causes of equipment failure. Consequently, a Failure Mode and Effects Analysis (FMEA) technique will be applied to detect potential failures that may exist. The technique will be implemented to describe the root causes of failures in critical equipments based in the study of historical maintenance data and the workers knowledge. This technique aims to discover and catalogue failure modes (FM) of components in a respective equipment. The optimal periodicity will be defined for the main FM’s with an increasing Failure Rate (FR) and discussed with the MD´s personnel for matters of calibration. The method associated to inspection activities will be studied, to perceive the current state of predictive maintenance (PdM) at the factory. A MP will then be created integrating both time-based and condition-based tasks. An Integer Programming (IP) will be applied in the MP results to support Work Orders (WO) allocation in a certain period.

To summarize, the following activities will be executed:

- General analysis of the CL´s top loss factors through different angles to discover major problems;

- Implementation of an ARM model to determine unknown relations. It also generates an incentive to improve TPM;

- Detection of critical equipments with top losses associated to Availability and historical failure study using a RCM method with FMEA technique application to assign FM´s. Posteriorly, the optimal periodicity is determined to perform PM in the most relevant FM´s, taking into account the unique characteristics regarding each one;

- Study of the Predictive Testing and Inspection (PT&I) field and methodology proposal to be integrated in the MD functions. This method is considered disruptive due to the potential impact the information taken from inspection tools can arrange to line control;

- MP proposal composed by both PM and PdM tasks, calculating the risk analysis for each FM or considered system to support management decisions related to tasks allocation during planned maintenance hours. Such MP can eventually extract data from the maintenance and business program to manually or automatically calculate FM´s deterioration function;

- Formulation of Integer Programming (IP) into MP solutions to support decision-making based on considered decision variables (DV) and restrictions.

1.4 Method followed in the project

This section describes the steps taken during the project. In Attachment A, a Gantt chart is represented to demonstrate the activities and methods executed during the time frame witnessed at the company.

In the initial two weeks, the facility and MD were presented followed by integration and adaptation phase, as well as the selection of the study subject. In a second phase, a study of the equipments failure rate (FR) was made and a Pareto chart created concerning CL´s equipments top losses. Later, the data collection monitoring method was studied. This approach was made to determine the current state of maintenance at the factory and its available resources. The analysis of the CL through the dataset extracted from the business software was then executed. Afterwards, the dataset was processed to generate potential attributes that can allow a better understanding in detecting line´s major problems. The ARM model was then applied, framed by a proper study. After, a statistical test was made to determine the most likely equipments in necessity of an adequate PM. The RCM approach begins with the analysis of the selected equipments failure´s report. A FMEA was then implemented and discussed with the maintenance technicians (MT).With the assistance of the MT´s and the reports, a set of FM´s was then proposed. The FM´s were subject to statistical tests, determining respective FM´s distribution functions and associated costs, obtaining the optimal periodicity. A PT&I tool was tested confirming inherent value. A MP was was proposed to the MD. It was also integrated with an IP method to improve his function.

1.5 Dissertation Structure

The dissertation is divided in five chapters, being the current one the introduction to contextualize the purpose and conditions in which the project is developed.

The second chapter approaches the scientific available information that supports the whole scientific methods and techniques utilized in this dissertation.

The third chapter elucidates the present situation at the BOF fabric, more specifically the MD structure and the CL main factors.

In chapter four, several solutions are proposed to tackle the main problem, through methods elaboration and proposed methodologies to be implemented, following the conditions quoted since the start of the project.

Chapter five, finally, concludes the whole project made and gives a proposal for future work to constantly improve TPM.

2 Scientific review of subjects covered

This chapter demonstrates the fields of study approached and revises the scientific information that supports this project.

2.1 Total Productive Maintenance (TPM)

TPM is an approach with the goal to maximize equipment effectiveness in a system. It is purposed to practice and implement the “Eight Pillars Strategy”. It strives to take concept of zero production defects and applying it to equipment to have zero breakdowns and minimal production losses (Kigsirisin et al, 2016). According to Shagluf et al (2014), TPM is an approach that organizes all employees from top management to shop-floor workers. The following five critical success elements are defined for delivering benefits from TPM: 1. Maximize equipment effectiveness; 2. Establish a thorough system of preventive maintenance (PM) for the equipment’s entire life span; 3. Involve all departments (engineering, operations, and maintenance); 4. Involve all employees from top management to workers on shop-floor; 5. Promote TPM through motivation management: autonomous small group activities.

According to Nakajima (1988), the goal of TPM through the “Eight Pillars Strategy” motivates officers to achieve 85.00% of equipment effectiveness to be world class and a benchmark for a typical manufacturing capacity. According to Rajput et al (2012), The strategy can be described as:

1. 5S methodology (Sort-Set in order-Shine-Standardize-Sustain);

2. Autonomous maintenance Operator is able to take care of small reparation on failed equipment without maintenance officer;

3. Kaizen “Kai” means change and “Zen” means good for better. The principle of this is “a very large number of small improvements are more effective in an organizational environment than a few improvements of large value;

4. Planned maintenance - The method and activity to prevent equipment breakdown aim for continuously producing quality goods;

5. Quality Maintenance - It is aimed for maintaining equipment to be perfectly ready to operate and produce quality goods without breakdown;

6. Training workers intends to capacitate officers to perform all required functions of equipment;

7. Officer TPM to improve productivity and efficiency in the administrative roles, it aims to establish work procedure for officers to follow to eliminate any breakdown causes;

8. Safety, Health and Environment is focused on promotion and activity to predict and prevent any damage from work.

2.2 Overall Equipment Effectiveness

The literature reveals that no standard formula exists for OEE calculation. It is a measurement used to determine how efficiently a machine is running (Rajput et al 2012). The OEE is constituted by the Availability, Performance and Quality Key Performance Indicators (KPI). Equation [2.1] represents OEE formula.

$$OEE = \text{Availability} \times \text{Performance} \times \text{Quality} \qquad [2.1]$$

Each KPI possesses two main elements in their composition, the TPM "6 big losses". Table 1 represents each indicator´s element, potential causes and countermeasures. The countermeasure proposals show that both KPI´s are well interconnected. It is concluded an effective autonomous maintenance (AM) and PM plan improves the system globally.

Table 1 – Description of the OEE framework
(adapted from: O´Brien, 2017; Optimum FXConsulting, 2015; Lobo, 2016c)

Indicator	Element	Causes	Countermeasures
Availability	Equipment failure/breakdown	Major component failure; Unplanned maintenance; Breaks	Improve PM scheduling and reduce RM; FMEA application; Effective Parts Strategy
	Set-up and adjustment	Changeovers; Planned maintenance; Material and labor shortages	5S Organization; Knowledge transfers; Retrain personnel
Performance	Idling and minor stop	Inefficient work processes; Poorly operating equipment	AM; Line adjustments; Equipment overhaul; Regular equipment PM´s
	Reduced speed	Untrained operator; Nominal speed wrongly established	Operator formation; Line Balance calibration; Nominal value adjustment.
Quality	Production rejects	Product out of specification; Damaged product	PL analysis to eliminate defects; Error proofing
	Reduced yield (on start up)	Scrap created before nominal running after changeover; Product out of specification or damaged at start of run	5S Organization; Planned Downtime Management; Precision Setting

The Availability, Performance and Quality equation are [2.2], [2.3], [2.4], respectively. Each term can assume various names in industry.

$$Availability = (Loading\ time - Operating\ time) \div Loading\ time" \quad [2.1]$$

$$Performance = (Operating\ time - Net\ Operating\ time) \div Operating\ time \quad [2.2]$$

$$Quality = (Total\ Production - Produciton\ Rejects) \div Total\ Production \quad [2.3]$$

The Quality indicator measures commonly by product unit instead of time unit due to easiness obtaining the terms.

The remaining time after Quality Loss is subtracted and called “Fully Productive Time” or “Valuable operating time” (https://www.oee.com/oee-factors.html). Figure 3 depicts the OEE framework clearly.

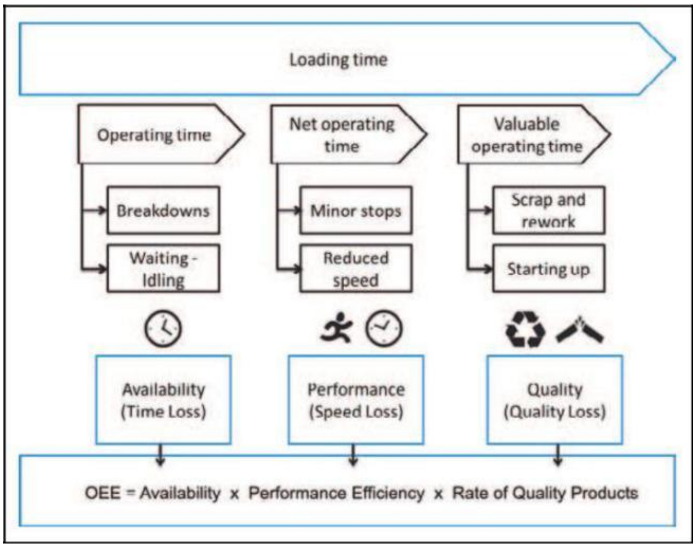


Figure 3 – Representation of OEE composition (source: Shagluf et al 2014)

Maintenance

Maintenance is defined as the combination of all technical, administrative, and managerial actions during the life cycle of an asset intended to retain it in, or restore it to, a state in which it can perform the required function. The main goals of maintenance on a production plant are to assure a required level of technical availability, optimize entrepreneurial productivity and flexibility and the product’s quality itself.

In addition, the sub-goals are: to keep and restore the functionality of installations; to ensure and augment the utilization of production function and resources; to minimize outage costs; to guarantee work safety and comply with legal regulations; to minimize maintenance costs (Lobo, 2007a).

Maintenance methodologies

The efficiency of the whole manufacturing plant is dependent on the sustainable performance of the equipment, which can lead to improvements related to quality, cost and time. The availability of the PL plays a central role to achieve the desired performance level. Table 2 illustrates the types of maintenance commonly adopted by industries.

Table 2: Maintenance policies
(Adapted from Parajapathi et al, 2012 in Basri et al, 2017)

Features	Maintenance policies			
	Corrective Maintenance (CM)	**Preventive Maintenance (PM)**	**Predictive Maintenance (PdM)**	
Maintenance Approach	Reactive	Proactive	Proactive	
Maintenance category	Fixing after failure	Time-based maintenance(periodic)	Diagnostic-based maintenance (condition monitoring)	Prognostic based maintenance (reliability centered)
Good for failures	Random age-based	Age-based	Prevents to occur (near-optimal)	Prevents to occur
Expensive (manpower)	Maximum	Little Less	Moderate	Minimum
Initial Deployment Cost	None	Low	Expensive	Most Expensive
Computational Cost	Least	Little higher	Higher	Highest
Schedule required	Not applicable	Based on the standard useful life of component or history of failures	Based on current conditions	Based on forecast of remaining equipment life
Action	Inspect, repair or replace after failure	Inspect, repair or replace at predetermined intervals, forecasted by design and updated through experience	Inspect, repair or replace based on need. Continuous collection of condition-monitoring data	Forecasting of remaining equipment life based on actual stress loading

Corrective Maintenance (CM)

CM is characterized by a Reactive Maintenance (RM) approach, also known as “run-to-failure”. It takes place when the deterioration condition of an item results in functional failure. An entirely RM program overlooks opportunities to influence item survivability. RM can be a better approach if after an RCM analysis the comparison between cost and risk of failure item and all the expenses needed to perform the maintenance task to mitigate the expected cost of failure lead to that decision (Dhillon, 2002).

The advantages of a CM policy are: no initial investment. The disadvantages are: unscheduled downtime; increased labor costs (Overtime); increased expedited shipping and manufacturing costs; Un-optimized staff resources (Sillivant, 2015).

The Mean Waiting Time (MWT) and Mean Time to Repair (MTTR) constitute the time required to perform a CM activity. The MWT occurs after a breakdown until the start of the repair beginning the MTTR which finishes until the first accepted product is made.

Preventive Maintenance (PM)

PM is introduced after the recognition of the need to prevent failure. PM has been implemented along with emerging technologies since such systems are generally more complex. Predictive

Maintenance (PdM) also uses a proactive maintenance (PrM) approach and is considered an advancement of PM. PdM normally relies in Condition-Based Monitoring (CbM) systems. A PM method involves predetermined maintenance tasks that derive from equipment functionalities and component lifetimes. In PM, tasks are planned to change components before they fail and are scheduled during line stoppages or shutdowns. PM integrates managerial and operational phase (Simões et al, 2011).
The managerial perspective commits to analyze the data and support the decision-making for the maintenance tasks. The operational perspective refers to the execution of maintenance actions consisting of technical aspects and tasks standardization. The managerial perspective is considered of greater importance since the maintenance tasks can easily impact the system efficiency negatively which then require further planning actions (Basri et al, 2017).
The pros of a PM approach are: increased System Availability; minimized logistical downtime; reduction of unscheduled downtime; costs decrease by parts and labor optimization; maintenance events planned; logistical support optimized.
The cons are: high initial investment; savings not seen immediately (Sillivant, 2015).

Autonomous maintenance (AM)

AM refers to the human capital development among production operators (PO) supported by maintenance technicians and engineers to perform easy daily maintenance activities aside from planned maintenance. AM activities are of great importance to a TPM mentality, since it improves both production and maintenance directly. AM allows to continuously evaluate natural deterioration and perform best maintenance practices to increase component life expectancy. The goals of AM are: PO´s conduct basic maintenance; early detection and resolution of anomalies; maintenance teams are just focused on advanced prevention activities (Lobo, 2017b)

The general steps of AM are: initial cleaning; elimination of contamination sources; establishing AM standards (e.g. in lubrication and cleaning); general inspection; workplace organization (Min et al, 2011). All the recurrent repairs must be catalogued into Standardized Work with the steps, tools and possible component substitutes identified. Standardized Work also allows evaluating failure complexity and repair action to decide if is benefic to train production operators (PO). Figure 4 represents the transformation an effective AM is expected to achieve.

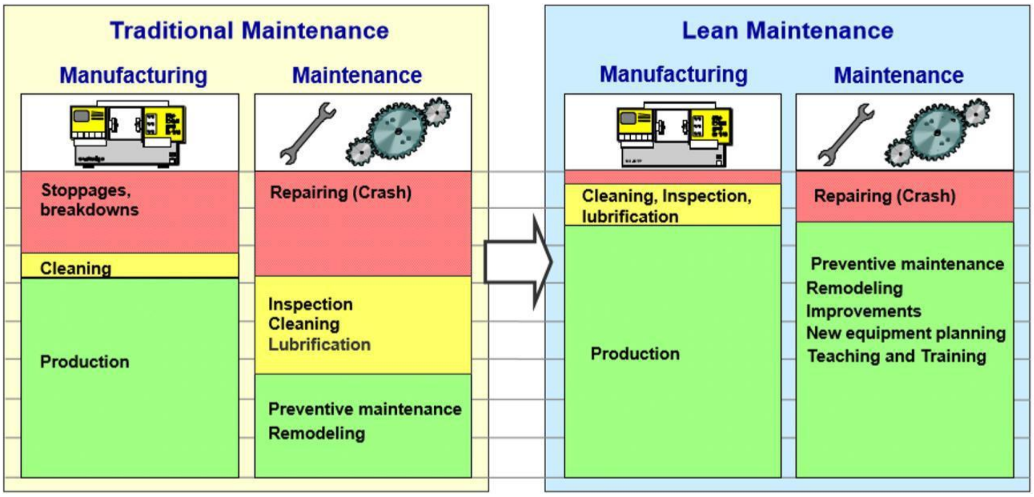


Figure 4 – Representation between a traditional and lean maintenance (source: Kaizen Institute, 2016)

Reliability Centered Maintenance (RCM) Approach

The RCM method uses PM, PT&I, CM and PrM techniques integrally to increase the reliability of a machine or component to function properly over its designed life cycle with minimal maintenance.

PT&I also known as condition monitoring uses non-intrusive testing techniques, visual inspection and performance data to assess machinery condition. Continuing analysis of equipment condition-monitoring allows planning and scheduling of maintenance repairs in advance of functional failure. The PT&I data collected can be used in several ways to determine the condition of the equipment and identify potential failure. The methods are based in data analysis (e.g. Trend analysis and Pattern recognition).

PT&I is possibly impracticable to apply in all Failure Modes (FM) therefore other types of maintenance should also be practiced. Inserts into a diagnostic or prognostic-based maintenance performance, taken in equipment or forecasting of equipment life, respectively.

The goal of RCM is to provide the designed function with the required reliability and availability at the lowest cost. An RCM analysis is based on a Failure Mode and Effects Analysis (FMEA) technique. The analysis is used to determine appropriate maintenance tasks to address each of the identified failure modes and their consequences (NASA, 2009)

FMEA is applied to an identified system. For each system identified, there can be multiple FMs. The FMEA addresses each system function and the dominant FMs associated with each failure, examining the cause of a failure. Often, the effects of a failure are the same such as equipment degradation. The FMEA analysis is normally applied with the support of worksheets where the system Function, Functional Failure, FM and source of failure are addressed.

CbM decisions with proactive event driven computing

The emergence of the Internet of Things (IoT) and the Industry 4.0 provide the extensive use of monitoring resources in enterprises with the extensive use of physical and virtual sensors. Taking advantage of the big data generated from a large number of sensors require the development of event monitoring and data processing systems able to handle real-time data in complex, dynamic environments. The “Detect-Predict-Decide-Act” proactivity principle can be mapped to the CbM framework in order to develop associated information systems and algorithms (Bousdekis et al, 2018).

Ideally, CbM allows maintenance personnel to:

-Perform only currently needed maintenance

-Minimize spare part costs

-Minimize system downtime

-Reduce time spent on maintenance

The challenges in a CbM implementation are:

-High initial costs;

-Major or total restructuration in maintenance methodologies;

-Increased number of parts (the CbM installation itself) that need maintenance and checking; (Tsotetsi I., 2016)

2.3 Statistics applied to maintenance

This section reviews the scientific information available to analyze in depth the historical failure data.

Reliability

Reliability is the probability that a system will adequately perform its intended function for the intended period of time under the intended operating conditions (Lobo, 2017a). Reliability analysis aims to estimate equipment life expectancy. Therefore, the goal of maintenance management is to control the level of risk, considering all outcomes.

Failure Rate (FR) and bathtub curve

FR is a parameter highly used in maintenance representing the frequency a system fails, expressed in failures per unit of time. The parameter is described by equation (2.4)

$$FR = (Nr^{\,o}\, of\ failures \div Total\ running\ time) \qquad (2.4)$$

In maintenance, there are several sorts of FR stages during an equipments life. Those stages are described in Figure 5, where the “bathtub curve” is displayed.

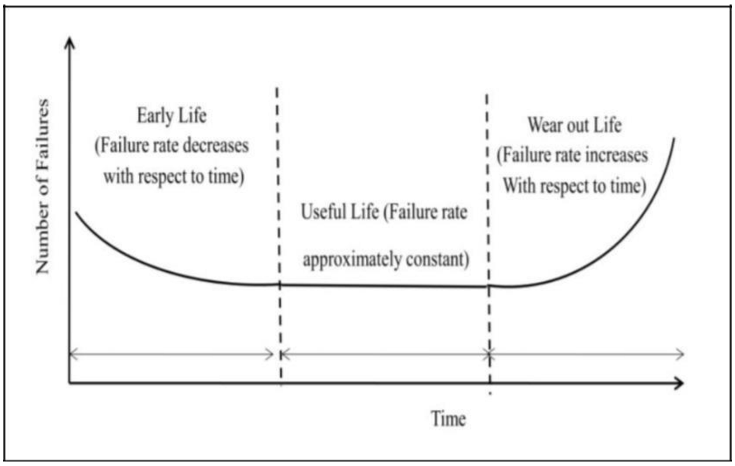


Figure 5 – Typical bathtub curve (Adapted from Raju et al 2017 in Vagenas 1997)

Laplace Test

To determine if the FR is constant over time or if systems failures (e.g. a set of FM´s) are Independent and Identically Distributed (IID), a Statistical Test (ST) is executed assuming as Null Hypothesis (H0) it is constant and follows a normal distribution Zt ~ N (0,1). The test is described in equation (2.5), limited by time.

$$. Z_t = \sqrt{12 \times N} \times (\textstyle\sum_1^N t_i \div (N \times T_0) - 0{,}5) \qquad (2.5)$$

Where:
t_i is the moment in which occurred failure i
N is the total number of failures
T_0 is tests final moment limited by time

H0 is rejected if Z_t exceeds a critical value (CV) (α/2) where α is a stipulated significance level. If Z_t rejects H0 and is positive the FR is increasing (Assis, 2004).

Weibull Distribution

Due to flexibility, the WD is commonly used to enhance the effective reliability of any equipment, such as electronic or mechanical ones (Raju et al 2017). The distribution function and respective parameters are described by equation (2.6) (Lobo, 2017a).

$$f(t) = \frac{\beta}{\eta} \cdot \left(\frac{t-\gamma}{\eta}\right)^{\beta-1} \cdot e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}}, \quad t \geq 0$$

β : shape parameter $[\beta > 0]$
η : scale parameter $[\eta > 0]$
γ : location parameter $[-\infty < \gamma < +\infty]$

$$f(t) = (\beta \div \mu) \times ((t-\gamma) \div \mu)^{\beta-1} \times e^{-((t-\gamma)\div\mu)^{\beta}}, t \geq 0 \qquad (2.6)$$

Where:
β is the shape parameter $[\beta \geq 0]$
μ is the scale parameter $[\mu \geq 0]$
γ is the location parameter $[\gamma \geq 0]$

The beta parameter is of major interest for maintenance purposes due to the information it retrieves. The value 1 indicates the FR is constant and the function reduces to an exponential distribution. If above 1, the FR is increasing and decreasing if below 1.

Weibull parameters estimation

Through Equation 2.7 the determination of beta parameter is possible, calculating the other two by consequence. The data is comprised between times-to-failure and time-to-repair (non-failed) records, for a respective system in the maintenance field. Non-failed units are considered as suspended items (or right censored).

$$\left(\sum_{i=1}^{r} t_i^{\beta} \times \mathbf{ln}\, t_i + \sum_{j=1}^{k} C_j \times ts_j^{\beta} \times \mathbf{ln}\, t_j\right) \div \left(\sum_{i=1}^{r} t_i^{\beta} + \sum_{j=1}^{k} C_j \times ts_j^{\beta}\right) - (1 \div \beta) = (1 \div r) \times \sum_{i=1}^{r} \mathbf{ln}\, t_i \qquad (2.7)$$

Where:
t_i is the number of i failed units
ts_j is the number of j non-failed units
C_j is the number of ts_j repetitions

Risk Analysis and optimal periodicity

Obtaining the distribution function and, *a priori*, knowing the corresponding costs of a corrective and preventive maintenance action for a certain system, it is possible to determine the optimal periodicity. This periodicity is the time interval that corresponds to the minimal cost of risk evaluation. The risk formula is specifically applied to maintenance evaluation, as shown in Equation 2.8 calculates the Expected Value (EV) for a given time since system functioning through cumulative distribution function and associated costs for each scenario.

$$\mathrm{EV}(t_p) = C_p \times \left(1 - F(t_p)\right) + C_f \times F(t_p) \qquad (2.8)$$

Where:

t_p is the periodicity
$F(t_p)$ is the probability of failure occurrence until a certain periodicity tp
1- $F(t_p)$ is the reliability
C_p is the preventive cost
C_f is the corrective cost

2.4 Business Analytics

One of Business analytics research interests that gains importance for TPM improvement is data mining. The improving PrM methodologies increasingly integrate CbM in the Production Line (PL). Such reliable and constant monitoring, excluded from human error, is then processed into a data model with due operations that return valuable results. Through data visualization or data processing it is possible to better understand and improve decision-making related to the PL management (Miguéis and Borges, 2016a).

The ARM method

The Association Rule Mining accelerates the decision to establish an appropriate TPM management strategy inducing to a more reliable and effective response respective to time and costs (Djatana and Alitu, 2015).

ARM analyses associations between items (patterns) that are: frequent; unexpected; actionable. This method creates a rule for each combination of items: an item set. This item set can be divided into two sub item sets, one composed by the antecedents (causes) and the other constituted by the consequents (effects or results). The association rule´s types are: Actionable (contain high-quality, actionable information); Trivial (information already known by managers); Inexplicable. Both trivial and inexplicable rules occur more often (Borges, 2016).

The item sets can be firstly filtered by an indicator value such as: support, confidence, lift, conviction.

Support

The support value indicates how frequently an itemset appears in the dataset. The greater the support the greater the importance attributed to the itemset. Equation 2.9 defines support.

$$supp(X) = |\{t \in T; X \ni \mathrm{t}\}| \div |\mathrm{T}| \qquad (2.9)$$

Where:
X is an itemset
T is a set of transactions of a given database

Confidence

The confidence of a rule is a conditional probability of how often a rule is true when the itemset appears. Equation 2.10 depicts the confidence measure.

$$conf(X => Y) = supp(X \cup Y) \div supp(X) \qquad (2.10)$$

Where:
Y is an itemset

Lift

Lift refers to the deviation to the expected frequency if antecedent and consequent were independent (1 if independent). It compares the pattern frequency against the frequency computed while assuming statistical independence. If the value is above 1 both itemsets are positively correlated and the opposite below 1 (Borges, 2016). It is represented in equation 2.11.

$$lift(X => Y) = supp(X \cup Y) \div ((supp(X) \times supp(Y)) \qquad (2.11)$$

Conviction

Conviction is symmetric to lift and also follows the correlation rule. It is a measure of implication and has a value of 1 if items are unrelated. Conviction is sensitive to rule direction and captures the notion of implication (Borges, 2016). It is shown in Equation 2.12.

$$conv(X => Y) = \big(1 - supp(Y)\big) \div (1 - conf(X => Y)) \qquad (2.12)$$

Correlation

Correlation is another important concept used in data analysis. Correlation is any statistical relationship between two variables, either causal or not. Extends between values 1 and -1. The value of 1 for correlation means a perfect linear and increasing (both variables) relationship. If the value is 0 the variables are independent.

2.5 Integer Programming (IP)

Mathematical programming is a ramification of operational research, where the term 'programming' means 'planning'. In an IP at least one of the variables takes integer values. Mathematical Programming Models aim to optimize (maximize or minimize) a function subject to restrictions (reflect the existence of limited resources) (Camanho, 2016a).

The model has a set of decision variables (DV) (e.g. possible Work Orders (WO) or labor scheduling) that are subject to restrictions (e.g. available time) and reach for a concrete objective. Therefore, by addressing scenarios through identifying the primary goal and the constraints to the operations, Linear Programming is a highly useful tool for maintainability engineering (Brall, 2018).

The resumed aspects of a mathematical programming model (Camanho, 2016a) are:

1. Decision variables (study subjects that adapt to proposed objective and restrictions);
2. Objective function (maximize or minimize);
3. Set of restrictions.

Binary Integer Programming

Certain programming models include binary DV´s (e.g. the decision to consider the variable in the solution). These DV´s can only assume the values 0 and 1.

3 Analysis of the Current Situation

The first step to resolve a proposed problem is to identify the variables to consider. In practical terms, every factory possesses unique characteristics. Chapter´s 3 goal is to properly understand the working environment at BoF´s factory and associated factors.

3.1 BoF factory description

The BoF factory mainly focuses in office furniture products and is divided into 2 sub factories: Lack and Print (L&P) and Foil. The MD where this study takes place is responsible for the whole PL´s in the BoF factory. The CL is of greater interest since it represents Foil´s bottleneck (normally limiting Foil´s production capacity) and had the worst OEE in the previous years. Since this thesis studies the CL, the main F&W´s production unit, the detailed description of the L&P factory is unnecessary. In Figure 6 is represented the BoF plant with the different sub factories (Foil and L&P in yellow and blue, respectively), Foil´s PL´s (BoS, F&W and EB&D), the MD and his workshop in red, the cutting area in green and packing area in orange. This BoF layout is also shown in attachment B in greater detail.

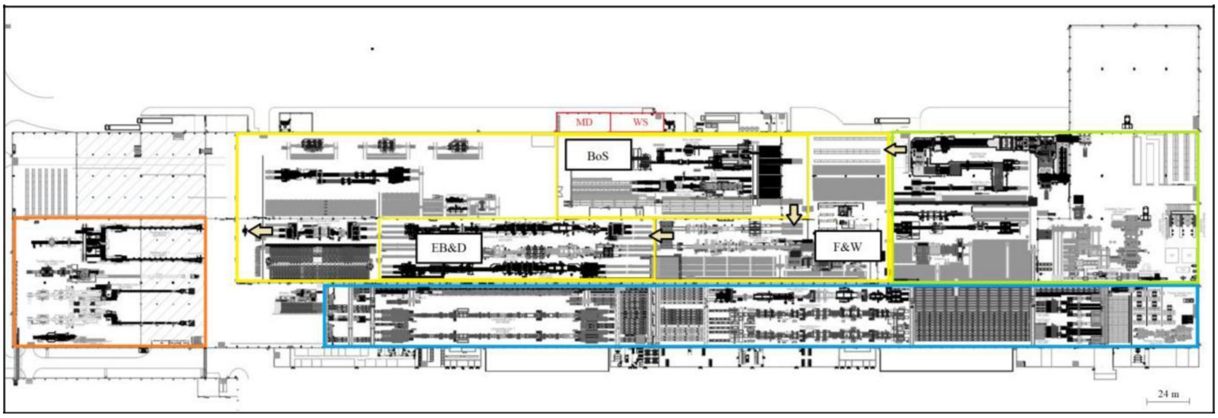


Figure 6 – BOF factory plant representation

Foil´s production process characterization

Both factories are supplied by the cutting area. The material is then separated to one of the lines. The products difference between the connected lines is the surface finishing - painted or foiled for L&P and Foil, respectively.

Foil has three main production units with specific operations: Board on Style (BoS), where wooden slats are applied in the laterals and center of the material and then filled with card, called “honeycomb” due to their characteristic format; the Foil&Wrap (F&W), where the material is coated with paper sheets and the principal PL is the CL; the Edgeband & Drill (EB&D) where the collage of the borders, drilling and cutting is done. Nuts are also inserted in the drilled holes. After the material passes through these processes it is then transported to the packing area where the workers ensure the packaging of the material and store it into the central warehouse.

Complete Line description

The CL is the main work unit belonging to the F&W. The material is firstly polished in the laterals and base. The equipments that perform this function are the “Bargstedt TBH” and “Butfering SWB – Calibrator”. The material is then coated in its laterals, by the equipment “Homag FPL”. Afterwards, it passes through the buffer “Bargstedt - TFR” that verifies material specifications and stores “Work in Process”. The buffer increases production capacity and divides the PL in two lines by storing or supplying the first and second half with production material, respectively. This first half in the line originates many performance losses to fulfill the quality parameters. In the next phase paper sheet is stamped in the product bases by the machines "Homag FKF" and "Homag KAL". This operation requires high temperatures to stamp effectively. In the final phase, the material is firstly filtered through quality measures in the machine "Holzma – Quality Box" by human-inspection. Then the material is cutted and stored in the "Holzma – saws cart". Figure 7 shows the CL representation.

The CL had a major change in the line in 2016, substituting the Homag KAL initial pre-melting function of heating the glue by a machine which stamps the sheets. This change assures a higher quality for the manufactured products.

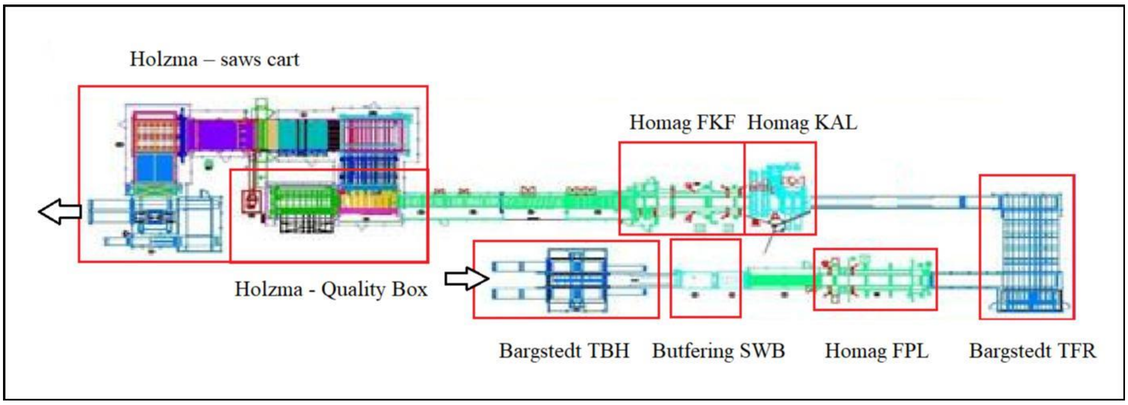


Figure 7 – Complete Line Layout (edited and source: IKEA Industry)

3.2 The Maintenance Department Structure

The BoF´s maintenance department (MD) is independent from the one at PFF. The organization chart of the MD is represented in Figure 8. It reveals the organizational structure of the department. The department has five main functions. The Maintenance Responsible is accountable for 10 workers while the supervisors are, in average, answerable by 7 workers. This signifies the organizational structure is relatively flexible.

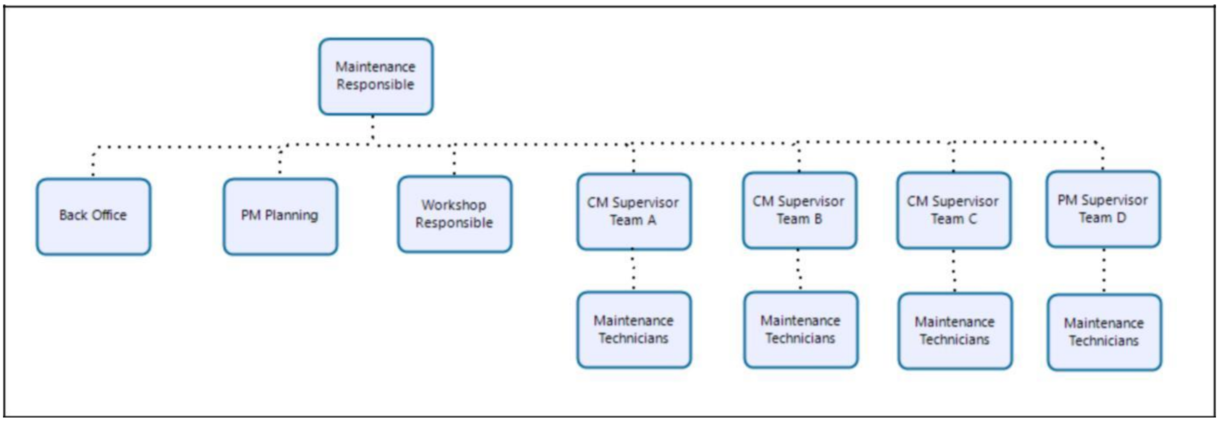


Figure 8 – MD organizational chart representation

3.3 Monitoring & Business Software

In the last two years an Enterprise Resource Program (ERP) has been integrated along with the IKEA Industry activities. It is a Business software that collects, organizes and displays information to assist all types of department (e.g. financial department, ISD, MD, PD) – *QlickView*. Respecting to maintenance and production functions, this software displays in a section the KPI´s of the OEE in every PL as well as the waste in terms of available working hours. In another section, it displays more detailed information about a certain PL´s behavior, during a certain time, with respective characteristics. This behavior represents a stage of the line, which normally changes when the line stops. This type of monitoring automatically retrieves a value for short stoppages (e.g. micro stop) or it can be classified by the responsible production operator (PO) at the moment, in case of a greater stop.

CL´s OEE determination

The data gathered by *QlickView* characterizes each phase with an attribute named “stop code”, classifying lines momentum, such as “normal velocity”, “unplanned time” or “mechanical failure”. In figure 9, the studied data is dated from January to August, 2018, referring to the available working hours and exported from *QlickView*´s KPI section to the program *Excel*. It represents the volume of available time per month, the time the line is available for manufacturing and the actual manufacturing time. The lowest working hour volume is in August, due to holidays and annual preventive planned maintenance, performed mainly by the equipment`s manufacturers team.

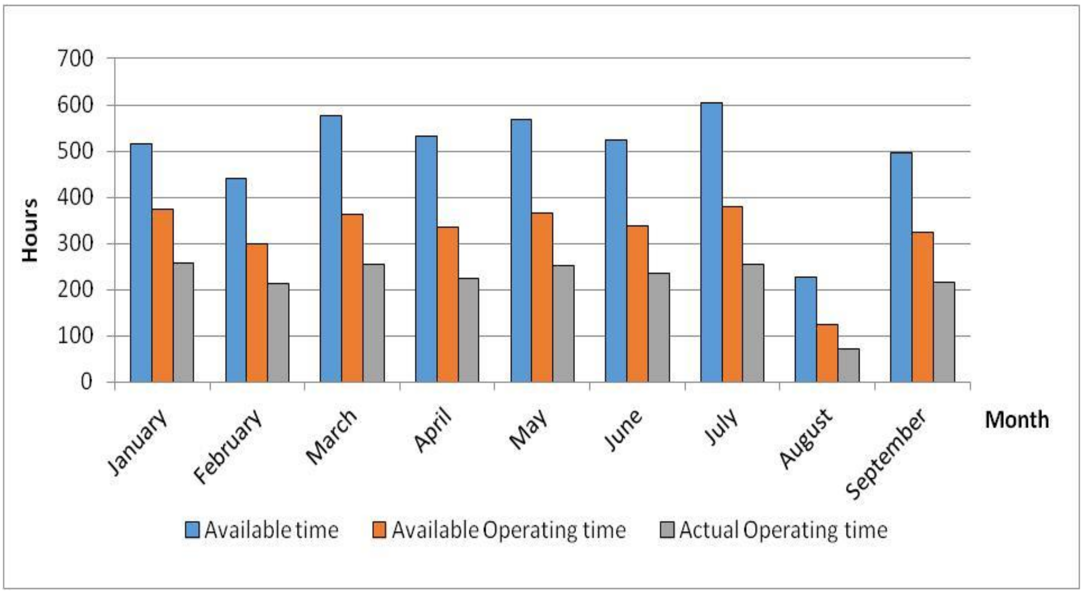


Figure 9 – Histogram of working time per month

The proportion of “Available Operating time” compared to “Available time” lead to the estimation of the Availability. Performance indicator is the proportion of “Actual Operating time” compared to “Available Operating time”. The values are also displayed in attachment C, with an obtained weighted average of 64.97% and 68.40%, respectively. The Quality KPI is excluded from the KPI section in *QlickView*.

These values generate an average OEE of 39.61% for the CL. It indicates low efficiency of the line, a common value for manufacturing companies starting to track and improve their efficiency loss with straightforward measures such as cataloging stoppage reasons and addressing the critical sources of downtime. Figure 10 characterizes the different benchmarks of OEE with due classification accredited worldwide in industry. With the Information

Systems Department (ISD) assistance, the annual opportunity cost of the CL´s stoppage is obtained and divided by annual available working hours: 9 350.00 Euros/hour. The average opportunity cost per month is then calculated.

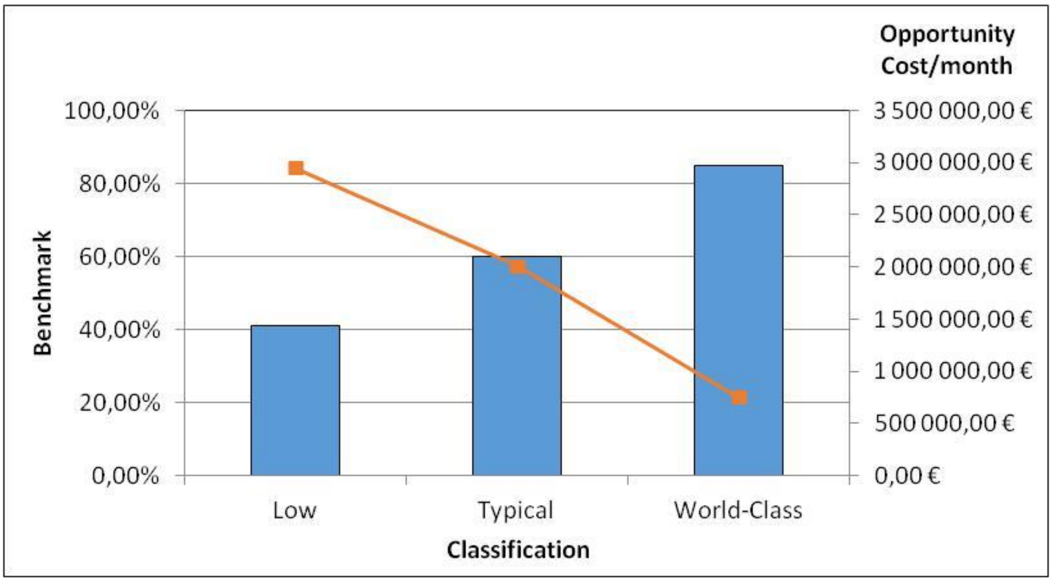


Figure 10 – Histogram of OEE benchmarks with respective classification and CL´s Opportunity Cost per month represented in a line (adapted from: https://www.oee.com/)

Pareto chart and Top Losses determination

A Pareto chart is represented in figure 11 illustrating the major line losses per efficiency type. The data is extracted from *QLickView´s* line functioning section for the same time interval used to determine OEE. The dataset presents major relevant attributes: "ID"; "PL"; "error code"; "time lost"; "date"; "notes"; "product name"; "NPC" (nominal product capacity). The attributes have the following format types, respectively: *integer*; *polynomial*; *integer*; *real*; *date*; *polynomial*; *polynomial*; *real*.

Each type of loss is constituted by selected "error codes" that enter the category. The red line represents the cumulative percentage of the main losses by hours lost. The blue bars belong to Performance losses, the green bars represent PL Availability losses while the purple bars represent Quality in terms of wasted hours. The yellow bar is excluded from the "6 big losses" of TPM and line efficiency - representing the time lost due to stagnation in consequent PL´s, concluding the exit buffer reached maximum storage capacity. It is noticed "Reduced speed" is the major big loss with 32.93% of total hours lost while the second is "Equipment Failure" with 18.38%, which composes the Availability efficiency aspect with 18.38%.

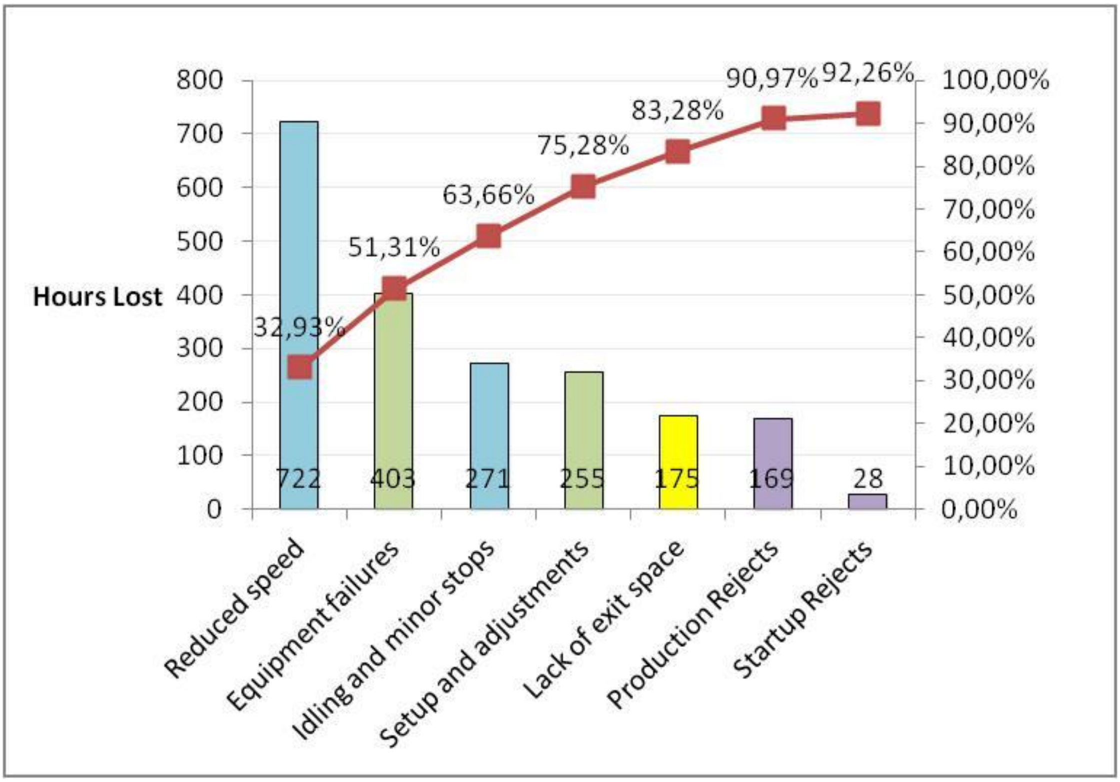


Figure 11 – Pareto diagram with main losses of the CL

Figure 11 contrasts with attachment C results where the Performance indicator is superior to Availability. It can be explained due to wrong allocation of "error code" by human error or wrong automated function when extracting or organizing the data. While figure 11 uses the constitution of several reason codes for each top loss, attachment C uses a different dataset also from *QlickView* which aggregates the losses in a different manner (e.g. the Performance measure only accounts losses in the reason code "3100" (reduced speed) although there are losses of performance in the code "3000" (normal speed)). This disparity reveals the applied methodology is still in an initial phase. To corroborate this premise, several "reason codes" stopped being used after April, 3 being aggregated into a more ambiguous "reason code" (e.g. the codes "vacuum" and "lubricate" started to be allocated into "first level maintenance"). Such change in methodology becomes more practical to the operator however removes value due to lack of detail identifying root causes and a greater loss of control.

Product type research

The analysis of the dataset also shows findings of interest using the manufactured products as objects of study. The line produces a vast number of items which characterize a line stage. The dataset presents 7 major types of products with 118 possible variations in the studied months.

An analysis of the items frequency reveals the existence of one product containing 3,22% of total misused time, another covering 2,11% and a third with 1,00%. Although a product originates abnormal wasted time, it can also have a proportional manufacturing time frequency to cover those losses.

To normalize each product´s wasted time, the calculation of the ratio between wasted time and phase frequency for each product is then processed. The phases respecting all types of unplanned time are excluded from the dataset. The obtained average is: 3.33 (minutes/frequency) with a standard deviation of 2.12.

One of the products above 1,00% frequency has an abnormal ratio compared to the remaining: the "*Besta FW BT 02 GY1"*, with a value of 10.11 minutes/occurrence. It also has a frequency of 2.11% for total time lost as shown in Table 3, which represents the three products considered to have significant high ratios and/or frequencies. Table 3 also denotes the major root causes ("error codes") of each product.

Table 3 – Table containing top 3 items with highest wasted time per frequency

Item Name	Besta FW BT 02 GY1	Besta FW SD 02 WH2	Besta TV FW TP 03 WH2
Wasted Time(minutes)	3204,31	4885.10	1528.84
Frequency (%)	2,.1%	3.22%	1.00%
Ratio (minutes/occurrence)	10.11	5.10	6.62
Top "Error Code" and frequency	"4702" (28.21%)	"3100" (32.72%)	"3100" (25.63%)
	"3100" (18.34%)	"5125" (15.06%)	"5100" (15.63%)
	"5200" (10.64%)	"5200" (7.28%)	"5123" (9.46%)

The obtained root causes reveal interesting facts. In the first item, the code "4200" means "Lack of space at the exit" which is excluded from the CL´s functioning and provides irrelevant information to the product´s influence over the line. Code "3100" means "reduced velocity", representing 18.34% of total lost time, which is directly related to the Performance indicator. Another 10.64% of wasted time is possibly related to poor AM or electrical inspection since "5200" means "Eletrical failure" being majorly caused by lack of powder aspiration, which accumulates in the electrical system and danifies it.

The second product has 32.72% of wasted hours associated with "Reduced Velocity". The 15.06% value is associated with a specific machine problem, the "Holzma A box". The 7.28% value is also attributed to electrical failures.

In the third product 25.63% is attributed to "reduced velocity", 15.63% ("5100") to "mechanical failure" and 9.46% to another specific machine, the "Homag 2 – Separator".

Several conclusions and countermeasures can be applied from the found root causes, such as increasing focus in AM while product "1" and "2" are being processed or determining the failure causes for the mentioned specific machines when processing the product. The Performance associated to product "2" and "3" can also be reviewed to determine if the theoretical nominal value is correct and adjust potential causes for deviations in the line or reinstruct the PO´s.

As referred, the ERP monitoring is in an initial phase of implementation where the "error codes" attribution to each phase made by the production team is unstable. In Table 3 is denoted the changes made in April, 2018 to "error code" attribution since, per example, the code "5100" aggregates all codes between "5101" and "5199", losing information.

3.4 Maintenance activities

The entities responsible for the production area are the maintenance and production departments (MD and PD, respectively). Each one follows different functions to secure the proper efficiency and effectiveness of the line.

Autonomous Maintenance

The PD´s PO´s are constantly active during the 24 hours in the 5 working days of the week, plus additional hours at Saturday depending on the scheduled PM and product completion for the weekend. The PO´s has the responsibility to assure the continuing function of the line and inspect the quality of the products in the working hours. The operators execute AM also known as “first level maintenance”, where, as the name indicates, the more basic maintenance operations such as cleaning and inspection, are performed to increase the system´s overall reliability. Such operations can be lubricating tension areas periodically or by assessing condition in critical operation areas, replacing accessible components with proper knowledge of his state and corresponding component´s costs or eventual line stoppage for replacement. As referred previously, one important characteristic of working with wooden material is the powder created in the diverse operations. That dust is mainly responsible for electrical failures in connections or components such as sensors. The dust accumulates in narrow critical operation areas leading to a constant attention on aspiration activities which are of most crucial interest to line efficiency. If the maintenance activity requires more complex knowledge in the repair process and/or handling respective tools, maintenance technicians are contacted to plan the proper maintenance activity. Besides those maintenance responsibilities, the PO also has a monitoring and inspection responsibility, acknowledging causes for line stoppage and reporting anomalies or information of interest to the MD such as the actual condition of a certain machine or component.

Corrective Maintenance (CM)

The MD has MT´s responsible for certain PL´s, performing CM activities when a failure causes line stoppage and is out of PO´s repairing capabilities. Those activities can lead to considerable losses in production times considering all the CM steps between a failure occurrence and line properly functioning, ending with the first accepted product in accordance to quality measures.

During this activity three main stages occur: Mean Wating Time (MWT); Mean Time to Repair (MTTR); Line testing. The MWT starts with the failure detection by the PO. In case the failure is out of PO´s capacity to repair, he then reports the occurrence to the MT. In case the failure cause in the equipment is acknowledged by the PO, the MT is informed and gathers the material needed to perform the correction. Otherwise, if the PO unknowns the failure cause, the MT goes firstly to the damaged equipment and recognizes the failure type. Only then he goes to the workshop to reunite the required repair items. It is possible that the MT also unknowns the failure cause and has to report the event to more experienced workers or lastly to the machine manufacturers support.

The MWT also depends in the possibility of stock unavailability for all potential component substitutes – it is common for a damaged component to be replaced by one with different characteristics (mechanical, electrical or functional) that can still run the system properly during a certain period. Although it diminishes the component life cycle due to improper utilization and obligates to a consequent maintenance activity to be scheduled in the MP. Such possibility avoids line stoppage, however occupies extra MP available time and increases additional expenses in the long-term. The MWT increases if the MT is unavailable, (e.g. occupied with another CM activity, in a working meetin). Such hypothesis conditioning MWT leads to an estimated average ratio of 6.35 compared to MTTR, by evaluating the dataset from *QlickView*. On the other side, the value can also indicate the breakdowns are quick to repair.

In the next phase the MT proceeds to repair, accounting the MTTR.

In the last phase the machine is subject to testing, ensuring the proper system functioning. In this stage, the machine often fails to run due to wrong root cause identification or lack of technical handling in repair (due to the complexity of the equipment). This phenomenon is known as the first stage of the "bathtub curve" where the failure rate is decreasing as the time increases. In Figure 12 the whole flow chart of the CM is shown. This figure is shown in greater detail in attachment D.

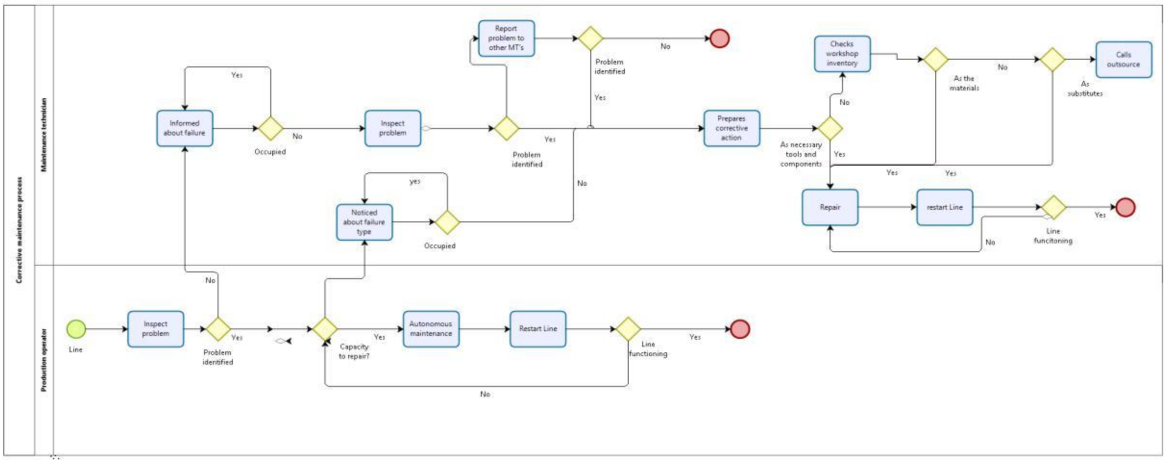


Figure 12 – Flow chart of corrective maintenance activity (created in *Bizagi Modeler*)

Preventive Maintenance (PM)

Since 2013, the MD activities followed preventive maintenances with Standardized Work Orders (SWO) to execute scheduled PM actions and inspections. Those SWO are pre-established by the equipment´s manufacturers, as shown in Attachment E and F for one of CL´s equipment – the "Homag KAL 620". The MP´s are written in Portuguese language, the idiom mostly used at the factory, dated June, 2013 as represented in the spreadsheet´s top right. Both MP´s are meant be performed in a monthly basis with the estimated task´s MTTR represented. The "interventions" section displays PM activities belonging to the AM area such as "lubricating" or "cleaning" equipment. The sum of the task's MTTR is 6.7 hours. Considering F&W´s PL has 13 principal machines and Foil has 3 main PL´s, the monthly PM plan would take more than one week to be executed, without breaks.

Therefore, due to a tight available time to perform planned maintenance as well as low availability of qualified labors, the maintenance managers tackled the optimal SWO´s to perform, by simplifying and eliminating orders. According with Oliveira, 2016, the relevant instructions were filtered, obtaining total planned time reduction for the execution of the maintenance activities. Several unnecessary, incoherent or repetitive activities were eliminated. Despite such efforts, the program optimization is considered insufficient to be executed in due time.

The MD´s PM plan is still considered ineffective. A new PM plan is consequently elaborated as shown in attachment G, composed of inspections tasks and a single PM annual program. The plan follows the utilized idiom and figures to assist BOF´s maintenance personnel. The new plan disregards the PM necessity through the year, diverting the PrM approach to a more reactive one.

The ineffectiveness problem relies in a PM plan that establishes a fixed scheduled time to perform maintenance activities. Such concept is wrong, since a PM task must be executed based in the last time an action is taken in a certain system, such as a component or single FM. The problem gains relevance due to increase in equipment complexity, augmenting the number of sub systems, with several components and consequently escalating FM´s. each with different deterioration levels. In such case, a single time-based maintenance task to execute in an equipment is rarely the best approach originating an ineffective PM plan.

Currently, the MD has PM actions scheduled annually, and during the year relies in a condition-based approach to maintain a PrM approach.

Preventive Maintenance compliance analysis

During the fiscal year 2018, the PM compliance of both Foil´s F&W and EB&Drill is displayed in Figure 13. The EB&D is also used to compare the compliance between two production units in Foil since there are different maintenance responsibles. The utilized data results from the MD recordings. The regular activity during May and August is due to the referred PM strategy. In this period, the end of the fiscal year, the maintenance team of the equipment´s manufacturers comes from the respective origin countries (e.g. Germany) to the IKEA factory, exploring the holiday period with more unplanned time to perform necessary PM tasks. This event assumes executing PM activities to components that require annual maintenance (normally the most expensive components with vital functions to line functioning) follow the best practices.

Considering the realization of different operations between the connected PL´s, which influence PM scheduling, the PM plan compliance retrieves a correlation of 0.82 between lines. The value reaffirms the execution of a rigid PM policy.

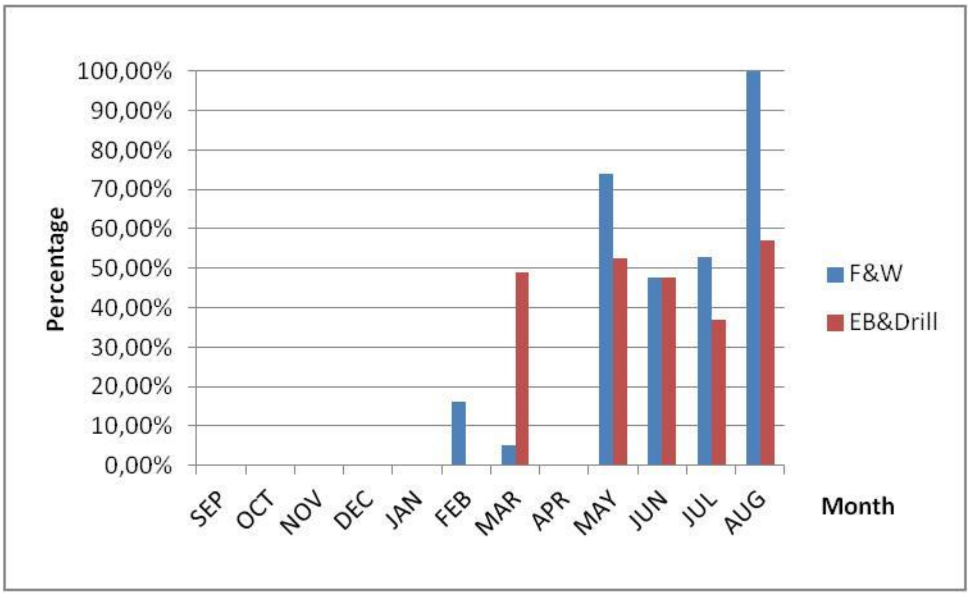


Figure 13 – Histogram of preventive maintenance plan compliance in two different areas of Foil (Foil &Wrap and Edge Band & Drill), in the fiscal year 2018

The action plan deviates from the established benchmark goal of 90.00%, in every month, to the PM plan compliance. Attachment H represents the PM plan compliance in the fiscal year 2016 (Oliveira, 2016). The histogram demonstrates the overall compliance in the two BoF´s sub factories, showing more consistent results with the intent to reach the suggested benchmark each month, reflecting a different PM plan approach. Despite the efforts, the MD currently concludes the annual PM minimizes maintenance costs.

The major factors that led to a change of strategy are then:

- PM plan requires unattainable execution time;

- PM plan suggests execution of non-valuable tasks;

- The apparent extra cost associated with infant mortality after maintenance actions;

- Risk of executing unnecessary preventive action leading to increase in equipment´s failure rate;

- High expenses elaborating a proper root cause analysis in the PL´s;

Unplanned line stoppages and PM plan compliance

An analysis of the relation between PM plan compliance and unplanned stoppages in the various PL´s describes the effectiveness of the established PM actions. The unplanned time for line stoppage is composed by: Equipment Failure; Idling and Minor Stops; Micro Stops.

It crosses data from the MD´s and *QlickView* recordings, between April and September, 2018. As referred in Chapter 2, maintenance activities influence all types of losses in a system, since all losses are related. In particular, maintenance produces a major impact in the reduction of all types of unplanned stoppages. It is also important to report that the MD records all F&W´s PM compliances, which have minor production units apart from CL. *QlickView*´s data, on the other hand, retrieves CL´s wasted time (in minutes).

Table 4 shows an extract from an *Excel* ´s spreadsheet where the correlation result from the two factors is obtained: -0.47. The negative result, as expected, explains that increasing PM plan compliance diminishes the wasted time. However, the value 0.47 indicates the plan is closer to produce random and independent wasted time values than to generate a perfect linear relationship. Summarizing, it is concluded that the plan is rather inefficient for the given data.

Table 4 – Correlation result between PM plan compliance and unplanned lost time in 2018´s respective months

		FEB	MAR	APR	MAY	JUN	JUL	AUG
F&W	PM plan compliance (percentage)	16,22%	5,26%	0,00%	74,00%	47,60%	53,00%	100,00%
	Unplanned lost time (minutes)	25404,96	19866,58	28488,11	26195,95	26141,93	28088,23	12773,21
Correlation		-0,47297						

Predictive Maintenance (PdM)

The MD currently actuates based in a condition-based approach with the goal to predict and take action in potential upcoming failures. The scheduling of maintenance activities is based in the equipment´s current assessed conditions. The MD stores information of a system´s deterioration phase, such as wear level, through PO´s monitoring or inspection when executing a maintenance action. The PdM approach can be measured by noise, temperature or measurable alterations in the working environment (e.g. the quantity of excessive glue accumulated in a reservoir). This type of monitoring requires the participation of experienced workers. Presently, the analysis and measurements are made through the human senses.

Normally, the MD has the majority of the weekend´s time available to perform planned maintenance and 3 hours during the week for each PL. Some activities can also be performed during working hours or line stoppage (e.g. material changeover time).

3.5 Maintenance software

The MD´s at IKEA Industry have their own software to support all aspects related to maintenance activities: the *MaintMaster*. This ERP is available in all MD´s computers and PL´s reporting computers to store and share information. It allows to: document machine failures in a specific PL and equipment; formulate planned maintenance activities; attach documents with defined SWO´s for all types of actions; consult a spare parts section for available components, with corresponding characteristics, number of units, respective supplier(s) and transaction documents. The program can conceive statistical data and export it to programs such as *Excel*. It is capable of sorting events occurred by corresponding characteristics (e.g. Operator and equipment).

The program is essentially used to annotate work orders. These WO´s are stored and enable workers to keep informed of line occurrences. A certain WO can already be completed with the intervening CM action displayed and respective characteristics (line and equipment, components used, operator assigned, time spent, priority level, date of occurrence and notes if necessary) or it can be suspended if the MT´s are unavailable, the priority level is low or some elements are absent, requiring a proper future WO to terminate the event.

When the PL supervisor is informed that a WO cannot be executed at the moment or a certain equipment requires an action in the near future (condition-based PrM), an order is scheduled in the MP section to be performed in a future weekend by the fourth turn, or during the 3 available line hours throughout the week or even in the course of line stoppages such as setups and adjustments. Although, there are WO´s that can be realized when the line is functioning. This is currently the main methodology adopted to secure line functioning, apart the AM.

The *Maintmaster´s* PM section exhibits PM activities to be performed at short term, with the possibility to be sorted by PL or equipment. These activities appear automatically in the program or can be added by the maintenance personnel. Each activity has at least one document (the PM plan) attached to explain the tasks “step-by-step”, tools required and estimated time. These documents are currently outdated being the majority from 2013.

Maintmaster also possesses a relevant section showing documented SWO´s with certain failures characteristics and necessary resources to solve it, documenting the solution of frequent problems making maintenance responses more efficient and effective.

Complete Line´s Equipment

The stored data in *MaintMaster* enables the analysis of failures occurred in CL´s equipment. The data collected refers to the fiscal year 2018 between September, 2017 and August, 2018. The chosen timeframe can be extended up to October, 2014 as represented in attachment J. However, the recent occurrences highlight concretely the equipments with higher wasted time. The data refers to machine breakdown excluding setup and adjustments, idling and minor stops and micro stops.

In Figure 14 a Pareto Chart identifies the critical machines with highest lost time (in hours). Given the data is completely recorded through human measurement, with the main purpose to share information between technicians and operators, it is highly susceptible to human error. Therefore, decimal places are considered redundant. The figure demonstrates the critical equipment is the "Homag – saws cart", causing the most time losses with a frequency of 23% and 74 hours, followed by "Bargstedt TSP - Exit" with 13% incidence and 39 wasted hours. The "Homag KAL – H2" appears in third place with 10% frequency and 32 hours lost, establishing a consequent consistency in the following equipment´s failure frequency up to five more equipments above 5% total wasted time.

The failures evaluation is ineffective since the reports are poorly structured. The main reason is that malfunctions are textually described. This approach diminishes the recordings potential to properly identify FM´s.

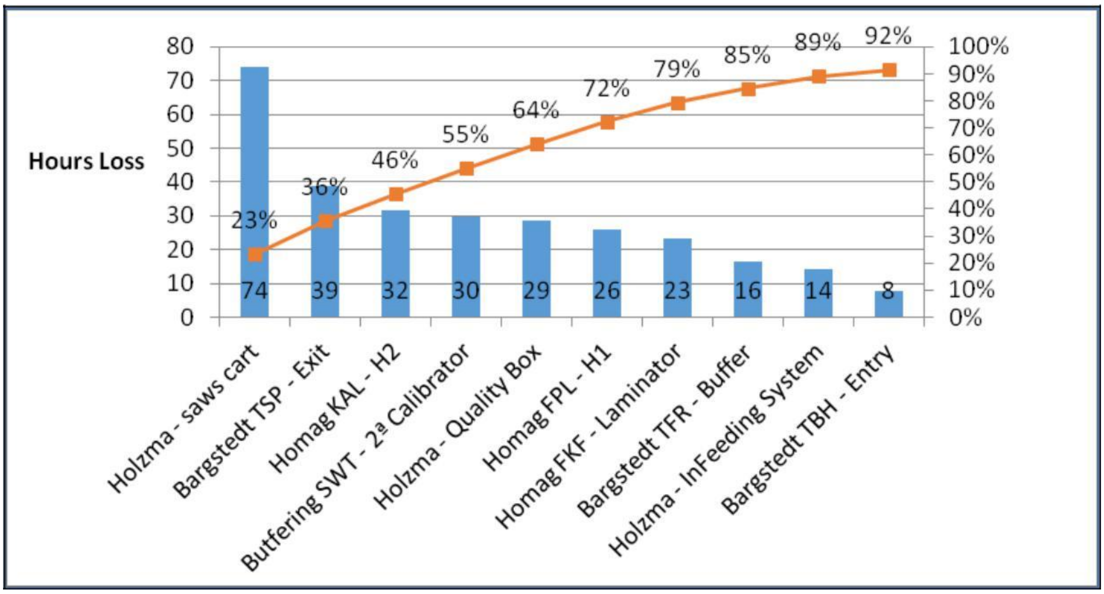


Figure 14 – Pareto Chart representing total hours loss per machine on Complete Line, between 01/09/2017 and 08/31/2018

4 Analysis of obtained solutions through methods and techniques application

The fourth chapter provides an amplified study of the CL´s conditioning factors. It also has the goal to find and identify solutions to CL´s inefficiency through the application of methods and techniques.

This chapter extends the business analysis processing the data set to extract maximum value. New attributes are generated resulting from calculations utilizing previous attributes as variables. This procedure enables to extend CL´s wasted time analysis through additional angles.

Posteriorly, an ARM model is implemented to explore relations between factors associated to CL, creating prospective rules of interest to the interpretation of line functioning.

A RCM approach is also executed to identify FM´s and corresponding root causes on two selected critical equipments, over the application of the FMEA technique. Consequently, with the determined associated costs and statistical analysis, the optimal periodicity is determined for each system of interest.

Along with calculating time-based tasks, PdM activities are also reviewed. A study of PT&I is made with the goal to research equipment´s condition from a distinct perspective.

Lastly, a MP is elaborated composed of the two studied maintenance processes to assist in the decision-making of WO allocation. The decision result is supported and optimized by a proposed IP formulation.

4.1 Business data processing

The continuous automated-monitored data extracted from CL presents powerful information. Each “idling and minor stop” and “micro-stops” data are difficult to register and measure due to the low time wasted per occurrence and therefore control this line losses. Such measures are displayed in *Qlickview*´s dataset, represented by “error code” ´s attribute. Each efficiency measure is composed by selected “error codes” as stated in Chapter 3. Due to the change in “error code” allocation methodology, the time lapse used in the dataset ranges between April and September, 2018.

A performance attribute (in percentage) is directly associated with the Performance indicators. In a first analysis, the performance values attributes are verified, some reaching values above 100.00% in some stages, suggesting the products nominal values lacks calibration and need review. The maximum theoretical production value for each product is fundamental to properly estimate maximum line efficiency. Otherwise, the reference value to calculate efficiency is misrepresented and provides wrong premises and estimates.

With the purpose to extend data interpretation and possibly detect new patterns, more attributes are created based on the already obtained:

Approximate Hour – the hour at which the events started. The hour attribute format type is an *integer* and ranges between 0 and 24, extrapolated from the “start time” attribute;

Shift – in *polynomial* format type has three possible labels (“morning”, “afternoon” and “night”). It is obtained by the combination between “hour of occurrence” and the respective hours belonging to each shift. It is also based in the factor time. This attribute´s goal aims to detect significant differences between work at different daily periods;

Day of the week – in *integer* format type detects differences in efficiency for each day of the week;

Team – in *integer* format type has four possibilities (“1”, “2”, “3” and “4”). This attribute contrasts with the “Shift” in the sense that focuses mainly in production´s team performance.

Although the 3rd shift always operates at “Night” and the 4th turn operates at the weekend, the 1st and 2nd turn switch “Morning” and “Afternoon” shifts weekly. Such calculation is made based in the combination between week number and shift type;

Material Changeover – in *polynomial* format this attribute creates a label composed by the previous and following product. This attribute observes possible material changeovers that significantly influence line functioning over adjustments made.

Daily hour analyses

Figure 15 represents minute’s loss per daily hour for the utilized dataset. Three peaks are observed in the figure for the hours “0:00”, “7:00” and “15:00”. This event appears to be related with shift trade, where interventions, inspections and material changeovers are made. It is also observed a tendency to the wasted time to increase gradually from the third to second shift.

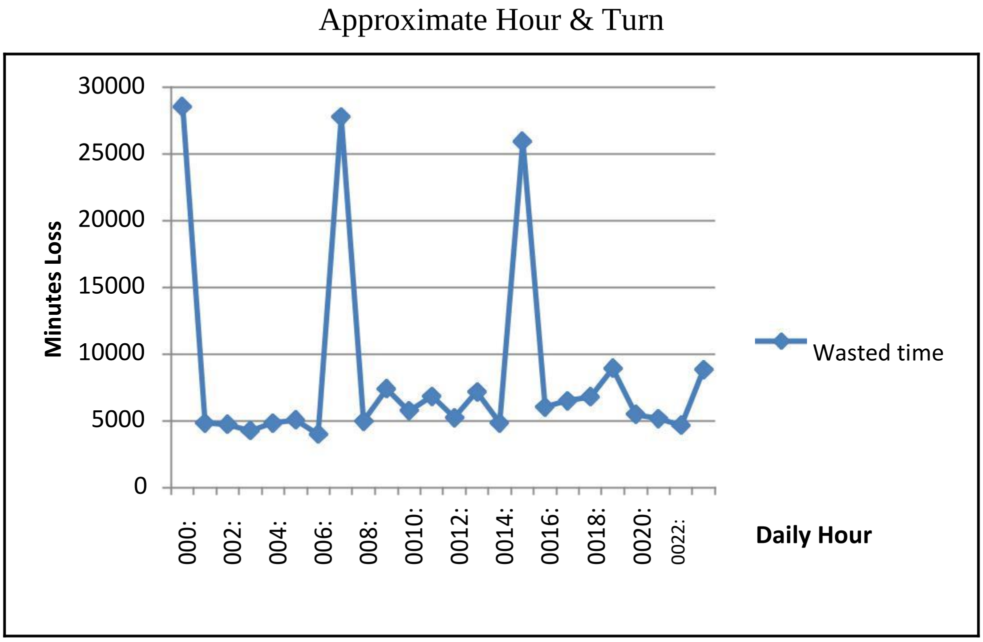


Figure 15 – Representation of minute’s loss per daily hour between 2/04/2018 and 28/09/2018

The exploration of the three critical daily hours is made in Figure 16, by wasted time. The equipment failures interventions follow an expected high percentage of total minute´s loss. The higher value at “7:00” can be explained due to the starting shift of the MD´s personnel other than the MT’s.

While “Reduced Speed” and “Setup and Adjustments” have a consistent tendency, “Idling and Minor Stops” augments significantly at “15:00”, approximately tripling compared to the second highest value at “7:00”. Such value must be discussed with the PD´s personnel.

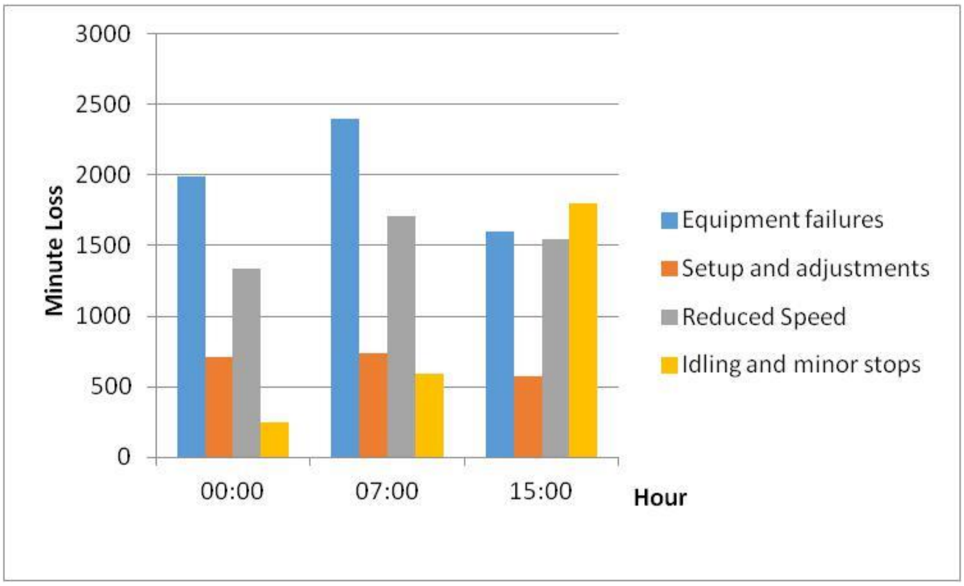


Figure 16 – Representation of minute loss by efficiency measure per daily hour between 2/04/2018 and 28/09/2018

Shift Analyses

Figure 17 represents each shift type divided by first and last 4 work hours. As observed, “Equipment Failures” follow a decaying pattern starting in each shift. “Reduced speed” and “Setup and Adjustments” are consistent through the whole day and “Idling and Minor Stops” measured between “7:00” and “18:00” daily hours show a tripling wasted time compared to the “Night” shift between “23:00” and “6:00” hours. The conclusions are the same respecting Shift and daily hour analysis.

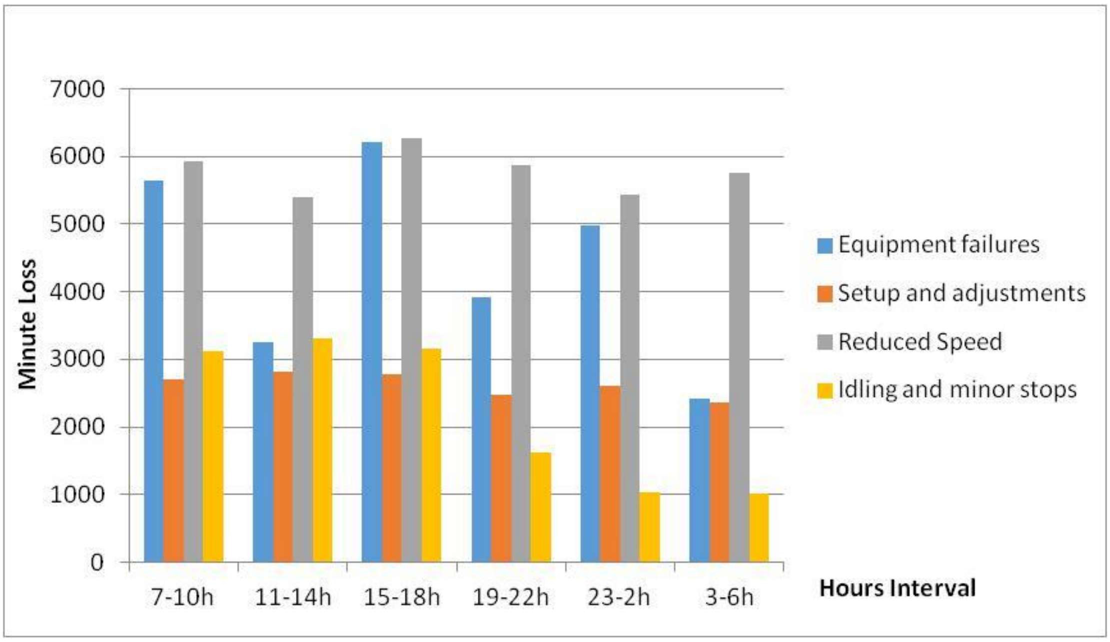


Figure 17 – Representation of minute’s loss by efficiency measure per 4 hours daily interval between 2/04/2018 and 28/09/2018

Week day analyses

Figure 18 analyses CL´s hours lost per week days. Assuming the week days have the same working hour’s volume, it is observed the line is more efficient in the middle of the week representing a down-shaped curve. The high values in the weekend for lost time is due to considering “Unplanned production time” into minute loss.

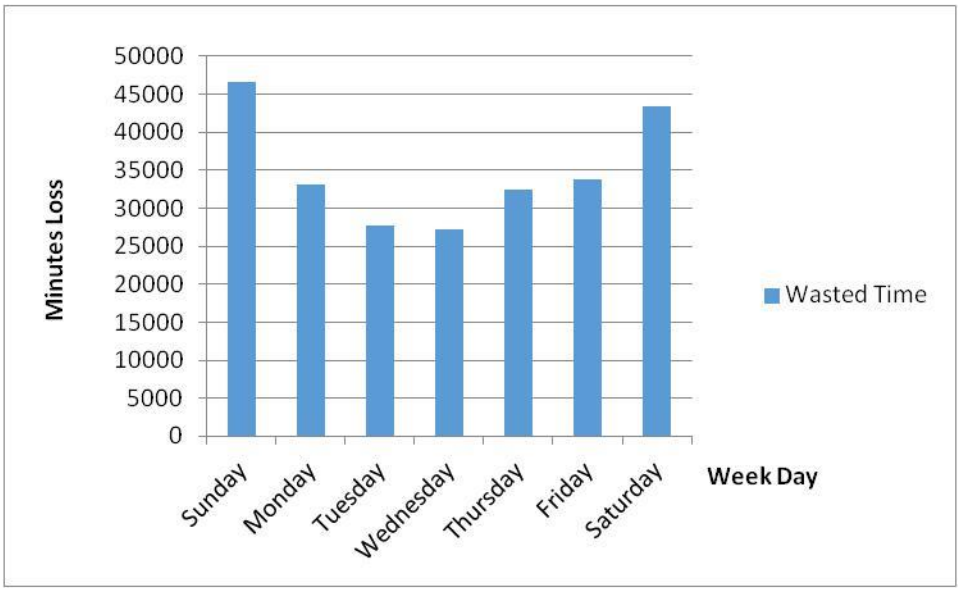


Figure 18 – Representation of minute’s loss per week day between 2/04/2018 and 28/09/2018

A more detailed description of how minutes are wasted by efficiency type per week day is found in Figure 19. “Idling and Minor Stops” efficiency at Thursday is more than the double of the total average. Such value can be purely random or due to factors such as operator's motivation. In general, the values remain consistent through weed days with an expected low volume for the weekend.

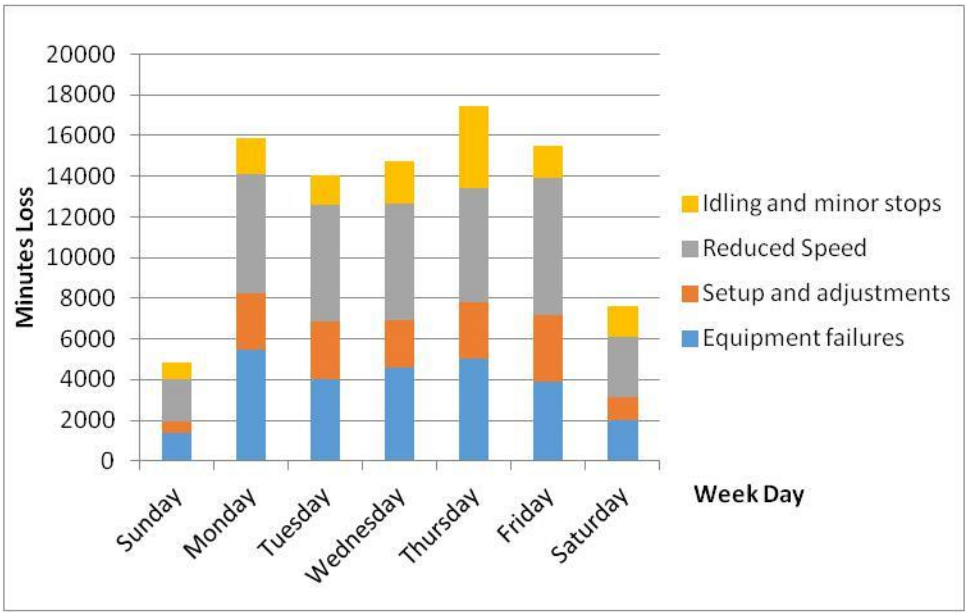


Figure 19 – Depiction of minute’s loss by efficiency measure per week day between 2/04/2018 and 28/09/2018

Attachment I illustrates the number of "Setups per week day", during the respective period. The number of setups is directly related to minute's loss in "Setup and Adjustments". In the figure, a down-shaped curve is observed, as in figure 18, inferring a possible explanation for the curve pattern. Although Figure 19 represents a consistent "Setup and Adjustment" pattern, the increase in setups can also influence the remaining efficiency measures.

Team Analyses

The attribute "Team" allows studying each team performance, as shown in Figure 20. Team "1" represents the "Night" shift, team "2" and "3" intercalate between "Morning" and "Afternoon" work schedules and team "4" respects the working days at the weekend.

Naturally, team "4" has the lowest wasted time for every efficiency measure since it also works considerable few hours compared to the remaining teams. The important finding to notice in the figure is the disparity between team "2" and "3", which work in same conditions.

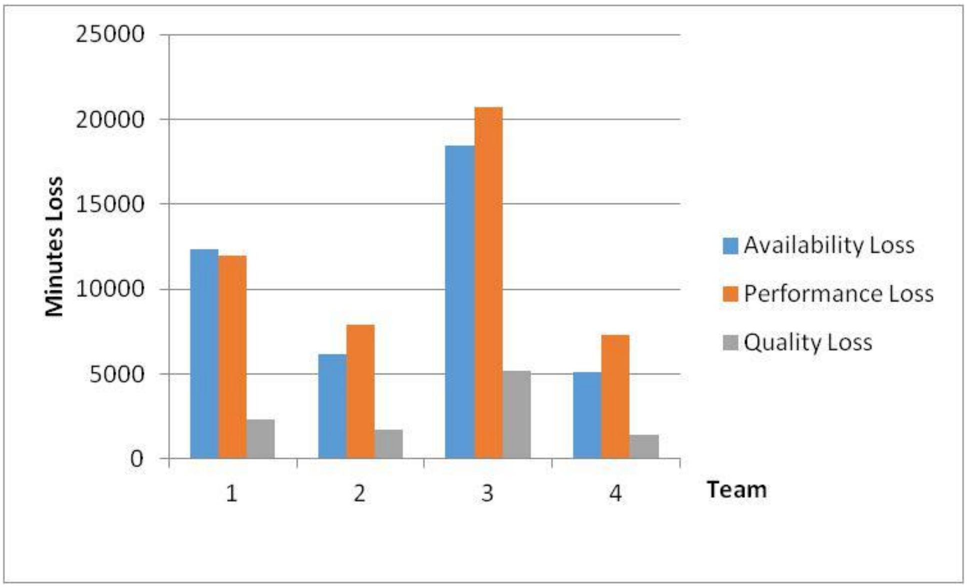


Figure 20 – Representation of minutes Loss by OEE measure per Team between 2/04/2018 and 28/09/2018

An intensified analysis is made focusing in team "2" and "3" efficiency measures by minute´s loss as depicted in figure 21. All measures are considerably higher for team "3". "Equipment Failures" ´s interventions are more than the triple for team 3. This event suggests discussion with both MD and PD personnel since the problem can be related to poor team´s AM or arrangement of interventions to be placed in team "3" daily hours.

All remaining measures picture that team "3" necessitates a need to change. To improve team "3" performance, the operators can exchange between teams to learn and teach best practices. Team "3"´s personnel training is another possibility.

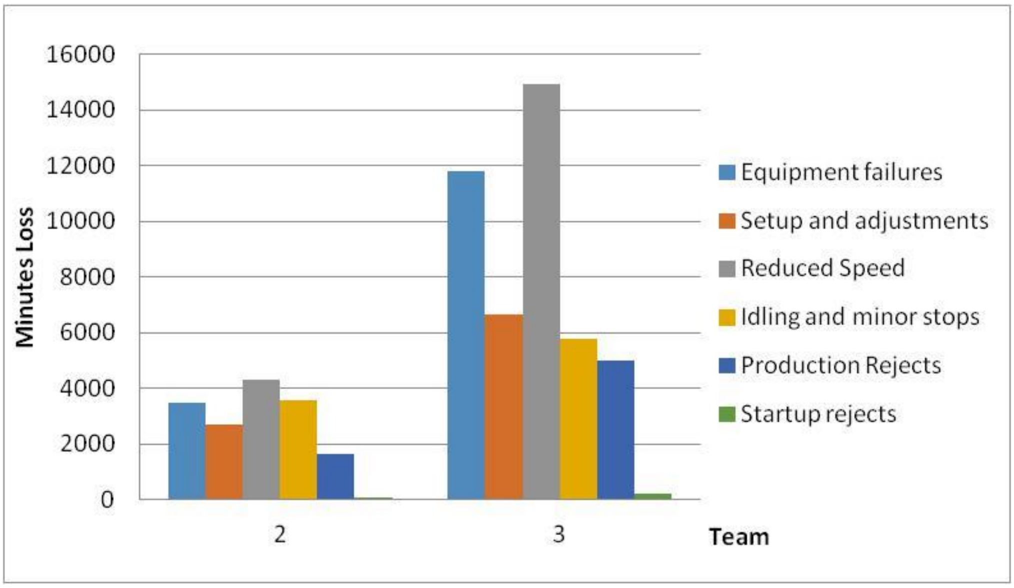


Figure 21 – Representation of minutes loss by efficiency measure per selected team between 2/04/2018 and 28/09/2018

Material Changeover

The “Material Changeover” attribute goal is to explore the “Setup and Adjustment” influence over a considered manufactured product by the previous one. During each setup the CL is subjected to calibrations to adjust product´s production, which can influence significantly line efficiency.

As in the process made in Chapter 3, for the products analysis, this attribute is pivoted and sorted in descending order by wasted time. The wasted time is divided by the number of occurrences per changeover. One changeover has at least one occurrence or phase. The number of combinations found is 909, considering the unplanned times as “No item” in previous or actual items.

Table 5 reveals the material changeovers that cause the highest wasted time per frequency. The average ratio is 3.52 and standard deviation 5.53. The table displays potential changeovers that deviate significantly from the average ratio. Both changeover ID´s 1 and 2 assume important relevance due to their frequency compared to all possible combinations and the elevated minutes/occurrence.

Table 5 – Representation of the most significant combinations in terms of wasted time

Changeover ID	Previous item	Actual item	Frequency (%)	Wasted time (minutes)	Number of occurrences	Ratio (minutes/phase)
1	Besta FW SH 02 WH2	Besta FW SD 02 GY1	1.18	1475.77	139	10.62
2	Stuva FW TB 12 WH2	Stuva FW TB 11 WH2	1.05	1310.80	114	11.50
3	Besta TV FW BT 04 WH2	Besta FW TP 01 GY1	0.5	703.35	31	22.69
4	Besta FW BT 02 BB2	Stuva FW TB 12 WH2	0.9	490.62	31	15.83
5	Stuva FW SH 18 WH2	Stuva FW TP 21 WH2	0.39	485.71	49	9.92

The five changeover combinations are subjected to an analysis by efficiency measure, as illustrated in Figure 22. "Equipment Failures" is the overall cause of inefficiency during the consequent item production. "Idling and Minor Stops" also produce performance problems in changeover ID 4.

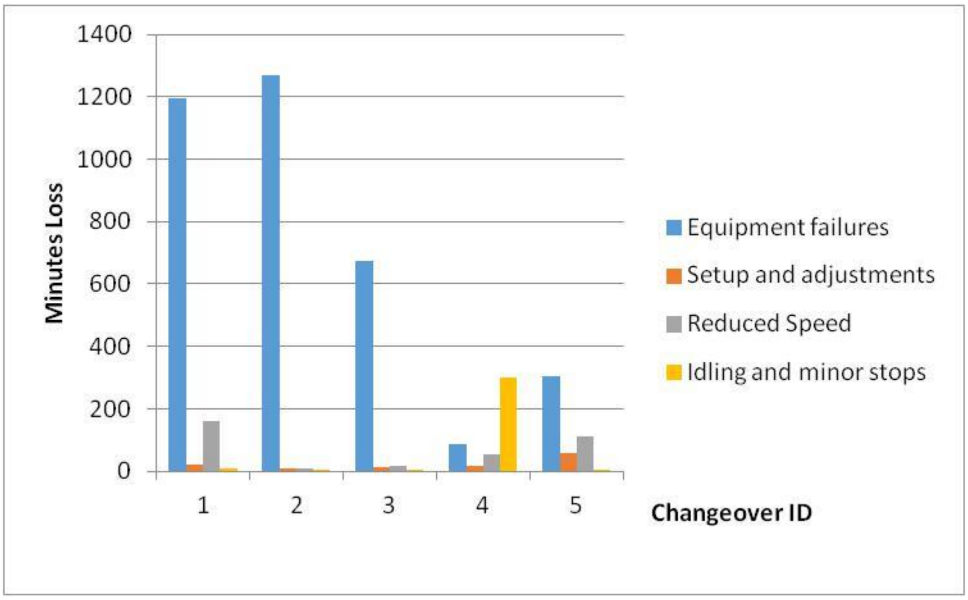


Figure 22 – Representation of minute's loss by efficiency measures per changeover combination

Nevertheless, to obtain more accurate results and avoid randomness, the dataset must be much larger to sustain the quantity of possible combinations. In addition, the number of setups per combination must be calculated (with the assistance of the PD´s ERP) - the dataset only enables to obtain the number of occurrences per combination (e.g. 40 occurrences can relate to 3 changeovers and 20 occurrences to 4).

CL´s analysis review

To summarize CL´s factors analysis, including in Chapter 3, the most important discovered facts to take into consideration, are:

- New methodology applied to "error code" annotates root causes in a more ambiguous form, implying loss of information;

- Product´s Ideal Cycle time requires retesting and calibration;

- Major causes of products with highest minutes/occurrence is related to performance efficiency, AM and breakdowns in specific machines;

- "Idling and minor stops" triples from "Night" to "Morning" and "Afternoon" shifts;

- Number of setups has a potential positive relation with wasted time;

- Team´s analysis reveals inconsistent results requiring an action plan to improve operator´s performance;

- Material changeover combination has a potential influence over line efficiency and must be integrated as a product´s KPI.

4.2 Association Rule Mining (ARM)

The ARM method follows the technological trends of automated monitoring and can be used to better understand relations in a complex system with innumerous factors. The application of this method can find undetected valuable patterns and incentivize a continuous improving TPM mentality by raising awareness to both maintenance and production personnel.

The dataset used is extracted from *QlickView* with occurrences between February, 1 and September, 28 of 2018. For the same motive explained in products analysis section, in Chapter 3, the data set is considered starting April, 3. Respecting data set structure, the considered attributes are: efficiency KPI´s (e.g. Availability or Performance); daily occurrences (e.g. number of breakdowns, setups occurrence and material delayed percentage); respective “error causes”. Each row represents a day in the stipulated time interval although some days are removed due to complete or almost inexistence of manufacturing time. The number of rows is 137.

The items are discretized (known as “binned”) between value intervals, considering the ARM method uses binary data. Otherwise, the items are assumed to be “True” or “False”. To generate the rules, causes are combined with effects. The number of possible combinations is often large requiring the proper analysis of rules characteristics to sort and easily find rules of interest. Filtering combinations by imposing restrictions in respective characteristic values diminishes the solutions size and time of processing considerably, helping find the intended rules.

Table 6 represents the selected attributes that can assume either the “antecedent” or “consequent” (cause and effect) condition. Each range value is obtained assuming each attributes value follows a normal distribution function, considering redundant the exact attribute´s distribution function to obtain the discrete interval values. The intervals can vary in three possible intervals: [0-33%]; [33-66%]; [66-100%]. For a certain considered value is assigned a “Label”. Certain intervals are excluded from the selected variables due to “good” efficiency (ML and DT means “minutes loss” and “downtime”, respectively).

The “Break Down per Day” and “Setup Occurrence per day” indicators assume a counting measure while the remaining are “binned” by percentage. The most critical and relevant “error codes” are also selected.

Table 6 – Representation of possible “cause” or “effects” labels with respective ranges

by *Downtime* **Antecedent (cause) or Consequent (effect)**		
Parameter	**Range Value**	**Label**
Availability Per day	0 – 70.75 % DT	A1
	70.75 – 84.24 % DT	A2
Performance efficiency per day	0 – 66.64 % DT	P1
	66,64 – 78.52 % DT	P2
Material Delay per day	4,91 – 9.54 % DT	M3
	9.54 – 100 % DT	M4
Setup & Adjustment per day	7.93 – 14.68 % DT	S3
	14.68 - 100% DT	S4
Break Down per Day	X < 4	B1
	5 <= X < 8	B2
	X >= 9	B3
Normal Velocity	-0.50 – 31.86 ML DT	3000b
	+ 31.86 ML DT	3000a
Reduced Velocity	192.89 – 262.63 ML DT	3100b
	+ 262.63 ML DT	3100a
Product Setup	44.83 – 73.97 ML DT	4100b
	+ 73.97 ML DT	4100a
Tool change / consumables	16.25 – 33.63 ML DT	4400b
	+ 33.63 ML DT	4400a
Adjustments/tuning	18.99 – 48.84 ML DT	4401b
	+ 48.84 ML DT	4401a
1º Level Maintenance(AM)	200.67 – 232.76 ML DT	4500b
	+ 232.76 ML DT	4500a
Micro – Stop	24.82 – 39.97 ML DT	4910b
	+ 39.97 ML DT	4910a
Mechanical component failure	29.74 – 145.86 ML DT	5100b
	+ 145.86 ML DT	5100a
Eletrical component failure	29.70 – 90.49 ML DT	5200b
	+ 90.49 ML DT	5200a
Aspiration Failure	43.14 – 88.54 ML DT	9200b
	+ 88.54 ML DT	9200a

The “OEE” and “Setups per day” are also considered as a “label”. In OEE´s case, since it is a global efficiency measure considering several types of inefficiencies, can only assume an "effect" status. In the other hand, the setups are preprogrammed by the PD, which can only represent a “cause”. Table 7 demonstrates “OEE” and “Setups per day” label with solely a consequent and antecedent function, respectively.

Table 7 – Representation of only possible “effect” and “cause” labels with respective ranges by *Downtime*

Parameter	Status	Range Value	Label
Overall Equipment Efficiency	Consequent	0 – 49.62 % DT	OEE1
		49.62 – 61.38 % DT	OEE2
Setups per day	Antecedent	X < 4	C1
		5 <= X < 7	C2
		X >= 7	C3

The program used to run the ARM model is the *RapidMiner Studio*. The created process is shown in Attachment K: the “Retrieve” operator access the dataset; “Select Attributes” enables to chose the study attributes; “Sample” allows to decrease the dataset with several purposes (e.g. reduce processing time or divide the data set); “Numerical to Binomial” – as the name indicates, changes the attributes type from “numerical” to “binomial”; “FP – Growth” calculates item sets that occur frequency allowing to impose a support value restriction; “Create Association Rules” is the operator that generates the association rules based in given item sets.

The maximum number of items per item set is considered 4 avoiding too complex rules to interpret and diminish processing time. Such restrictions make possible to have a rule with 3 antecedents and 1 consequent or the opposite. The number of sets obtained is 4993, however it considers all possible combinations (e.g. using “OEE” as a “cause”). Table 8 depicts the rules found with higher “Lift”, “Conviction” and “Confidence” assuring rules viability with high “correlation” and “implication” between labels.

Table 8 – Representation of identified rules ranked by confidence

Nº	Supp	Conf	Lift	Conv	Antecedent (cause)		Consequent (effect)		
1	0.250	0.800	2.560	3.438	C3	M4	4100a	3100a	
2	0.188	0.750	3.000	3.000	4910a		4100a	3100a	M4
3	0.188	0.750	1.500	2.000	P1	M4	OEE1		
4	0.188	0.750	2.000	2.500	4401b		3100a	P1	
5	0.188	0.750	2.400	2.750	C3	4910a	3100a	S3	
6	0.188	0.750	3.000	3.000	C3	5100b	4100a	S4	
7	0.188	0.750	4.000	3.250	3100a	M4	4100a	4401b	

An analysis of the created rules, allows inferring both rules nrº 2 and 4 can be actionable, while the remaining are considered trivial and already known to the interested party.

Rule nrº 2 suggests “Micro-Stops” cause high “Product Setup”, “Reduced Velocity” and “Material Delay”, with support and confidence of 18.8% and 75.0%, respectively. Although, it is already acknowledge the correlation between “Micro-Stops” and “Reduced Speed”, the reduction of one “cause” can greatly influence three line efficiency factors. The rule also presents high correlation and implication values.

Rule nr. 4 indicates that medium lost time in “Adjustments” take part in low “Reduced Velocity” and “Performance”. Despite “Adjustments” being dissociated from Performance, the rule suggests adjustments in setups may be ineffective and harm the line during manufacturing. It also presents acceptable values of correlation and implication.

The additional rules suggest potential relations already known such as higher lost time in “Product Setup” related to higher “number of setups” or low “Performance” causing low “OEE”. Although, a recurrent indicator in the trivial rules is high “Material delay”, suggesting that it negatively influences line efficiency.

Despite some potentially valuable results, a recurrent pattern is observed in “support” and “confidence” measures in Table 8: the dataset repeatedly iterates the association algorithm in the same instances. Such event happens due to the small dataset, requiring to be enlarged to gain better substantiated rules.

4.3 RCM approach

The RCM approach intends to study and identify equipment’s root causes and respective FM´s, initially through the extensive analysis of documented failures, as shown in Attachment L, and continuous discussion with maintenance and production personnel. The FMEA technique is applied to determine FM´s causes and elaborate effective maintenance tasks.

Both “Holzma - Quality Box” and “Holzma – saws cart” are selected in this project to apply the FMEA. Attachment M illustrates “Holzma – saws cart” ´s system analysis. This document is elaborated based in the failures report´s study and discussion with MT´s and PO´s. The columns display: “Subsystem”; “Component”; “Failure Mode”; “Root causes”. A single FM can result from different causes, possibly extending the study. A FM analysis can then generate new characteristics such as: “Mechanism”; “Reason”; “Cause”.

Although the document provides precise and high-quality information that helps controlling such complexity, the MD still faces a problem when selecting the “systems” to consider when performing preventive actions. Since it is practically impossible, with the available resources, to execute PM for each FM in the due optimal time, a PM activity normally includes a set of FM´s.

To better understand the different types of failures and their characteristics, which constitute an equipment, a diagram is displayed in attachment N, representing the “Holzma – QualityBox” stratified by “sub-systems” with respective Mean Time Between Failures (MTBF). The most recurrent “systems” are considered, despite the vast quantity of possible situations, when representing and calculating MTBF. It can be observed the MTBF´s increase as the systems are decomposed. This method can assist the PM responsibles to better understand and assess the optimal WO´s for planned maintenance.

One aspect to take into consideration is the number of equal components that can exist in a certain “system”. The problem is to decide to consider all components as equal - independent and identically distributed (IID) or if the conditions affecting components are different. Such subject must be discussed with the responsible MT´s in every scenario. Despite the MT´s advise, the ideal approach is to record all occurrences independently and afterwards execute an IID Laplace test. If the test is inconclusive (H0 unrejected) for all equal components, the same are aggregated to constitute a single FM.

4.4 Scheduling of PM tasks

This section´s goal is to obtain the optimal time to execute a preventive maintenance in a respective system or FM.

Laplace Test

Maintmaster allows extracting the historical failures to *Excel*. A statistical test based in Laplace formula is firstly executed for each equipment considering a constant failure rate as H0. This test´s goal is to detect the equipments with overall increasing deterioration level, although the equipments with an inconclusive test (H0 unrejected) can also possess increasing FR´s in subsystems. H0 is rejected if statistical test exceeds the stipulated critical value based on the chosen significance level of 5%. The test is considered bilateral (FR can be increasing or decreasing) therefore the significance level splits into 2.5% for each side, obtaining the values: 1.96 and 1.96.

The equipments which reject H0 are: "Butfering SWB – 2º calibrator"; "Holzma - Quality Box"; "Holzma – saws cart"; "Homag FKF – Laminator". The statistical tests retrieve the values 3.91, 2.72, 4.84 and 9.93, respectively. All FR´s are increasing since the values are positive.

Failure Mode findings

The selected machines, which also reject H0, are studied in depth with access to the notes taken in each reported failure. For the "Holzma - Quality Box" and "Holzma – saws cart", 42 and 130 FM´s are identified, respectively. In the first and second machines, 10 and 9 FM´s are selected, respectively, subject to the condition: N >= 3. Those FM´s "label" and "nrº of occurrences" are represented in Table 9, for the "Holzma - Quality Box".

The commas in each "label" stratify the system into sub-systems, helping identify the represented FM.

Table 9 – Representation of recurrent FM´s with nrº of occurrences at "Holzma – Quality Box", between 10/2014 and 09/2018

FM	B-Box	A.Stop.Bolts	A.Sensor	A.Cylinder	A.Roler.Misaligned	A.Stop.Broke	Aligner
Nrº of occurrences	16	12	12	11	9	7	7
FM	A.Misaligned	A.Roler. Belt	Infeed	A.Stop.Misaligned			
Nrº of occurrences	6	5	5	3			

Afterwards, the FM´s are subject to the estimation of the respective Weibull distribution parameters, using the available data - both "time-until-failure" and "time-until-repair" are considered. For purposes of best practices only the PM´s carried out annually (in August) are considered as "time-until-repair" (or "incomplete" referring to the usage). An example of this categorization is shown in Table 10. Both time until failure and repair attributes are displayed in the first and second column, respectively. The third column is a standard attribute, relating to "time-until-repair" repetitions', assuming the PM plan is properly executed, which results in consistent time-based actions. Such methodology is not followed, since the PM plan is rigidly scheduled for August with the respective intervention of equipments manufacturers' team.

The values are then processed in the weibull objective function (O.F.). By resorting to *Excel´s Solver,* the beta parameter is obtained, assuming the O.F. needs to be equal to 0. If the beta value is above 1, it is assumed the FM´s FR is increasing, concluding the equipment cost can be reduced through scheduling of PM action.

Table 10 – Representation of running times at FM "Saw.Engine.Electricerror" in "Holzma – saws cart", between 10/2014 and 09/2018

FM	Cart.Engine.Error		
ti(Complete)	tj(incomplete)		Cj(rep)
696,696002	188,24		1
538,6758286	455,5		1
341,2196071	513,22		1
847,856	287,46		1
652,38			
765,28			

Costs determination

The costs associated with a FM´s or equipment PM and CM action are a critical factor in determining optimal scheduling. The determination of such expenses is rather complex due to several factors. For matters of simplification, it is considered opportunity cost of line stoppage and component cost to constitute cost determination. The MD has a workshop where the components are repaired, greatly reducing component´s cost. This fact enhances PM actions since the disparity between PM and CM costs augment, due to MWT increase in weight in costs determination formula.

The stoppage time is integrated by the MWT, MTTR and the testing as described in Chapter 3. With the assistance of the ISD, the value of average running hours respecting line stoppage is determined: 9350 Euros/Runninghour.

The preventive cost considers MTTR, testing and component cost.

Optimal Periodicity

The FM´s optimal periodicity is determined by the value that minimizes risk evaluation: EV (tp). Such procedure enables minimize costs through scheduling of FM´s tasks compared to the manufacturer's initial recommendation, due to the unique specific environment influence over equipments and associated costs.

Table 11 illustrates an example of how optimal periodicity calculation is made for a given FM. This procedure also utilizes *Solver,* with the goal to minimize the O.F. (C(tp)). The respective FM name is "A.Cylinder", related to the event of the component cylinder breaks in the subsystem "A-box" at the equipment "Holzma – Quality Box". The optimal periodicity is approximately 1392.53 running hours, which corresponds to approximately 4 months, given the average running hours per day is 10.75. The table also represents the FM´s weibull parameters: beta (shape) with value 2.81; n (scale) with value 2042.82. It shows the preventive (Cp) and corrective (Cf) action costs: 5225 and 14 575 Euros, respectively. This periodicity presents the minimal cost: 6.19 Euros/hour. The FM´s reliability (S (Tp)) is 71.12% for 1392.53 running hours.

Taking into consideration the equipments PM plan follows discrete time-based orders (e.g. weekly, monthly and annually), a maintenance task can be added or edited to execute a monthly task.

Table 11 – Representation of optimal periodicity and corresponding cost in Failure mode "A.Cylinder" at equipment "Holzma – Quality Box"

FM	A.Cylinder
Lim_inf=	0
Lim_sup(Tp)=	1392.53
Factor_forma=	2.8099
Vida_caract=	2042.823
Cp=	5225
Cf=	14575
F(Tp)=	0.2887
S(Tp)=	0.7113
C(Tp)=	6.1944

4.5 Predictive Maintenance Findings

Advances in monitoring technologies lead to more control over the equipments functioning state. Automated monitoring can retrieve machine condition information in real time. The majority of IKEA factory´s monitoring is human-based with irregular inspections made by AM or when a maintenance action is performed in certain equipment. This project proposes to improve PdM maintenance actions resorting to PT&I tools. Although PT&I enable assessing equipment condition, the causes remain unidentified. Monitoring techniques are: temperature, voltage and vibration monitoring; sonic (ultra-sonic) testing; non-destructive testing.

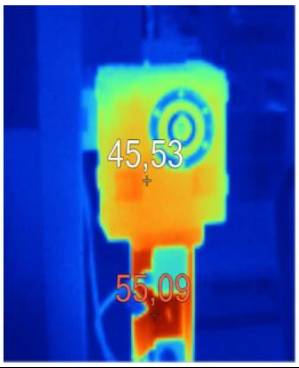
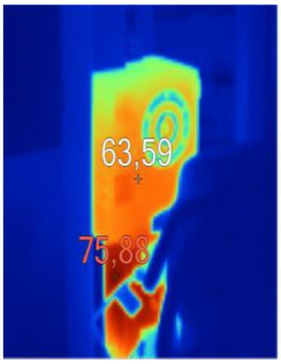
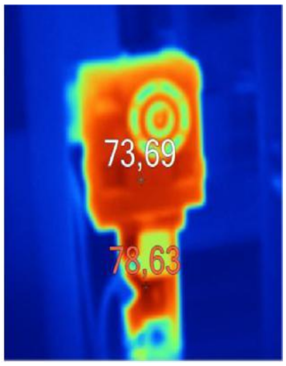
It is known heating components (e.g. engines and rotors) full running with a temperature above 5º the normal operating temperature, lead to a 50% decrease in the component life cycle. The causes can be multiple, although, per example, a common rotor axis misalignment can cause unbalanced load and rise temperature, which can be easily fixed and calibrated.

Furthermore, another technique to easily monitor component´s system functioning is electrical voltage. The accumulated dust resulted from manufactured wooden products is a common cause of electrical and mechanical failures, since the accumulated powder in the system generates more heat. A voltage imbalance of at least 5% can result in a 50% reduction in component life expectancy, present safety concerns (fires) and increase electrical usage. The voltage imbalance normally results due to an increasingly insulation degradation which can be repaired with a simple and cheap task. Additionally, voltage imbalance can be the cause for increase in component temperature.

One of those PT&I tools was tested in this project: MD´s workshop provided an available Thermal Imager. The tool captures the distribution, maximum or chosen location temperature of a selected component. The tool´s model is "Fluke Ti32" with a temperature measurement accuracy of +/- 2º and a temperature range of [-10; 600] ºC. Knowing the normal functioning temperature when at full work, with the assistance of manufacturer's catalogue, the data collected can be a high-quality indicator of an equipments current state.

A more proactive maintenance, using the thermal imager (or another PT&I tool) daily in specific targets can predict early potential problems. Table 12 displays images took in the equipments engine "Butfering SWT - 2nd calibrator", with the access to the software SmartView 4.3 representing dispersion, highest temperature, and a chosen point. For a more rigorous approach in the method, the shooting angle must be the same, preferably performing a 90º angle with the engine and taking two more photos with a 45º angle. It is necessary to confirm the PL is operating at maximum capacity to assure evaluating conditions.

Table 12 – Images taken with thermal imager at due dates with reference image of the engine at Butfering SWT - 2nd calibrator

Reference Image	Date: 8/10/2018 15:30	Date:15/10/2018 11:25	Date: 23/10/2018 16:44
			

A proposed report is shown in Table 13, with a full diagnostic of the motors temperature. The dispersion and maximum temperature attributes provide valuable patterns caused by certain FM´s that can be recognized by a technician's expertise. The results provide high-quality information following an improvement of maintenance management methods.

This information is then stored in the supervisor portfolio influencing posterior stock-orders and planned maintenances - time available, tasks and operators. The equipments follow a sequence of inspections to control the level of deterioration.

Table 13 – Proposed report to diagnose component temperature

Equipment	Date	Maximum Temperature (ºC)	Average temperature (ºC)	Dispersion	Material	Note
Butfering SWT - 2º calibrator	8/10/2018 15:30	55º	46	Increasing top to bottom	-	-
Butfering SWB – 1º calibrator	8/10/2018 15:29	51	41	Increasing bottom to top	-	-
Butfering SWT - 2º calibrator	15/10/2018 11:25	76	64	Increasing top to bottom	-	-
Butfering SWB – 1º calibrator	15/10/2018 15:24	59	55	Uniform	-	-
Butfering SWT - 2º calibrator	23/10/2018 16:44	79	74	Uniform	-	-
Butfering SWB – 1º calibrator	23/10/2018 16:43	68	64	Uniform	-	-

However, some heating components are difficult to access, making the inspection relatively time consuming added up with the “extract and report” phase.

Monitoring measurements

A difficult problem to tackle is the quantification, in terms of probability of component´s reliability, of a certain human-based monitoring. A well experienced operator or maintenance technician is required to accurately assess the probability of a given component to fail during a certain period of time (e.g. determining a 20% probability of failure for the next week due to noise evaluation).

Therefore, to simplify inspection reports it is proposed that the noted monitoring are classified discretely between 1 to 5, as the probability of failure in a week or a certain number of running hours.

The goal is to make the quantification the most accurate possible, discussing with the MT´s experts the possible patterns each FM can assume (e.g. a technician may state the probability of a components fails next week is 10%, but 50% in the consequent 3 weeks). This method intends to acknowledge a component failure function and also establish a strategy for the next planned maintenances preparation.

4.6 Program editing and data-crossing

Both Enterprise Resource Programs (ERP) provide valuable information concerning PL´s condition. However, the information is too imprecise referring the exact system where an occurrence took place. While *QlickView*´s monitoring section only specifies the PL, *Maintmaster* can only reach the affected machine.

It is suggested that both software’s are restructured, implementing new attributes: “Equipment” for *QlickView;* “System” referring the concerned component or sub-part of the machine; “Failure Mode” regarding the exact type of failure. The “Failure Mode” offers a list of previous identified and agreed FM´s. This process requires the Information Systems Department (ISD) assistance to edit the failure reporting. Since *QlickView*´s monitoring is only established for the overall PL, new attributes require to be assigned manually by the Po or MT..

As the methodology develops, FM´s and “sub-systems” are continuously revised and updated. This suggested approach incentives workers collaboration and focus in line occurrences exploiting a broader control over the lines consequently improving TPM mentality.

The datasets restructuration also enables to cross data between softwares, since they now have attributes in common. Using the Excel´s add-in tool *PowerPivot,* the data can now be crossed through the creation of an intermediate dataset, related to time period, as illustrated in attachment O. The information can now be pivoted between ERP´s and improve system´s analysis. For example, equipment´s occurrences can be studied in a certain quarter respecting *MainMaster* and *QlickView*´ s reporting’s.

4.7 Maintenance plan elaboration

This project proposes a maintenance plan (MP) which integrates both preventive and predictive maintenance. The time-based tasks are obtained through the study of failures and costs associated with corrective or preventive maintenance for each “system”. This method adapts to the previous one, established by the machine's manufacturers, where the influence of the unique features of PL´s is not accurately accounted and the trade-off between maintenance costs is far from optimized. It is also assumed the proper quantification of the condition-based maintenance.

The MP is then elaborated with the goal to determine and allocate FM´s EV per hour respecting “system” ´s WOs. The calculated values support decide the set of tasks to perform during available hours at the weekend.

Only the tasks that require line stoppage are considered. It is assumed the other tasks are of PO´s responsibility through AM or the MT´s can execute during week days. The MP considers 4 results for every FM, estimating a task value for each posterior 4 weekends. This means the MP presents a global solution for approximately one month period. For matters of simplicity, the extra three available maintenance hours for each PL are grouped to the consequent weekend.

This MP proposes the use of an *Excel* spreadsheet and ideally extracts failure data from *Maintmaster* and *QlickView* automatically calculating respective “system´s” function distribution parameters, optimal periodicity and expected values.

Before characterizing the MP attributes, there are two important facts to consider:

1 – In practical terms, the WOs regarding PM are only executed posteriorly to an inspection. If significant information enables infer the equipment is functioning properly the preventive action is canceled and a future inspection is scheduled for monitoring, changing the WO status to condition-based. After failure or replacement, the WO returns to time-based calibrating the FM distribution function with the recent data obtained;

2 – Due to the vast number of FMs in each equipment and PL, a need to aggregate WOs emerge. A set of WOs is decided to be performed regarding his full value, rather than a single FM. The set can constitute a component, a subsystem or a whole equipment. To this event is also applied fact nr. 1.

The MP is then characterized by the following specific or grouped attributes:

Factory; PL; Equipment; Subsystem; Component- Indicates the exact location where the WO takes place;

FM – Refers the considered FM;

Beta (shape) and n(scale) - The 2 WD parameters are displayed for which the WO status is time-based.

MTTR (hour) - mean time to repair characteristic of each FM´s WO;

MWT (hour) - mean waiting time calculated by the average ratio of 6,4 compared to the respecting WO´s MTTR. Although, due to the factors considered in the CM methodology section at chapter 3, the value can be further refined;

Cost of component (Euros) – The average cost of the respective component, considering the evaluation between repair or replacement cost and each possibilities weight. This attribute can be decomposed into two, if the difference in component cost for preventive or corrective actions is considered significant;

Cp (preventive) (Euros) – Cost respecting a WO preventive action. Includes component cost (repair or replacement) and cost of line stoppage regarding MTTR;

Cf (corrective)(Euros) – Also includes component cost, and cost of line stoppage, composed by MWT, MTTR and setup until production of the first quality piece;

Stock (quantity) - informs the number of spare parts available regarding the component. The possibility of replacing a component by a different one is explained in chapter 3. Although such measures are not exploited;

$MT_{i=1}^{L}$ (Binary) - The MT´s capacity to execute the WO (for N numbers of MT´s);

$CB_{j=1}^{4}$ (Probability) – relates to FM´s reliability during the consequent 4 weeks, discretized by week and measured by inspection. The CB_1 attribute refers to the last inspection made. Consecutive values are equal or greater to previous ones, considering the deterioration factor. The data regarding the inspections made to the FM by the experienced MT´s must be properly stored to facilitate the best accurate forecast possible to consequent weeks;

Note (Text) – Due to inspection complexity and difficulty quantifying a condition-based analysis, notes support the function estimation;

Last action (Date) – day when the last respective WO occurred;

Actual running hours (Hours) – Value obtained based in "Last action" and the actual day, estimating running hours occurred, based in the average running hours per day;

Optimal Periodicity (Hours and days) – Divided into 2 attributes informs the ideal periodicity to realize the PM action, if it is that the case;

F(Actual) (Probability) – The probability of failure expected at the actual time;

$F_{j=1}^{4}(jWeek)$(Probability) – Probability of failure for the next 1 to 4 weeks (calculated by the difference between F(jWeek) and F(Actual);

$EV_{j=1}^{4}$ (Euros) – Expected value obtained from the risk formula presented in chapter 2;

$NEV_{j=1}^{4}$ (Euros/Hour) – Lastly, a measure of expected value divided by respective MTTR, normalizing the WO´s value;

Other metrics are used to assist calculations such as: Actual time (Date); Average running hours per day (Hours); Opportunity cost of line stoppage (Euros/hour). The WD parameters and timing results can be manually obtained or a significant effort by the ISD can be done to automate the calculations. Such measure would constantly update the failures timeframe to a more recent one, actualizing the parameters. In result, the final values regarding PM actions would be also updated.

The MP spreadsheet is shown in Attachment N. It considers the FMs or systems estimated for the CL´s selected machines, although, can be implemented in the whole factory. Due to his dimension, it is split into two figures. The equipments are differentiated by color to assist recognition.

The MP responsible can formulate more accurately an action-plan for the next four weeks based in the most valuable set of FM´s through the normalized metric EV (Euros/Hour).

The MP spreadsheet is shown in Attachment P, due to his dimensions. It considers the FMs or systems estimated for the CL´s selected machines, although, can be implemented in the whole factory. The equipments are differentiated by color to assist recognition.

The MP responsibles can more accurately formulate an action-plan for the next four weeks based in the most valuable set of FM´s through the normalization of the metric EV (Euros/Hour).

4.8 Binary Integer Programming

Each FM´s NEV (Euros/hour) values develop in different manners through the weeks, based in the distribution functions, FM conditions reported after inspection and costs associated with preventive and corrective actions, which generate a decision-making problem. This problem requires the formulation of an IP to optimize the solution.

The available time for PM in each week imposes a restriction that influences the objective function to maximize the PM value. A problem associated with task-order allocation is then formulated, following the Binary Integer Programming method.

The formulation is then represented as:

- Binary decision variable:

$FM_{i,j} = 1$ if FM_i is included in the PM_j; 0 otherwise
Where: i = FM number;
j = PM number (or week).

- Objective function:

Maximize EV (Euros/Hour) = $\sum_{i=1}^{M}\sum_{j=1}^{N} FM_{i,j} * NEV_{i,j}$
Where:
M = number of identified FM´s;
N = number of weeks;

$NEV_{i,j}$ = Expected Value per hour for the FM_i in PM_j.

- Restrictions:

$$\sum_{i=1}^{M} \sum_{j=1}^{N} FM_{i,j} \leq 1$$

$$\sum_{i=1}^{M} MTTR_i * \ FM_{i,j} \ \leq ST_j \text{ (For a certain } PM_j\text{)}$$

$$FM_{i,j} \text{ is a binary variable}$$

Where:

ST_j = stipulated time for PM_j;

$MTTR_i$ = Mean time to repair for the FM_i;

The problem representation is illustrated in Table 14. Resorting to the *Solver* tool, the respective restrictions are inserted, binary values categorized, values chosen to be iterated and a respective cell to be maximized.

The table shows part of an excel spreadsheet where the 1st restriction can be seen horizontally consequent to the binary table and the 2nd restriction is displayed vertically to the right of the binary table.

To ST_j is given a hypothetical value respecting the PM_j. The NEV (Euros/Hour) table is withdrawn from the PM spreadsheet as well as the MTTR, to maximize the sum value shown at the bottom right of Table 14.

Table 14 – Representation of binary IP formulation for the MP results

	Fm1	Fm2	Fm3	Fm4	Fm5	Fm6	Fm7	Fm8	Fm9	Fm10	Fm11	Fm12	Time		ST
PM1	0	0	0	0	0	1	0	0	0	1	0	0	0,305365	<=	0,5
PM2	0	0	1	1	0	0	0	0	1	0	0	0	0,484303	<=	0,5
PM3	0	0	0	0	1	0	0	1	0	0	1	0	0,414623	<=	0,5
PM4	1	1	0	0	0	0	0	0	0	0	0	1	0,481237	<=	0,5
Total (<=1)	1	1	1	1	1	1	0	1	1	1	1	1		Week EV /h	
Expected Value(1)/h	7386,152	9447,77	784,4543	2561,216	4803,089	733,8841	2677,352	5438,62	4458,809	71206,75	27346,34	50317,27		71940,63	
Expected Value(2)/h	14624,01	35915,9	1048,566	4508,744	9084,663	908,4635	4779,844	10281,58	8240,873	71206,75	27346,34	50317,27		13798,18	
Expected Value(3)/h	22074,31	44738,61	1439,647	6455,225	13367,15	1163,649	6914,78	15069,98	11941,95	71206,75	36253,44	50317,27		64690,57	
Expected Value(4)/h	29581,27	53561,33	1978,116	8392,149	17587,41	1513,82	9068,211	19741,89	15540,83	71206,75	36253,44	60255,71		143398,3	
														Sum	
MTTR	0,159985	0,15625	0,156919	0,15625	0,104798	0,152459	0,501695	0,153574	0,171134	0,152905	0,15625	0,165002		293827,7	

In fact, the O.F. can integrate more DV´s to the IP if required. For the MTs can be assigned a certain order-tasks, creating a new BDV ($MT_{i,k}$) where the value is 1 if for the MT_k (k = MT identification) is assigned the FM_i , or 0 otherwise. The MT´s can not be able to perform a certain FM_i, so a variable $C_{i,k}$ is imposed as a restriction referring a binary table of capabilities to a certain $MT_k$and FM_i. The needed time for each MT_k in PM_j is then assigned, and/or the MT_k can impose a time restriction for PM_j.

It is possible to consider a MT is unable to handle a specific FM at a certain level of deterioration, generating the BDV: $MT_{i,j,k}$. However, this possibility is redundant to the objective of the implementation.

The new O.F. results:

Maximize EV (Euros)/h = $\sum_{i=1}^{M} \sum_{i=1}^{N} \sum_{k=1}^{L} FM_{i,j} * EV_{i,j} * MT_{i,j,k}$

Where:

L= number of MT´s.

Additional restrictions:

$$\sum_{k=1}^{L} MT_{i,k} * \ FM_i \ * \ C_{i,k} \ \ \leq 1 \text{ (For a certain } FM_i \text{ and considering only 1 } MT_k \text{ is needed)}$$

$$\sum_{i=1}^{M} MTTR_i * \ \ MT_{i,k} * FM_i \ \leq STMT_{j,k} \text{ (For a certain } PM_j \text{ and } MT_k\text{. The } MTTR_i \text{ is considered the same for each } MT_k \text{)}$$

$$MT_{i,k} \text{ is binary variable}$$

Where:

$STMT_{j,k}$ = stipulated time for the MT_k in the PM_j.

The MP can now allocate optimal order-tasks considering MT´s conditions and available time to effectuate PM in each week, in order to maximize the NEV (Euros/Hour). This methodology used to better determine and control order-tasks values to be assigned, can only serve as a basis in the decision-making management. The vast complexity of variables in place, easily make an assumption fallacious, potentially resulting in a negative impact to maintenance costs. This methodology can only be effective along with a vast knowledge of the current situation in the given system.

5 Review, conclusions and future work perspectives

This chapter presents the conclusions of the work developed in the project, with a final revision of the obtained results in both business and maintenance analysis. Several solutions are proposed in the short and medium term. A future work forecasting is also approached following up technology development, with the final goal to rise PL´s efficiency to a higher level.

5.1 Review and conclusions

The initial problem proposition motivating the elaboration of this dissertation respects equipment *downtime* analysis, due to lack of control over the event, which impacts PL´s availability, affecting the expected maintenance results. Therefore, there was a need to study in more detail the historical failures and re-elaborate the preventive maintenance plan, with the collaboration of the MD. However, given the factory´s existent resources, opportunity has arisen to develop a broader study involving all TPM areas and exploit further engineering fields.

One of BoF´s PLs, the CL, was chosen to be the central study subject due to the significant top losses influencing OEE and his major importance to the factory as the regular *bottleneck*.

The studied data is extracted from two different ERP´s mentioned in this work, with different goals and data organization, nevertheless providing useful information to the study of the factors influencing PL´s efficiency.

Firstly, a business approach was made to the CL. A data analysis of CL´s OEE indicators was made through *QLickView* ´s data, concluding the highest losses are related to Performance. The data set is mostly automated, providing accurate data. Several data analyses were made pivoting the data in *Excel*, accessing aspects from different perspectives. Relevant information was found during the pre-processing phase. Subsequently, certain attributes were processed to explore CL´s elements, based in the already obtained. The results of interest obtained are:

- “Idling and minor stops” is significantly reduced during the night shift suggesting the other shifts can improve in the same field. Proposed resolutions are: alternating workers between shifts to transmit or obtain knowledge from the efficient team; Retrain the labor or observe workers errors during shifts.

- Team analysis findings show one of the scheduled interchanging teams has a considerable overall indicators difference (especially “reduced speed”) with the other in the same conditions. This fact relates to the previous one, but better specifies the team that causes such difference.

- The material changeover research observes the influence of materials during setup. Some product combinations show considerable deviant wasted time per occurrence, in comparison with the average. It is then proposed a study for top losses due to setup (or adjustments) and specific products. Certain combinations can be acknowledged and avoided by the PD. It is also concluded the utilized dataset is too short compared to the vast number of possible combinations, which can more probably provide wrong results.

An introduction to data mining modeling was made. The ARM model retrieves possible actionable rules, allowing to better understand relations between PL aspects. This application is important to find undetected patterns and connect the MD to the fields embrace emerging technologies. However, the data set is considered too short and the recent reporting process too ambiguous. The study of the line factors by product manufacturing instead of days provides a more extensive study field, which may be made in collaboration with the PD and its central ERP. Thereafter, a more intensive study to “error codes” originates greater results.

A general maintenance analysis was performed to the CL´s machines with higher *downtimes*, accessing the program *Maintmaster*. A Pareto chart was then elaborated with failure records from the fiscal year 2018. The results were: 23% of total wasted time belongs to “Holzma – saws cart”; 13% is created by the “Bargstedt TSP – Exit”; another five machines present values between 5 and 10%. These results lead to the conclusion that high *downtimes* are caused by other factors than the malfunction of one or more machines, due to the consistency of equipment´s wasted time.

An RCM approach was applied in two CL equipments: “Holzma – saws cart” and “Holzma – Quality Box”. These machines were primarily chosen in consequence of the Laplace test made to the critical machines, finding evidence of an increasing overall FR.

The equipments historical failures were studied in depth, to identify critical FMs and obtain their distribution function parameters and associated preventive and corrective costs achieving the respective optimal periodicity. All costs and data regarding maintenance activities need to be supported and calibrated in conjunction with the maintenance and production department.

The majority of maintenance activities done in the PLs are based in PdM. It is proposed a re-elaborated report to properly quantify observations taken collected during inspections or AM to equipment´s condition. It is also proposed the implementation of PT&I tools and methods to the MD activities. This proposal is considered to be the one which brings fastest and highest returns in short and medium term. It requires low investment and is easily executed. This monitoring with specific tools such as: thermal imager, voltage meter and vibration meter makes a huge impact in the equipments current condition assessment, providing high valuable information to better control and plan maintenance activities.

It is also proposed the restructuration of both ERP´s data sets, to add three major attributes to augment control over PLs, improving TPM and enabling crossing data between programs, through the Excel´s add-in *PowerPivot*.

A MP was elaborated and proposed in *Excel* integrating both preventive and predictive WOs. The results are determined by EV (Euros/Hour) for each WO and week of the consequent month. This MP is expected to rise maintenance methodologies and ultimately increase efficiency measures at mid-term. It can only succeed with the total collaboration of PL´s shareholders and a mentality oriented to continuous improvement.

Lastly, the MP originates a decision-making problem, since it is projected for approximately a month interval (four possible weeks). This problem was formulated applying Integer Programming, where binary decision variables, objective function and restrictions were established. Other hypothetical conditions were combined into the problem demonstrating its flexibility.

The implementation of such methodologies requires a regular meeting with the interested departments to approach and discuss the proposed changes and the goal it intends to accomplish. Regular meetings need to be scheduled in order to update developments and proceed to adjustments if required.

These methodologies and solutions given for explored problems have the goal to increase OEE from the approximately current value of 40.00% (considered as “low”) to a benchmark of 60.00% (“typical”) in the short and mid-term (up to 3 years).

5.2 Future work project

It is expected the continuous usage of the proposed methods to: analyze all aspects referring to the PLs; identify and update FMs ensuring maximum control; increasingly improve activities related to PT&I in the whole fabric. Such maintenance action plan imply a restructuration in maintenance activities with the potential to more accurately assess equipment condition and predict machine breakdown, therefore improving results.

Respecting the MP development, many other factors and variables can be considered to improve model adjustement to reality. The MWT is only considered for CM activities. However, exists a time lapse between WO´s execution. As shown in figure 6, BoF dimensions represent considerable distances between MD and PL´s. It is proposed a study of the lost time between locations (represented by the matrix: D(; ;) where expresses a certain location in the factory and is the total number of locations), which influence the optimal MP solution.

In the long-term, an investment project should be initiated to implement the disruptive technologies such as the IoT sensors. These sensors will continuously detect equipment condition. The project eventually studies the optimal number and types of sensors to install in a single equipment as well as the optimal ERP to collect and process the data. As stated in Chapter 2, the project application will minimize spare parts costs, downtime and reduce maintenance assets. Such implementation results in enormous changes in maintenance methodologies and how it is perceived. Most MD´s functions will suffer a transition from technical to managerial, mainly oriented to PdM, focused in data mining research, constantly analyzing forecasting models to be tested and executed.

The full implementation of this new project, subject to a comprehensive study and added-up to the previous suggested methodologies, provides the resources to obtain a “world-class” OEE above 80.00%.

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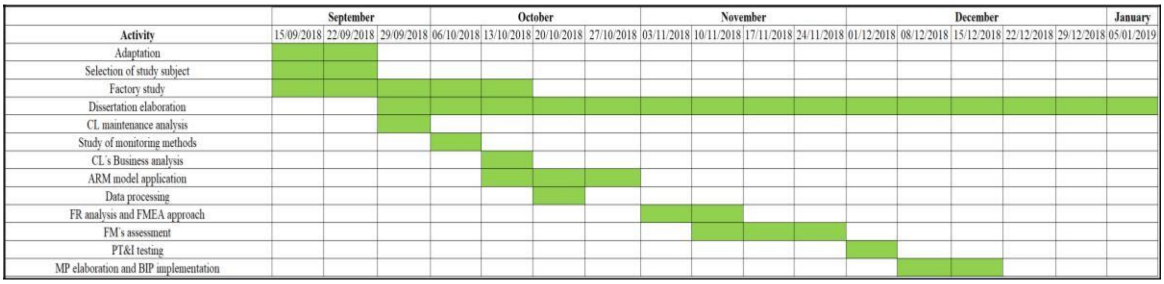
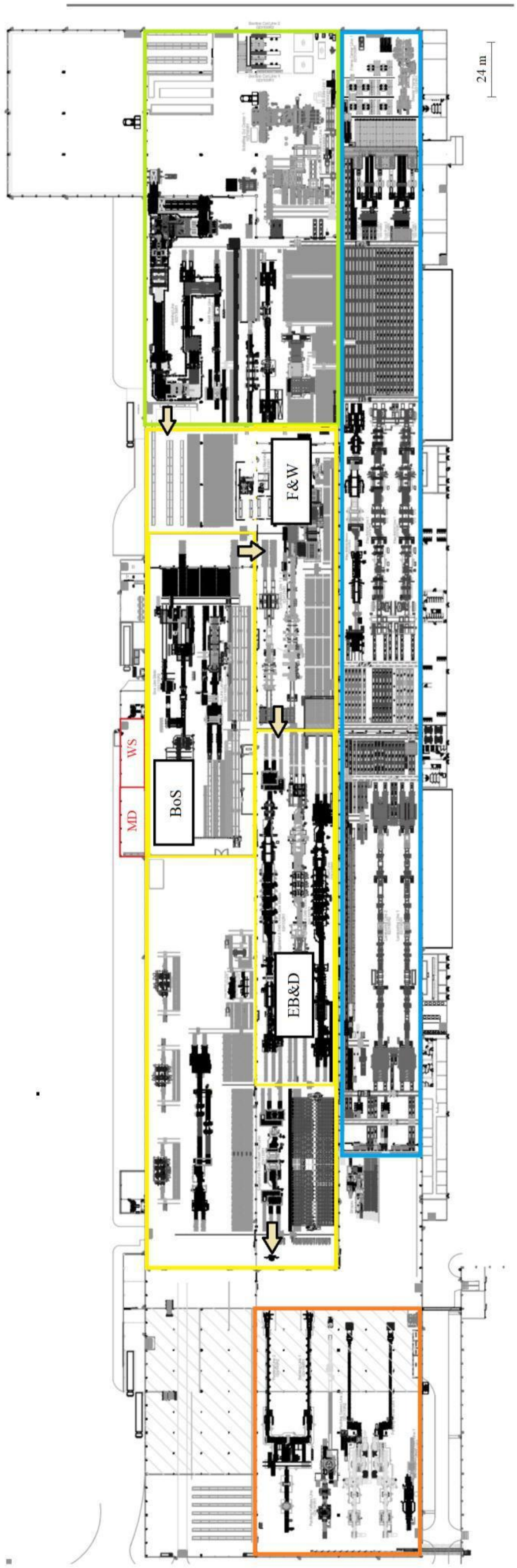
https://corporatefinanceinstitute.com/resources/knowledge/finance/business-life-cycle/

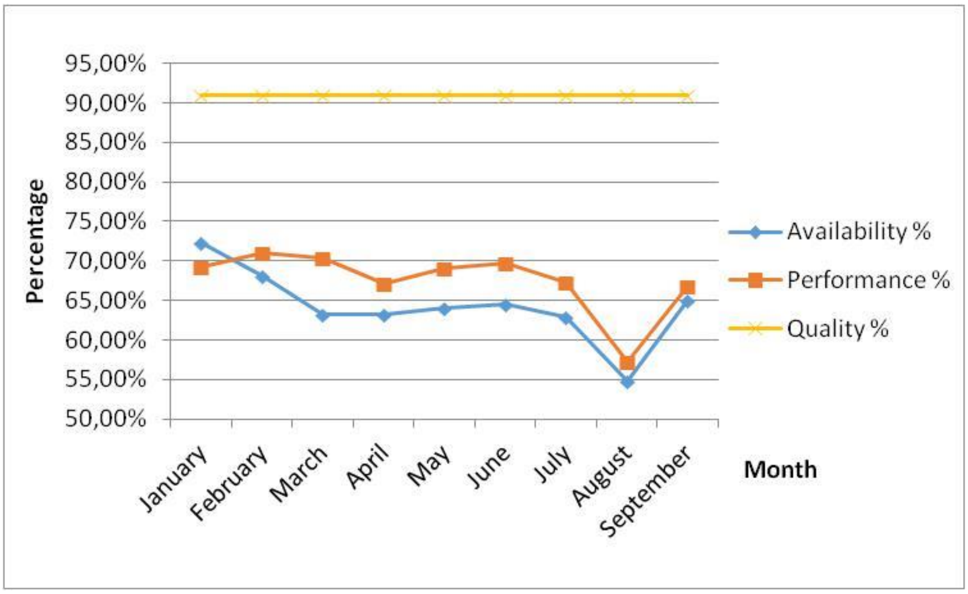
Attachment A: Gant chart representation of project elaboration



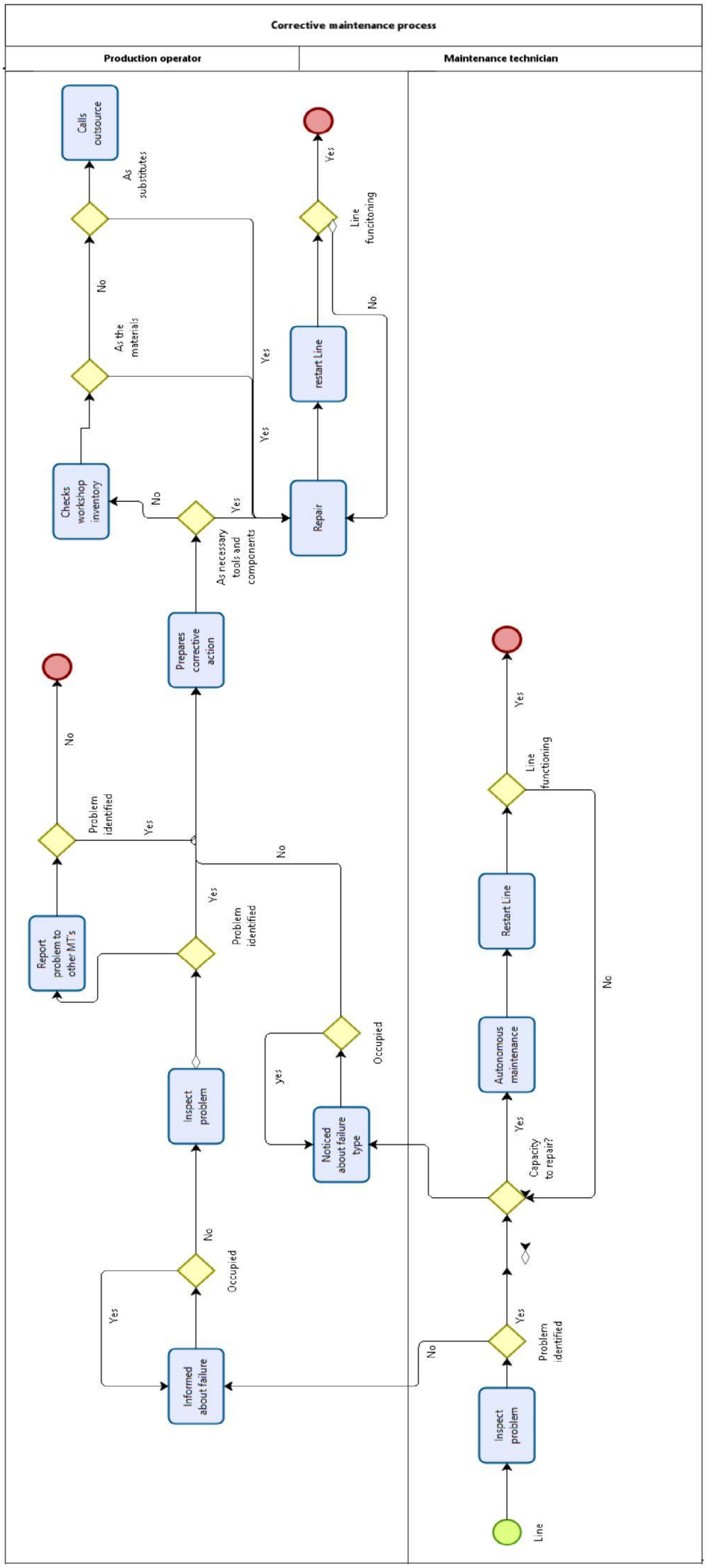
Attachment B: representation of BOF factory plant



Attachment C: Representation of CL´s efficiency measures between January and September, 2018



Attachment D: Flow chart of corrective maintenance activity (created in Bizagi Modeler)



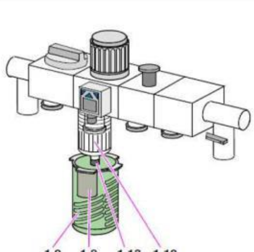
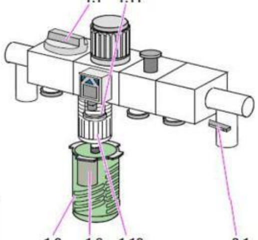
Attachment E: PM monthly Intervention plan for the machine “Homag KAL 620”

Swedwood PORTUGAL	Instrução Trabalho Manutenção	DATA: 04-06-2013	ITM-1094 01
		ELABORADO POR: Ana Mota	APROVADO POR: Joaquim José Silva

FÁBRICA: Foil	ÁREA: WRAP & Foil	LINHA: Complete Line	POSTO TRABALHO:	DESIGNAÇÃO DO PRODUTO:	INFORMAÇÃO ADICIONAL: U202000074 - HOMAG KAL 620

Foil F&W - Manutenção Preventiva Mensal - Intervenção HOMAG KAL 620

- EHS - Qualidade - 1ª Peça OK - Formação - Processo - Manutenção - Manutenção 1º Nv - Produção - Dica SWOP

No	Instrução	Material Necessário	Equipamento de apoio	Tempo Previsto (h)		Observações	IMAGENS/ESQUEMAS
1	Unidade de manutenção do ar comprimido		Carro de ferramenta	0.4		**Limpar a válvula de purga do condensado:** Carregar a malha 1.8 e retirar o cesto de protecção 1.9, girando-o; Desaparafusar o depósito 1.10; Desaparafusar a purga do condensado 1.13; Limpar a purga do condensado 1.13 com benzina para lavar; Aparafusar a purga do condensado 1.13; Aparafusar o depósito 1.10 e apertar à mão; Colocar o cesto de protecção 1.9.	
2	Unidade de manutenção do ar comprimido		Carro de ferramenta	0.4	Dica	**Substituir o filtro:** Fechar a válvula de segurança 1.1; Alimentação de ar está desligada; Extrair o ar na válvula de esfera 2.1; Carregar a malha 1.8 e retirar o cesto de protecção 1.9, girando-o; Desenroscar o depósito 1.10; Substituir filtro 1.11; Lubrificar ligeiramente a rosca do depósito; Aparafusar o depósito 1.10 e apertar à mão; Colocar o cesto de protecção 1.9. Nota: Ter atenção ao vedante durante a substituição do filtro; perda de pressão.	
3	Agregado de aplicação de cola Quick Melt 34		Carro de ferramenta	1		Limpeza da unidade de aplicação de cola.	
4	Grade de protecção - Porta com segurança		Carro de ferramenta	0.2		**Verificar o interruptor de segurança:** A porta tem de estar trancada; O interruptor de segurança não pode apresentar danos. A chave no interruptor de chave só pode ser tirada na posição 0.	
5	Trituradores de papel que se encontram associados a extracção - parte superior da Homag 2	Ar comprimido; Pano seco	Carro de ferramenta	0.2		Limpeza e remoção dos resíduos dos trituradores de papel.	
6	Rolamentos	OKS 641 / Equivalente; OKS 2661 / Equivalente	Carro de ferramenta	0.3		Limpeza dos rolamentos.	

AJUDAS EHS:	AJUDAS CHAVE:	Dep. Tec.:	Dep. Qual.:	Dep. Prod.
		VÁLIDO DE:	A:	

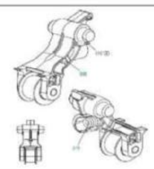
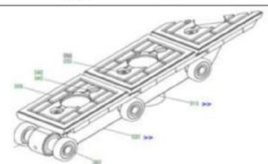
Attachment F: PM monthly Inspection plan for the machine “Homag KAL 620”

Swedwood PORTUGAL	Instrução Trabalho Manutenção	DATA: 04-06-2013	ITM-1090 01
		ELABORADO POR: Ana Mota	APROVADO POR: Joaquim José Silva

FÁBRICA: Foil	ÁREA: WRAP & Foil	LINHA: Complete Line	POSTO TRABALHO:	DESIGNAÇÃO DO PRODUTO:	INFORMAÇÃO ADICIONAL: U202000074 - HOMAG KAL 620

Foil F&W - Manutenção Preventiva Mensal - Inspecção HOMAG KAL 620

- EHS - Qualidade - 1ª Peça OK - Formação - Processo - Manutenção - Manutenção 1º Nv - Produção - Dica SWOP

No	Instrução	Material Necessário	Equipamento de apoio	Tempo Previsto (h)	Observações	IMAGENS/ESQUEMAS
1	Agregado de aplicação de cola Quick Melt 34		Carro de ferramenta	0.2	Verificar o funcionamento da sonda de aplicação de cola.	
2	Agregado de fresagem fina		Carro de ferramenta	0.2	Verificar o separador e o rolo sensor e ajustar.	
3	Reservatorio de pré-fusão		Carro de ferramenta	0.5	Verificar o bom funcionamento do sistema pneumatico do empurrador de granulado para fusão, válvula de descarga para o reservatório intermédio. Verificar resistencias.	
4	Equipamento de corte GR-100 / GR-160 (trituradores)		Carro de ferramenta	0.5	Verificar os rolamentos e substituir caso necessário.	
5	Mangueira da alimentação da zona de aplicação		Carro de ferramenta	0.3	Verificar estado dos orificios de entrada e saida. Substituir se apresentar muito constrangimento.	
6	Bicos aplicadores de cola		Carro de ferramenta	1	Verificar resistências.	
7	Rodas pressoras	Part Number: 2-212-19-0050	Carro de ferramenta	0.5	Verificar rodas pressoras da correia de transporte.	
8	Transporte	Part Number: 4-060-18-0055	Carro de ferramenta	1	Verificar estado das chain pad´s. Se necessário substituir.	

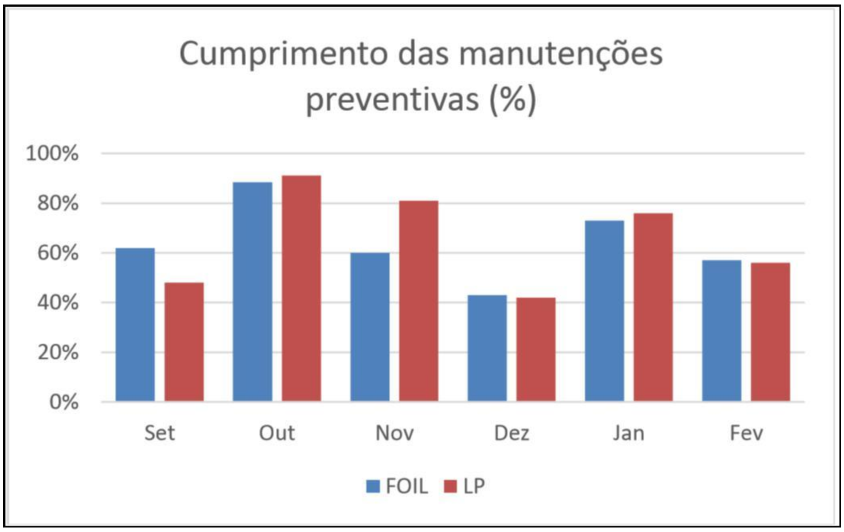
AJUDAS EHS:	AJUDAS CHAVE:	Dep. Tec.:	Dep. Qual.:	Dep. Prod.
		VÁLIDO DE:	A:	

Attachment G: PM new monthly plan for the machine “Homag KAL 620”

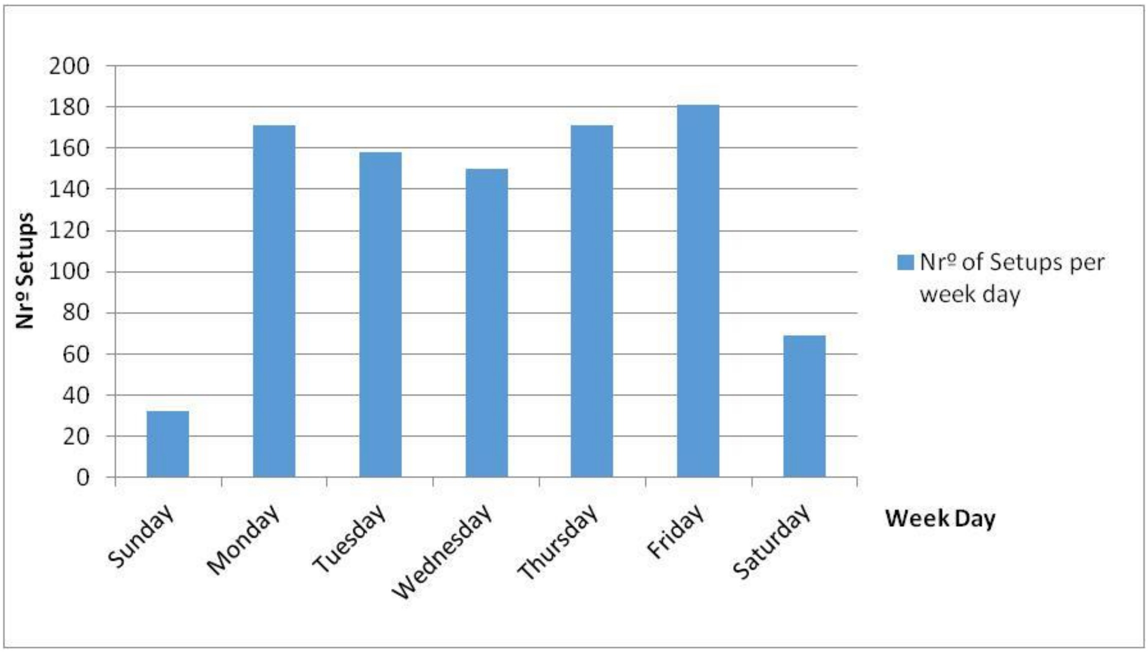
IKEA Industry Paços de Ferreira	Plano de Manutenção FOIL - Foil&Wrap - CompleteLine	Data:	
Manutenção - BoF	Homag KAL 620	Código IKEA	U202000074
		Código Fabricante	0-200-41-4212

Frequência	Nº	WES	Tarefa	Ref. Fabricante	Ref. Armazém	Qtd.	Mês
Mensal	1		Verificar o bom funcionamento do sistema pneumático do empurrador de granulado para fusão e da válvula de descarga para o reservatório intermédio. Verificar resistências.				
	2		Verificar rolamentos do equipamento de corte GR 100/ GR 160 (trituradores).				
	3		Verificar estado dos orifícios de entrada e saída da mangueira da alimentação da zona de aplicação.				
	4		Verificar rodas pressoras da correia de transporte.	2-212-19-0050			
	5		Verificar estado das chain pad's e, se necessário substituir.	4-060-18-0055			
	6	5608	**Substituir filtro da unidade de manutenção do ar comprimido.**				
	7	5629	**Limpar a unidade de aplicação da cola.**				
	8		**Limpar e remover resíduos dos trituradores de papel que se encontram associados à extração. (Parte superior da Homag 2)**				
	9		**Limpar os motores de aspiração de filler e cola.**				

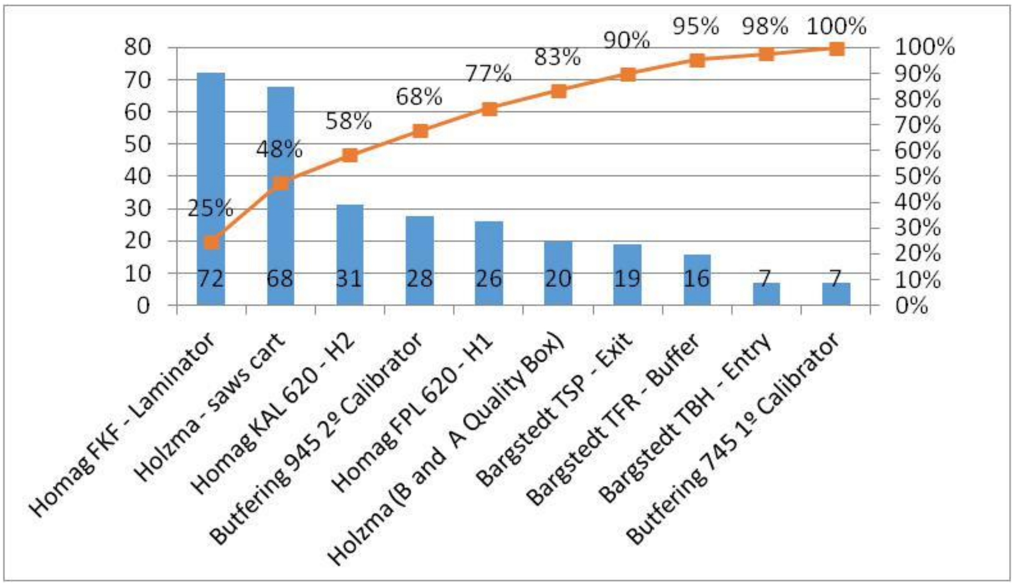
Attachment H: Histogram of preventive maintenance plan compliance in at Foil and Lack & Print, in the fiscal year 2016 (Diogo, 2016)



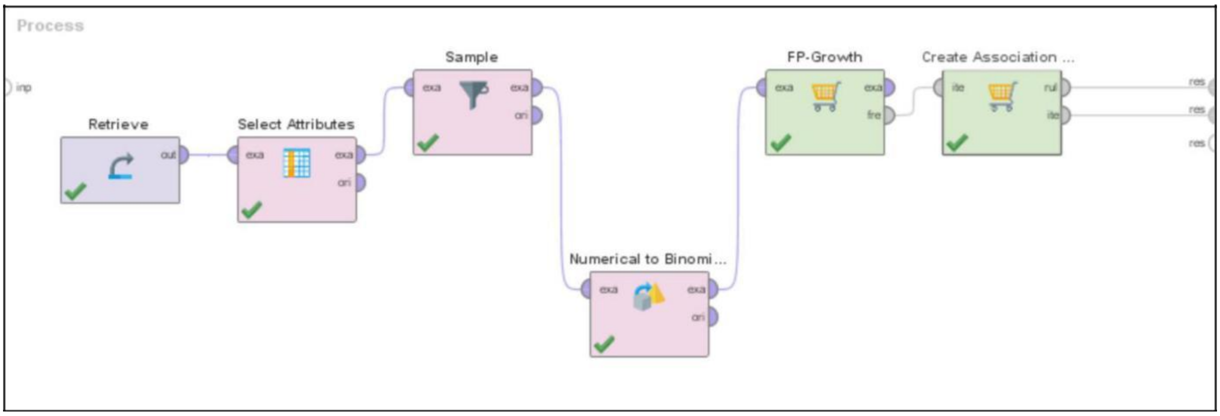
Attachment I: Figure Representation of setups in each day of the week in the time period 31/01/2018 to 30/09/2018



Attachment J: Pareto chart representing total number of failure hours per machine at CompleteLine, between 2/10/2014 and 08/31/2018



Attachment K: Modeling of the ARM method in RapidMiner Studio



Attachment L: Example of a failure reported to the equipment Holzma – Quality Box, with highlighted valuable information

Encomenda

IKEA Industry
Paços de Ferreira

De		To	
	Antonio Barros IKEA Industry Portugal, Lda.		Antonio Barros IKEA Industry Portugal, Lda.

U202000178 - HOLZMA (B and A Quality Box)

Localização do objecto do site: 020 Site\022-70000 BOF - Lack&Print & Foil Fabrica\024-90000 FOIL\024-93000 PRODUÇÃO\024-93300 Foil & Wrap\6201 Complete Line

Cilindros de bloqueio não em baixo. **091879**

Data de início	**14/06/2017**	Prioridade	**A: Com Paragem de Producao / Production Stop or Danger**
		Prazo de entrega	-

tempo paragem: 20 minutos.
Antonio Barros, quarta-feira, 14 de junho de 2017, 06:31
...Adicionou Comentário...

Cilindros de bloqueio não em baixo.
linha parou, fui verificar e de facto os mesmos estavam todos em baixo, mas não existia confirmação do sensor, todos apagados com exceção do primeiro, como aquilo funciona em serie, basta um falhar que os restantes não trabalham.
após analise 1 a 1, verifiquei que era o segundo sensor, estava muito baixo , tive de subir um pouco o sensor.
ficou ok, a trabalhar impecavel:
também verifiquei que o "batente" do batente da A-box estava partido , removi o mesmo e enviei para fazer um NOVO.

Tempos planeados

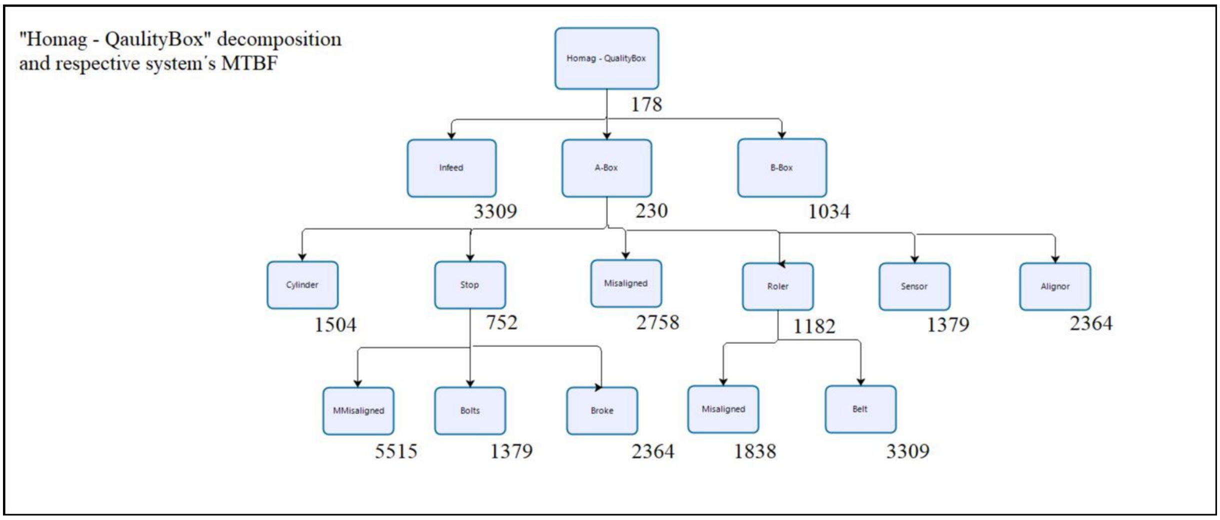
Pessoa\Grupo	Planeado para	Duração planeada	Descrição
Antonio Barros	14/06/2017	0,2 h	

Marque a factura como se segue: **U202000178 - HOLZMA (B and A Quality Box)/N.° Enc.: 091879/(no cost type)**

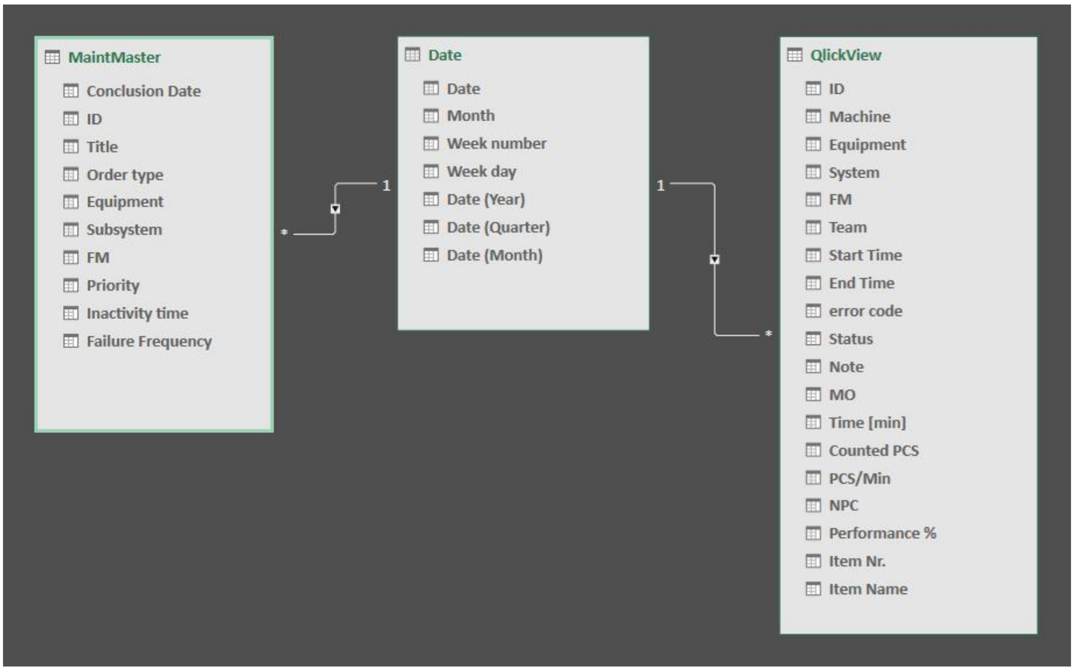
Attachment M: Holzma – saws cart” system analysis representation

Subsystem	Component	Failure Mode	Root causes
Saw	Brake	Conditioned position	Misalignment, Control Error, Control Circuit Failure, Mechanical Imbalance, Residual Accumulation, Bad Contact, Fatigue, Air Leakage, Bad Contact, Control Error, Overload
	Car	Reduced Velocity	
	Engine	Contactor failure	
		Conditioned position	
		Incisor failure	
		Ripped belt	
		Conditioned Material	
		Torn tube	
		Thermal	
	Skate	Encoder	
		Screw failure	
		Conditioned Material	
	Software	Input error	
Contactor	PLC	General error	Bad contact, misalignment
Electric System	Power supply	Non identified	Control Error, Residual Accumulation, Control Circuit Failure, Phase Unbalance, Cable fault, Misalignment
	Sensor	Conditioned Material	
	Cable	Conditioned Material	
	Sensor	Conditioned Material	
Cylinder	Relay	Conditioned Material	Fatigue
	Sensor	Sensor failure	Cable failure

Attachment N: "Homag – QualityBox" decomposed into sub-systems with respective MTBF´s (created in Bizagi Modeler)



Attachment O: Representation of “Diagram View” with created relationships between datasets at Excel´s PowerPivot add-in



Attachment P: Representation of the proposed MP

Factory	PL	Equipment	System	Component	FM	beta(shape)	n(scale)	MTTR+MWT(	Component	Cp (Euros)	Cf (Euros)	Stock	MT1	MT2	MT3	CB1	CB2	CB3
BoF	CL	lzma - Saws c	Saw.Cart	Belt		1,28	2216,6	5	6000	10000	45500	1	s	x	x			
BoF	CL	lzma - Saws c	saw.Cart		Electricerro	1,37	983,29	1	500	3500	14175	1	s	s	s			
BoF	CL	lzma - Saws c	ectricsystem		Error	1,25	1252	1	5000	5000	28350	2	s	s	x			
BoF	CL	lzma - Saws c	Saw.Cart	Engine	Error			1	7500	12500	48500	1	s	s	s	0,1	0,2	0,3
BoF	CL	lzma - Saws c	Saw.Cart		Misalignment			0,5	200	1000	5000	1	s	x	s	0,8	0,8	0,8
BoF	CL	zma - Quality	A	Cylinder		2,8	2042,8	1	2000	5225	14600	1	s	s	s			

CB4	Note	Last Action(Date	Actual Running	Optimal periodicity	F(actual)	F(1week)	F(2weeks)	F(3weeks)	F(4Weeks)	EV1(Euros)	EV2	EV3	EV4	MTTR(Hours)	NEV1(Euros/H)	NEV2	NEV3	NEV4
		43422	666,25	2743,17323	0,19319	0,0238658	0,047656	0,071293814	0,094715825	10847,2342	11691,78	12531	13362	0,78125	13884,45975	14965	16040	17104
		43426	625,25	1041,24508	0,41597	0,0482898	0,094233	0,137646572	0,178423161	4015,49343	4505,938	4969,4	5405	0,15625	25699,15796	28838	31804	34590
		43353	1373,5	1459,17304	0,67461	0,0231446	0,044902	0,065323644	0,084465733	5540,4259	6048,452	6525,3	6972	0,15625	35458,72575	38710	41762	44623
0,4		43445	430,5							16100	19700	23300	26900	0,15625	103040	126080	149120	172160
0,8		43382	1076,25							4200	4200	4200	4200	0,078125	53760	53760	53760	53760
		43384	1055,75	1392,52623	0,14574	0,0267723	0,055797	0,086926157	0,119971279	5475,99044	5748,1	6039,9	6350	0,15625	35046,33883	36788	38656	40638