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SYSTEM FOR THE MANAGEMENT OF THE TECHNICAL MAINTENANCE OF A COMPANY

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ABSTRACT

This project consists on the creation and development of a model to manage technical maintenance within a company. The first part of the model is based on a control system made through worksheets using the EXCEL program. This part allows the analysis and decision making for the continuous improvement of maintenance and to reach pre-established objectives. The second part consists on a simulation system made through the ARIS program (software used in the business modelling). This part allows to test and simulate the proposed improvements for technical maintenance and observe their consequences.

Prior to the creation and development of the model, certain indicators have been defined as control variables of the system, specifically the KPIs. Thereby, a search and a selection of the most useful indicators have been carried out in order to evaluate maintenance in the model. The KPIs quantify the different sections of the maintenance and allow to work with numerical values. In this way, maintenance comparisons can be made through the values of the indicators.

Finally, an exemplary case has been displayed to portray the operation of the model. In this section, the initial state is analysed and solutions are proposed. Then, each one of them is simulated to observe the effects in the maintenance plan. At the end, a comparison is made between them and they are organized accordingly to their improvement in the technical maintenance plan.

CONTENTS

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1. GLOSSARY

ARIS: Architecture of Integrated Information Systems

BPM: Business Process Management

BPMN: Business Process Modelling Notation

EHS: Environment, Health and Safety

EPC: Event-driven Process Chain

IT: Information Technology

KPI: Key Performance Indicator

KRI: Key Result Indicator

MTBF: Mean Time Between Failures

MTTF: Mean Time To Failure

MTTR: Mean Time To Repair

PI: Performance Indicator

RI: Result Indicator

2. PROLOGUE

2.1. JUSTIFICATION

This project arises from the basic need for improvement of any company. It specifically focuses on the field of technical maintenance and the types of maintenance that exist.

At the beginning, the initial idea was to start from a real case and develop a model to manage it. Despite this, once the search for the KPIs started (parameters that would be used to manage and control maintenance), a new project perspective emerged. The new idea was based on creating a generic system that could be adapted to any company. In this way, the development was much more versatile and was not limited by a specific case.

2.2. MOTIVATION

The realization of this project has been motivated mainly by self-interest in the field of industrial organization. As a result of this interest, the intention was to carry out something related to the industrial organization field and, for this reason, contacted the Department of Business Organization of the ETSEIB was contacted.

Moreover, the fact of developing a model of its own was also an incentive. The creation of the whole control and simulation model from scratch and the fact that this model, in some way, can be used for the improvement of a company, also became an extra motivation to the development of the project.

3. INTRODUCTION

3.1. SCOPE AND PURPOSE OF THE STUDY

The main goal of the project is the development of a model that is useful for the management of technical maintenance. This model should allow to evaluate and control the different aspects of the technical maintenance. In addition, it will be complemented with a simulation model to carry out tests on possible improvements and compare them with the current state of the technical maintenance.

The whole project has been divided into three main blocks:

A first part of research and analysis where the main basic aspects of the technical maintenance are presented. In this, the different facets will be developed as well as the necessary parameters for its control. Emphasis will be placed on key performance indicators, basic indicators to evaluate the performance of processes.

The second part, the most extensive, will include a selection of the necessary indicators and the development of the two components of the model: the control worksheet and the simulation model.

Finally, the third part, will consist of an example to verify the correct operation of the model and to demonstrate how it works.

4. TECHNICAL MAINTENANCE

4.1. DEFINITION

Industrial maintenance is an activity that aims to preserve the state and operation of plant facilities and machinery. Its application allows to ensure a production with quality, profitability and security, maximizing the capacity of the entire process. The maintenance department is in charge of carrying out all the necessary activities. Within this, the maintenance management, is the field in charge of coordinating the necessary departments or operators and planning the actions in a certain period of time.

Maintenance is the product of failure, which happens when a mechanism stops responding as expected. Initially, the maintenance was based on the moment when the failure occurred and, then, the mechanism was just repaired by means of spare parts or replacing it entirely. With the development of the machines through the years, preventive maintenance was applied periodically, in order to avoid potential failures. At the moment, in addition, thanks to statistics and databases, there is a branch in charge of predicting failures, as well as studying them. Finding the origin or the cause of a failure provides useful information to avoid them or to improve the design of the machinery. Moreover, the analysis of the consequences of failures, can be useful to reduce and to assess them economically.

Therefore, the goals of maintenance are the following ones:

- Guarantee the operation of the machines correcting the failures.
- Avoid failures through revisions and spare parts by increasing the useful life of the machines or installations.
- Prevent failures and, therefore, avoid unnecessary accidents or production stoppages.
- Study the failures to reduce the consequences.
- Economically quantify the failures in order to take decisions.

4.2. TYPES

- Corrective:

Post-failure maintenance in charge of identifying the type of failure and act accordingly:

- Repair: The origin of the failure and the treatment to be followed are known. Affected parts are replaced.
- Temporary maintenance: In case of an unforeseen, unidentified or serious failure for security. The purpose is to stop the consequences or prioritize the operation even if the origin of the failure is not eliminated.

Depending on the severity of the failure, there are several alternatives based on the company's policy. If the operators are trained, up to a certain level of gravity, they are responsible for corrective maintenance. Otherwise, in case of a major crisis, it is necessary to contact the service or maintenance department in order to take the necessary actions.

- Preventive

Maintenance prior to the failure responsible for inspecting and evaluating the status of the object of study. It aims to reduce corrective maintenance while avoiding failures. It is done periodically, since it is based on the analysis of the state of the machine comparing it with the initial or factory state.

In order to define the state, the appropriate variables are used according to the machine and the values that are taken as corrects in the operation are established. The purpose is to maintain these variables in their operating ranges. If any variable is observed outside the range, the origin of this difference is analysed and corrected using spare parts or the necessary actions, such as the replacement of the equipment.

In this type of maintenance, imminent failures can also be detected and it is advisable to stop production and correct them immediately to avoid more serious consequences.

- Predictive

Maintenance prior to the failure that is in charge of deducing when this will be given. Its objective is to determine more carefully the planning of preventive maintenance.

Its execution is complemented with preventive maintenance since it uses the same variables. It studies the evolution of these and analyses them looking for behaviour or cause-effect relationships between variables and failures.

The ideal situation is given when, based on effective predictive maintenance, preventive maintenance is planned prior to the failure, returning the machine to the correct functioning state at the optimal time. It so, there is no need for corrective maintenance and, therefore, the failures and the possible consequences are avoided.

The maintenance management is responsible for defining an optimum maintenance plan where an adequate balance between the different types of maintenance is shown. The purpose is to define the smallest number of actions of each type with the lowest cost that entails the necessary maintenance.

5. KEY PERFORMANCE INDICATORS

Nowadays, every company has within its main objectives the internal improvement, the fact of achieving a goal in a given time. In order to achieve those objectives, a business strategy is needed in order to improve internal aspects or make changes in the different departments. However, a control system is also needed to analyse the evolution since the initial state of the company until the end of the period. This control has the goal of observing the improvement behaviour and calibrating or correcting it in case not being directed towards the goal. One of the major problems or difficulties in companies is to make good control and monitoring of the state since, in case the monitoring is not adequate, they may be making incorrect decisions that do not help to achieve their goals.

It is in this management section where the "Key Performance Indicators" or KPIs take part. KPIs are indicators that work with different variables and their progress can be translated into the behaviour of the company and, therefore, it shows its evolution towards the goals set.

As David Parmenter explains in the preface of his book (2007), the main benefits of KPIs can be grouped and discussed under the following three headings:

1) Alignment and linking of daily actions with critical success factors of the organization: communicate the necessary actions correctly and redirect and coordinate the strategies of the different departments towards the objectives of the company.

2) Improve performance: The evolution of performance is an objective starting point in order to make decisions. In addition, its variation affects directly the workers judging them indirectly, without pointing anyone individually. Improve performance provides motivation to the departments.

3) Creation of a wider property, empowerment and fulfilment: Coordinate the departments giving their own direction and goals and let themselves, as experts in their fields, make the decisions.

The management department, on the improvement field, is in charge of selecting the indicators and the appropriate variables to control the evolution of the company. After the identification of the objectives, in coordination with members of the affected departments, the indicated KPIs are defined. This action is crucial and very important, since a wrong choice could mean useless control of the evolution and, therefore, the loss of investment and time spent.

On the other hand, a total control is also incorrect. The tracking of the evolution of all the different aspects supposes an additional cost and time invested in the collection of the variables for the calculation of the KPIs.

Another mistake is to translate any measure as KPI. David Parmenter in Chapter I (2007) distinguishes four types of measures with the following definitions:

1) Key Result Indicators (KRI) give to the board a general summary of how the organization works. They show the results of the actions of each department, but they are subsequent to the actions and do not show the factors to modify.
2) Results Indicators (RI) point out to the management how the teams combine to produce results. They are a more general view of the KRIs.
3) Performance Indicators (PI) show to the management of which teams are delivering. They help departments align themselves with the general objectives.
4) Key Performance Indicators (KPI) indicate to the management how the organization is working on its critical success factors and, through monitoring, management is able to increase performance. They focus on the aspects of organizational performance that are the most critical for the current and future success of the organization.

To sum up defining the KPIs, 7 main characteristics are presented:

Nonfinancial	1. Nonfinancial measures (e.g., not expressed in dollars, Yen, Pounds, Euros, etc.)
Timely	2. Measured frequently (e.g., 24/7, daily, or weekly)
CEO focus	3. Acted upon by the CEO and senior management team
Simple	4. All staff understand the measure and what corrective action is required
Team based	5. Responsibility can be tied down to a team or a cluster of teams who work closely together
Significant impact	6. Major impact on the organization (e.g., it impacts on more than one of top CSFs and more than one balanced scorecard perspective)
Limited dark side	7. They encourage appropriate action (e.g., have been tested to ensure that they have a positive impact on performance, whereas poorly thought through measures can lead to dysfunctional behavior)

Figure 1: Characteristics of KPIs - David Parmenter

6. KPIs IN MAINTENANCE MANAGEMENT

García Saura analyses the key basic indicators in the maintenance management (2015). The most significant KPIs in the field of maintenance are classified in different areas of the company. In this way, depending on the strategy or the set goals, the most convenient ones will be used.

The classification follows the Balanced Scorecard by Robert Kaplan and David Norton that shows 4 perspectives:

1) Financial
2) Internal Business Processes
3) Internal Customers
4) Learning and Growth

6.1. KPIs in the Financial Perspective:

The indicators of this level focus on four main aspects: availability, cost, quality of the final product and safety, health and environment. The main goal from this perspective is to increase the availability of assets, maintaining or reducing the costs and meeting the quality requirements and EHS.

However, the main parameters related to the maintenance aspect are quality and cost. Quality requirements and EHS do not have a direct dependence on maintenance management. On the other hand, the availability of a machine and its reparation or replacement are important factors of the maintenance.

Hypothesis:

- A Machine breaks down before it stops manufacturing with the required quality.
- A Machine with a proper maintenance does not affect the EHS field.

a) Mechanical availability

Measures the availability of the assets based on the failures they present. This indicator evaluates the losses or the time invested in maintenance, with respect to the production time with the expected maintenance.

$$Availability\ (\%) = \left(1 - \frac{Losses\ for\ maintenance}{Planned\ production}\right) \times 100$$

Objective: $> 90\%$

Frequency: weekly.

b) Cost deviation

Measures the deviation of the cost used in the maintenance with respect to its budget.

$$Cost\ deviation\ (\%) = \left(\frac{Maintenance\ cost}{Maintenance\ budget} - 1\right) \times 100$$

Objective: ≤ 0

Frequency: monthly with estimates in order to detect unforeseen events.

c) Maintenance index

Compares the value of asset renewal in an instant of time with respect to the cost of maintenance during a period.

$$Maintenance\ index\ (\%) = \frac{Maintenance\ cost}{Renewal\ cost} \times 100$$

Objective: $\leq 2{,}5$ (Variable value that depends on the type of asset: it should be determined with previous data or manufacturer estimates).

Frequency: monthly estimated (Taking into account the cost of renewal and the depreciation).

6.2. KPIs in the Internal Business Processes Perspective:

The indicators of this level are raised with the objective of defining what internal processes are necessary to have a correct maintenance.

That's why different aspects of maintenance are taken into account: preventive maintenance, predictive maintenance, planning and execution of maintenance, maintenance reliability and cost control.

Preventive Maintenance:

d) Maintenance type

Measures the percentage of time spent on preventive maintenance compared to the total maintenance time. The accounting can be done with magnitudes of time or with work orders (number of times to carry out maintenance work).

$$Maintenance\ type\ (\%) = \frac{Preventive\ M.hours}{Maintenance\ hours} \times 100$$

Objective: $\geq 60\%$

Frequency: monthly.

e) Compliance of the preventive plan

Preventive maintenance may not depend on the company itself but on other factors such as the distribution company itself or the person in charge of manufacturing the equipment, or legal aspects of control. For this reason, the planned preventive maintenance plan may be delayed.

$$Preventive\ compilance\ (\%) = \frac{Preventiu\ M.h.done}{Preventiu\ M.h.planned} \times 100$$

Objective: $\geq 95\%$

Frequency: monthly.

Predictive Maintenance:

f) Compliance of the predictive plan:

Indicator related to the previous one, which shows the same results, but form another perspective. It sets the efficiency of the preventive plan defined by the predictive maintenance team.

$$Predictive\ compilance\ (\%) = \frac{Preventiu\ M.h.done}{Preventiu\ M.h.planned} \times 100$$

Objective: $\geq 95\%$

Frequency: monthly.

g) Predictive plan efficiency

Measures the optimum use of the capacity of the prediction plan. It counts the unverified breakdowns and compares them with the detectable ones.

$$Predictive\ plan\ efficiency\ (\%) = \left(1 - \frac{Undetected\ failures}{Detectable\ failures}\right) \times 100$$

Objective: $\geq 95\%$

Frequency: monthly.

Planning and execution of the maintenance:

h) Plan compliance

Measures from a general perspective the percentage of the execution of scheduled maintenance work. The interest of this indicator is to complement it with the reasons in the case of failure.

$$Planning\ (\%) = \frac{Scheduled\ work\ done}{Scheduled\ work} \times 100$$

Objective: $\geq 90\%$

Frequency: monthly.

i) Planning quality

While planning the maintenance, the time determined in the different tasks to perform is estimated with data. The error in this calculation can lead to dead times (estimated excess time) or lack of time and, therefore, delayed production.

$$Planning\ quality\ (\%) = \left(1 - \frac{Estimated\ time}{Real\ time}\right) \times 100$$

Objective: $< \pm 5\%$ (In any case > 0, as it would be over-estimating but it would not present delays).

Frequency: monthly.

j) Backlog

Compares the pending maintenance workload with the workload. It allows to calibrate the pending time to invest in preventive and corrective maintenance with the available time. In the event that it is located outside pre-established margins, it is advisable to invest or reduce resources in order to reset the load.

$$Backlog\ (Ddays)\ (\%) = \frac{Pending\ M.hours}{h\ working\ day\ \times worker} \times 100$$

Objective: between 5 and 10 working days

Frequency: daily with weekly enquiry.

k) Urgent maintenance works

Takes into consideration those urgent works that break the production plan. They differ from corrective maintenance as they present an imminent risk which should be noted: safety, environment, facilities, etc. In large industries (where there are several cases), there is the possibility of classifying them and analysing its probability (Useful information for simulations).

$$Urgent\ maintenance\ works\ (\%) = \frac{Urgent\ works}{Executed\ works} \times 100$$

Objective: $< 15\%$

Frequency: weekly.

Reliability:

l) Mean Time To Failure

Measures the average time between failures during production. The more defined the asset is, the more information can be extracted as it could be identified what has failed.

$$MTTF = \frac{Production\ time}{Failures}$$

Objective: It depends on the asset.

Frequency: weekly.

m) Mean Time To Repair

Measures the average time when fixing a type of failure.

$$MTTR = \frac{Maintenace\ time}{Failures}$$

Objective: It depends on the asset.

Frequency: weekly.

n) Mean Time Between Failures

Measures the average time between the reincorporation of the equipment to the production chain. It is also possible to create percentages of the machine working time or repair time based on the total time.

$$MTBF = MTTF + MTTR$$

Objective: It depends on the asset.

Frequency: weekly.

Cost control:

o) Extra time cost

Calculates the cost of the percentage of extra hours needed to perform the maintenance.

$$Extra\ time\ cost\ (\%) = \frac{Extra\ hour\ cost}{Work\ hour\ cost} \times 100$$

Objective: $< 5\%$

Frequency: monthly.

p) Cost of materials and spare parts

Calculates the percentage of the total consumed budget of maintenance reversed in material and spare parts.

$$Material\ and\ S.Parts\ cost\ (\%) = \frac{Material\ and\ S.Parts\ cost}{Maintenace\ budget} \times 100$$

Objective: $25\% < x < 35\%$

Frequency: monthly.

6.3. KPIs in the Internal Customers Perspective:

At this level the production department is taken as client and will be who requests or requires maintenance. The indicators will allow to assess the satisfaction of the department.

q) Level service

Measures the number of satisfied requests regarding the totality. The factors that determine whether or not to take action in front of a request are diverse: the impact on the production level and the value and time of the repair.

$$Level\ service\ (\%) = \frac{Satisfied\ requests}{Total\ requests} \times 100$$

Objective: $> 95\%$

Frequency: monthly.

r) Response time

Each maintenance action has a predetermined deadline and time. This indicator measures the percentage between the orders made within the term and the total of orders. The delay quantified in days can be calculated as the difference between the day of the application and the day of the maintenance action.

$$Response\ time\ (\%) = \frac{Satisfied\ requests\ on\ time}{Satisfied\ requests} \times 100$$

Objective: $> 80\%$

Frequency: monthly.

s) Reworks

It counts the number of maintenance action that must be carried out in a short period of time since the failure occurs repeatedly.

$$Reworks\ (\%) = \frac{Reworks}{Work\ orders\ done} \times 100$$

Objective: $< 1\%$

Frequency: weekly.

6.4. KPIs in the Learning and Growth Perspective

The indicators of this level focus on the quality of the organisation: occupational training, degree of employee satisfaction, etc. These indicators are managed and controlled by the HRM department.

7. CONTROL SOFTWARE

7.1. EXCEL

The Microsoft Excel program is a tool that works with spreadsheets that is used in the field of accounting, finance and management among others. The program includes an internal library with a set of formulas and functions that allows you to work with various data formats. In addition, there is also the option to graphically represent data in various types of graphs.

7.2. ARIS

The ARIS program and its versions belong to Software AG software company. The acronyms of the ARIS program correspond to Integrated Information System Architecture, a term that refers to business modelling.

This program is used in the management of business processes or BPM, the branch of the management in charge of modelling processes and workflows. The models serve as common language and are used by various parts of the company to review and redesign processes, to implement them or to administer and manage them.

The program works on process modelling from four points of view:

1) Function point of view: Shows all the activities in the process classifying them by types and the links between them.
2) Organization point of view: Shows the organigram of the company.
3) Data point of view: Shows all the information involved in the process and their variables.
4) Product point of view: Shows all the services and products offered by the company.

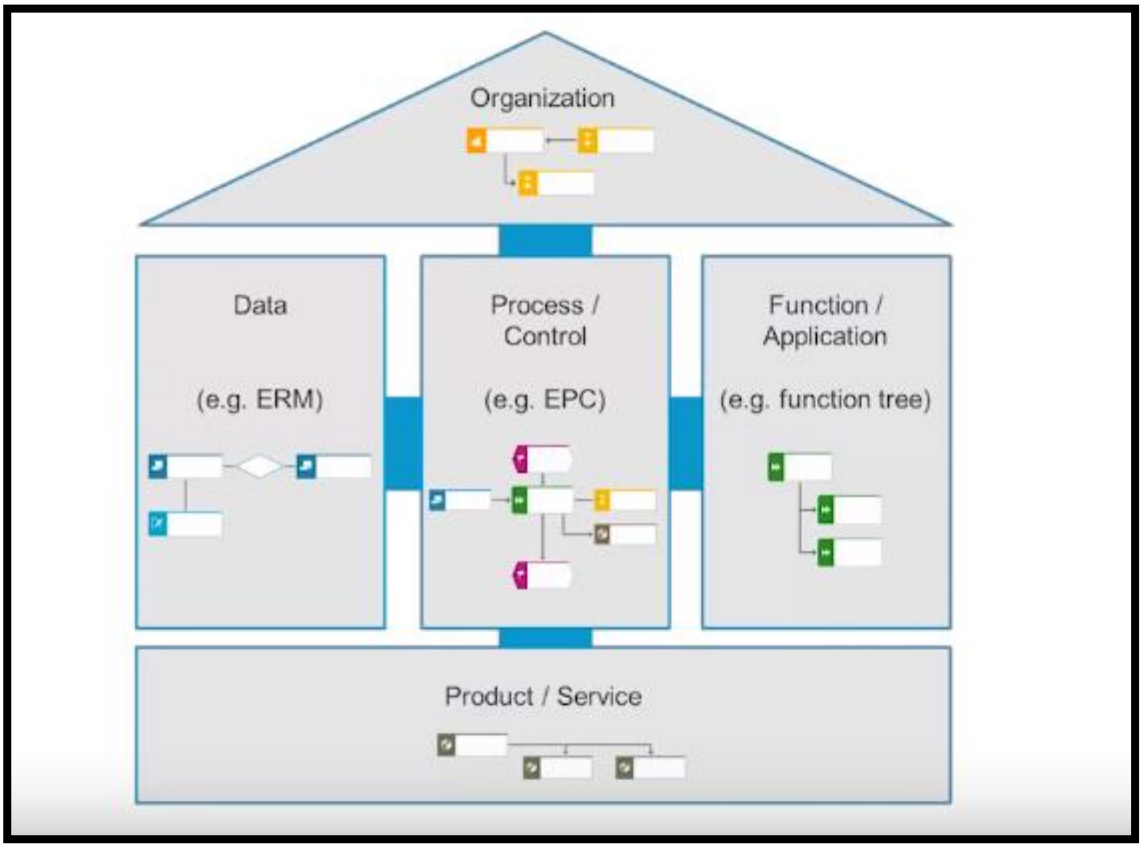


Figure 2: ARIS program points of view

The program has several models and each one has a wide range of variants.

Main ARIS Models:

a) Organisational Chart: Displays organizational structures. Enables the illustration of relationships between organizational units, roles and persons.

b) Process landscape: Gives an overview of the value-added processes in a company. In addition, it is used to represent hierarchies.

c) Business process: Describes a process as a sequence of events and activities. Information Technology systems, organizational elements or data may be added.

d) Data model: Illustrates data structures by means of data units (entities), including their relationships and properties.

e) IT infrastructure: Shows the IT infrastructure of the organisation. It allows to represent the networks, including hardware and IT systems.

f) System landscape: Shows the IT systems used by the organization and the areas (application domains) into which they can be divided.

g) BPMN diagram: Enables modelling of processes according to the Business Process Modelling Notation - also across organizations.

h) Whiteboard: Is used to gather and structure ideas and tasks. It is similar to post-it notes used with flip charts.

i) General diagram:

   a. Provides a selection of graphic elements to which meanings can be assigned and required. It includes content that is not covered by another model.

7.2.1. EPC Description

In this project will be used an EPC, a business process model:

The Event-driven Process Chain is a diagram to describe business processes. It integrates all relevant business perspectives and is embedded in the overall process landscape. While other diagrams provide an overview on the functional areas of an organization, EPCs are used to detail them on a procedural level.

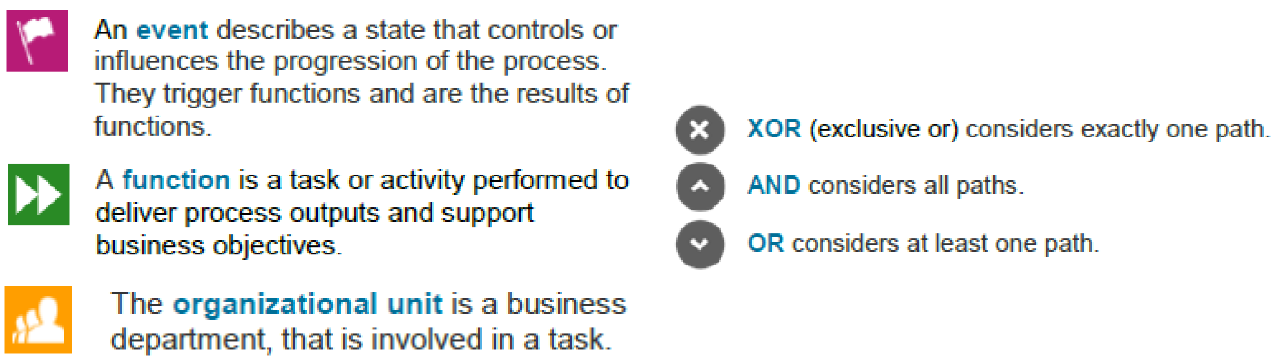


Figure 3: EPC core elements and connectors

8. SYSTEM FOR THE MANAGEMENT OF THE TECHNICAL MAINTENANCE

8.1. INTRODUCTION

A system for the management of the technical maintenance is a set of tools that aim to control, coordinate, plan and optimize the different activities that are needed for technical maintenance. Within a company, this system is designed by the management department in conjunction with the maintenance and other sectors involved. Its use allows to observe the evolution and achieve the objectives set by the company.

8.1.1. Description of the model

The designed model performs two main function: control the maintenance and its development on a weekly basis and simulate cases and compare it with real states. For this reason, the model presents two large blocks linked to its two parts: a control worksheet and a simulation model.

The first one collects the information of the events throughout the week, evaluates them and compares them with old data and the optimal pre-set values.

The second one, will use old data to describe the initial state and, after the simulation, it will create the following state. The simulated state could be added at the worksheet to compare it with other states.

The obtained results will be used to analyse the department behaviour, modify and correct the current strategy or optimize it to achieve the new goals.

8.1.2. Model simplifications

The model presents some simplifications to make it easier to apply and, therefore, it will be based under the premises described below.

a) The technical maintenance of a generic machine will be studied. The model will be used to control the behaviour of a certain type of machine within the production plant. In this way, more concrete results can be obtained, since the defined times of breakdowns and repairs will be more accurate, as well as the number of faults and the other parameters of the machine.
   In the opposite case, if all the involved machines are taken into consideration and its production, therefore, all parameters will be average values. In this way, differences between the machines cannot be observed.

b) All the maintenance types will be treated: corrective, preventive and predictive. The model will base on the following relations between the 3 types:
   - Corrective and preventive maintenance are complementary. If one of both is increased, the other will decrease and vice versa.
   - Preventive maintenance will be defined by the predictive maintenance. If the company invests in predictive maintenance, the preventive maintenance will be more accurate and, therefore, maintenance, from a general point of view, will be more efficient. In this way, less corrective maintenance will be needed.

   Both statements are based on the ideal situation presented in the first section:

   An ideal situation is given when, based on effective predictive maintenance, preventive maintenance is planned prior to the failure, returning the machine to the correct functioning state at the optimal timing. In this way, the need for corrective maintenance is avoided and, therefore, the failures and the consequences of these are avoided too.

c) The model will study maintenance from a temporary perspective. The goal is to evaluate the time of the different actions and, based on the results, optimize them to make the maintenance more effective and increase the production.
Therefore, the aspects related to the costs will not be considered. It is assumed that this task is developed by the accounting department, thus avoiding intervening in the costs.
In this way the study is simplified and the actions to take are more accurate, since they only focus on the scope of time.

d) Based on the 3 premises described, the model will use some of the indicators presented previously to be able to evaluate the maintenance at different times. Specifically, it is intended to be used weekly with a bimonthly record.

8.1.3. Parts of the model

The system for the management of the technical maintenance will consist of:

- A set of worksheets designed with the EXCEL program where the selected KPIs will be displayed with their corresponding graphs. This tool will be used to control and evaluate the different states and compare them among them and with the optimum values. In addition, simulated data can be added for future states and compare it with the actual state.

- Organization chart template with the ARIS program where the generic scheme of maintenance of a machine will be shown. The necessary characteristics will be added to extract the variables and calculate the selected KPIs. This tool will be used to create the different simulations between the expected results and the real ones.

8.2. KPIs SELECTION

As previously indicated, the designed system works on a temporary perspective and does not fall within the scope of costs. For this reason, the indicators presented previously related to costs have been ruled out:

From KPIs in the Financial Perspective:

b) Cost deviation

c) Maintenance Index

From KPIs in the Internal Business Processes Perspective:

o) Extra time cost

p) Cost of materials and spare parts

In addition, the following indicators from KPIs in the Internal Processes Perspective have been ruled out:

j) Backlog

The reason is that this indicator involves two study perspectives. As will be seen below, the unrealized work orders will be taken into account (units), but not the pending time (hours). This problem could be solved by giving different time values to the work orders depending on their type of maintenance, but this would hinder the study greatly. Since it would only be necessary for this indicator, this has been discarded. In addition, the information from this indicator is not lost because their study is comparable to the "e) Scheduling compliance" and, therefore, the same conclusions can be drawn.

K) Urgent maintenance work

As mentioned before, the maintenance related with urgent works differ from corrective because they present a risk for the production plant and, therefore, a definition of a new kind of maintenance would be necessary. Furthermore, this indicator is useful when classifying the reasons of each urgent work. In this way, by analysing them, probabilities can be extracted and, also, containment plans can be defined in each urgent work type.

Given these facts, this indicator has been ruled out because:

- The model created does not include definition and classification of the different work.
- The definition of another type of maintenance only for this indicator is not worth it.

8.3. VARIABLES AND KPIs

The selected KPIs use different variables to be calculated. In this section, the different variables are presented as well as the relation between them. Subsequently, it is shown how the formulas of the indicators with the defined variables would remain.

Table 1: Variables

VARIABLE		FORMULA	DESCRIPTION
Total time	TT (h)	$T_t = TP_P + TM_P$ $T_t = TP_R + TM_R + TW$	Amount of time available
Production	TP_k (h)	k ϵ (P – Planned hours, R – Real hours) $TP_R = T_t - TM_R - TW$	Amount of production in a day.
Repair time	TR (h)	$TR = MTTR'$ (from the previous period)	Average time involved in performing a repair.
Wait time	TW(h)		Average wait time for corrective maintenance
Maintenance time	T_{ik} (h)	i ϵ (C – Corrective, Pv – Preventive) k ϵ (P – Planned hours, R – Real hours) $T_{Ck} = UF \times T_f$ $T_{Pvk} = DF \times T_f$	Hours dedicated to type I maintenance. It can be Real hours or Planned hours.
Planned maintenance time	TM_P (h)	$TM_P = \sum T_{iP}$	Amount of time dedicated to maintenance planned in a day.
Real maintenance time	TM_R (h)	$TM_P = \sum T_{iR}$	Amount of time dedicated to maintenance in a day.
Detected failures	DF		Failures detected by the predictive maintenance.
Undetected failures	UF		Unexpected failures.
Total failures	F	$F = DF + UF$	Total number of failures
Scheduled work	SW_z	z ϵ (D – SW done, Ø – still pending) $SW = F = UF + DF$ $SW_D = R_{ST} + R_S + RW$	Number of planned work orders. Will stand out the ones that are done and, if they are not done, the reason should be written down.
Maintenance request	R_a	a ϵ (ø – at the moment the request is made), ST – Satisfied on time, S – Satisfied not on time, N – still pending) $F \rightarrow R$ $R = R_{ST} + R_S + R_N + RW$	Number of requests made to the maintenance department that must be satisfied. Represents the same value as failures.

Rework	RW		Number of maintenance work that must be carried out again in a short period of time.

Table 2: KPIs

KPI	DESCRIPTIVE FORMULA	FORMULA
Mechanical availability (%)	$\left(1-\frac{Losses\ for\ maintenance}{Planned\ production}\right)\times 100$	$\frac{TP_R}{TP_P}\times 100$
Maintenance type (%)	$\frac{Preventive\ M.hours}{Maintenance\ hours}\times 100$	$\frac{T_{PvR}}{TM_R}\times 100$
Compliance preventive plan (%)	$\frac{Preventiu\ M.h.done}{Preventiu\ M.h.planned}\times 100$	$\frac{T_{PvR}}{T_{PvP}}\times 100$
Compliance predictive plan (%)	$\frac{Preventiu\ M.h.done}{Preventiu\ M.h.planned}\times 100$	$\frac{T_{PvR}}{T_{PvP}}\times 100$
Predictive plan efficiency (%)	$\left(1-\frac{Undetected\ failures}{Detectable\ failures}\right)\times 100$	$\frac{DF}{F}\times 100$
Plan compliance (%)	$\frac{Scheduled\ work\ done}{Scheduled\ work}\times 100$	$\frac{SW_D}{SW}\times 100$
Planning quality (%)	$\left(1-\frac{Estimated\ time}{Real\ time}\right)\times 100$	$\left(1-\frac{TM_P}{TM_R}\right)\times 100$
MTTF	$MTTF=\frac{Production\ time}{Failures}$	$MTTF=\frac{TP_R}{F}$
MTTR	$MTTR=\frac{Maintenance\ time}{Failures}$	$MTTR=\frac{TM_R}{F}$
MTBF	$MTBF=MTTF+MTTR$	$MTTB=\frac{T_t}{F}$
Level service (%)	$\frac{Satisfied\ requests}{Total\ requests}\times 100$	$\frac{R_{ST}+R_S}{R}\times 100$
Response time (%)	$\frac{Satisfied\ requests\ on\ time}{Satisfied\ requests}\times 100$	$\frac{R_{ST}}{R_{ST}+R_S+RW}\times 100$
Reworks (%)	$\frac{Reworks}{Work\ orders\ done}\times 100$	$\frac{RW}{R_{ST}+R_S+RW}\times 100$

8.4. EXCEL WORKSHEETS

This part of the model consists in different Excel sheets where, each one, represents one working week. In this case, the model has been designed to simulate two months and, therefore, 8 working weeks. Furthermore, it has an additional sheet "Week 0", the first one, which represents the data from the previous month, used to determinate some information.

| Week 0 | Week 1 | Week 2 | Week 3 | Week 4 | Week 5 | Week 6 | Week 7 | Week 8 |

Figure 4: Weeks represented in different worksheets

Below, the different parts of each sheet of the model are shown and described:

a) Variables charts:

Grids that collect all the necessary variables. These are distributed in different groups according to their origin which is represented with different colours.

Information data	**Calculations**	**Real or simulated data**
Data extracted from the production plan, previous data, predictive maintenance or the actual state.	Data calculated automatically by the program.	Data extraxted from the simulation with the ARIS program.

Figure 5: Worksheets instructions

The first two charts represent the base information and the planned or expected values.

Table 3: Base and planned data

INUPUTS Stage 1			**INUPUTS Stage 2**		
VARIABLE	**VALUE**	**UNITS [/week]**	**VARIABLE**	**VALUE**	**UNITS [/week]**
T_t		[h]	T_{PvP}		[h]
DF		dimensionless	T_{CP}		[h]
UF		dimensionless	TM_P		[h]
T_f		[h]	TP_P		[h]
			F		dimensionless
			R		dimensionless

The last two charts represent the real values, at the end of the week, or in a simulation case, the simulated values.

Table 4: End of week or simulated data

INUPUTS Stage 3			INUPUTS Stage 4		
VARIABLE	**VALUE**	**UNITS [/week]**	**VARIABLE**	**VALUE**	**UNITS [/week]**
R_{ST}		dimensionless	SW		dimensionless
R_S		dimensionless	R_N		dimensionless
RW		dimensionless	SW_D		dimensionless
T_{PvR}		[h]	TM_R		[h]
T_{CR}		[h]	TP_R		[h]
TW		[h]			

b) Indicators chart:

This chart displays the following information from all the maintenance KPIs selected: the name, the optimum level and the value of each week.

The optimum level is determined in each different case. The indicators MTTR, MTTF and MTBF have the value set in the value of week 0, taken as reference. The other indicators, even there are theorical and proper optimum values, each company should define their own values. Being a bimonthly model, it can be changed throughout the year. Furthermore, if the company has some fixed goals, these optimum levels can be modified for target values.

In addition, the colours of the chart provide extra information (The following values are displayed as an example):

- Indicators: a, b, c, d, e, f, k, l

Table 5: Cell colour code 1

	Colour
Optimum level < Value	
Optimum level > Value	
Optimum level = Value	

– Indicators: g, m

Table 6: Cell colour code 2

	Colour
Optimum level < Value	
Optimum level > Value	
Optimum level = Value	

– Indicators: h, i, j

Table 7: Cell colour code 3

	Colour
Previous value < Value	
Previous value > Value	
Previous value = Value	

– Indicator j) has an extra line:

Table 8: Cell colour code 4

	Colour
Previous MTTR ≥ MTTR	OK
Previous MTTR ≤ MTTR	Warning

This extra line exists because, even if the MTBF improves, if the MTTR has worsened, the improvement of MTBF is not real. The goal is to increase MTBF and reduce MTTR at the same time.

Table 9: KPIs example values chart

KPI	Week / Optimum level	0	1	2	3
a) Mechanical availability	90%	98,30%	97,13%	96,21%	97,21%
b) Maintenance type	60%	63,27%	71,62%	71,60%	73,81%
c) Preventive compliance	95%	92,54%	95,00%	96,67%	97,20%
d) Predictive compliance	95%	92,54%	88,33%	96,67%	98,43%
e) Predictive plan efficiency	95%	75,00%	83,20%	87,67%	88,21%
f) Plan compliance	90%	92,50%	92,50%	90,00%	95,12%
g) Planning quality	5%	8,84%	5,62%	1,23%	4,76%
h) MTTF	98,78	98,78	118,15	112,36	115,02
i) MTTR	1,23	1,23	1,15	1,93	2,05
j) MTBF	100,00	100,00	120,00	114,29	117,07
		OK	OK	Warning	Warning
k) Level service	95%	92,50%	92,50%	92,86%	95,12%
l) Response time	80%	86,49%	94,59%	97,44%	100,00%
m) Reworks	1%	2,70%	1,00%	0,00%	2,56%

c) Indicators graphic representation

The following indicators have been represented over time. The indicators that are not shown is because they are not percentages or have values around 0%, and the graph shows values starting 50%.

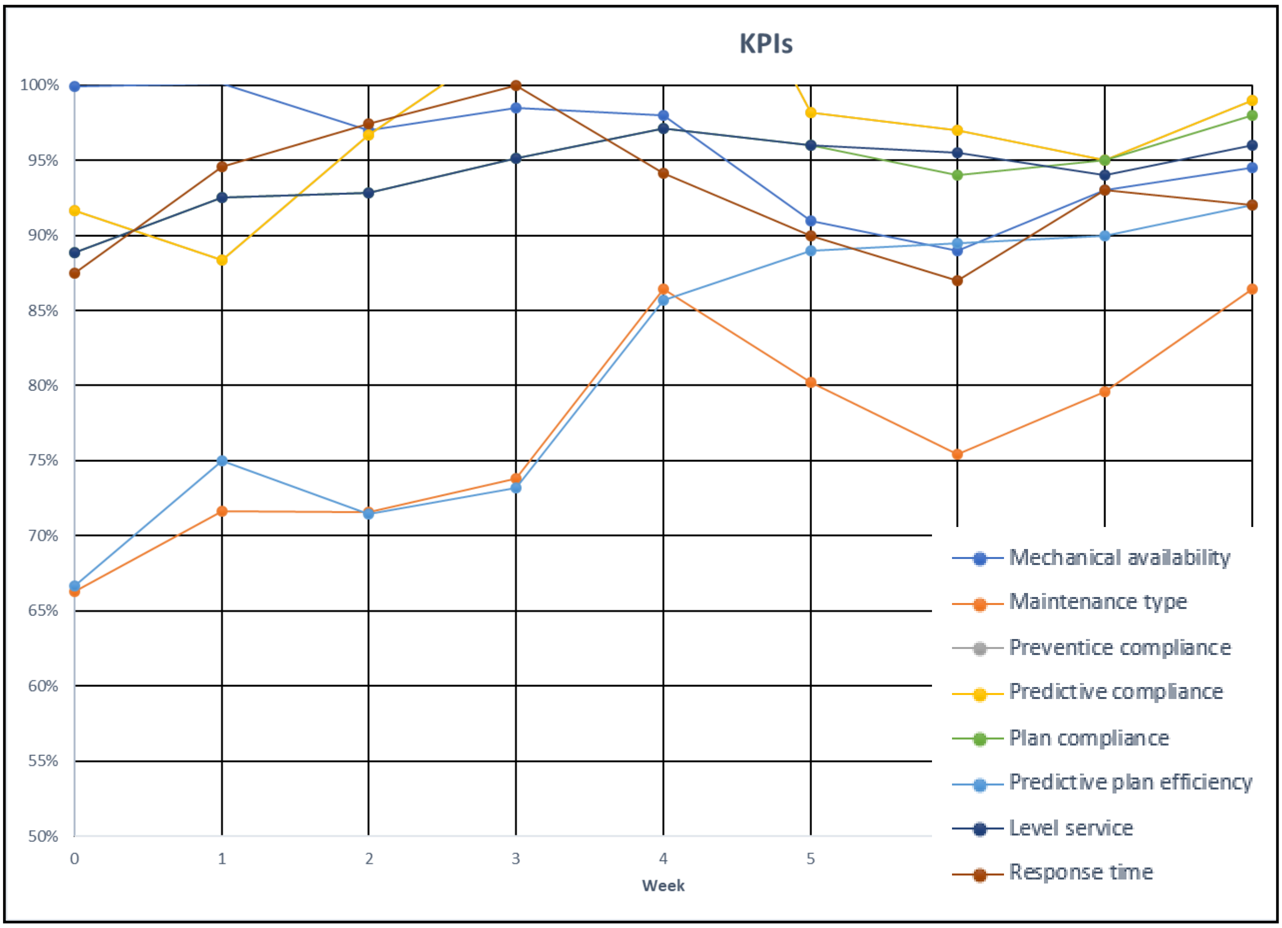


Figure 6: KPIs example values graphic

8.5. ARIS MODEL

8.5.1. ARIS Process diagrams

This part of the model consists of two ARIS diagrams which represent corrective and preventive maintenance. As mentioned before, both use an EPC model to reproduce the process diagram:

a) Preventive Model

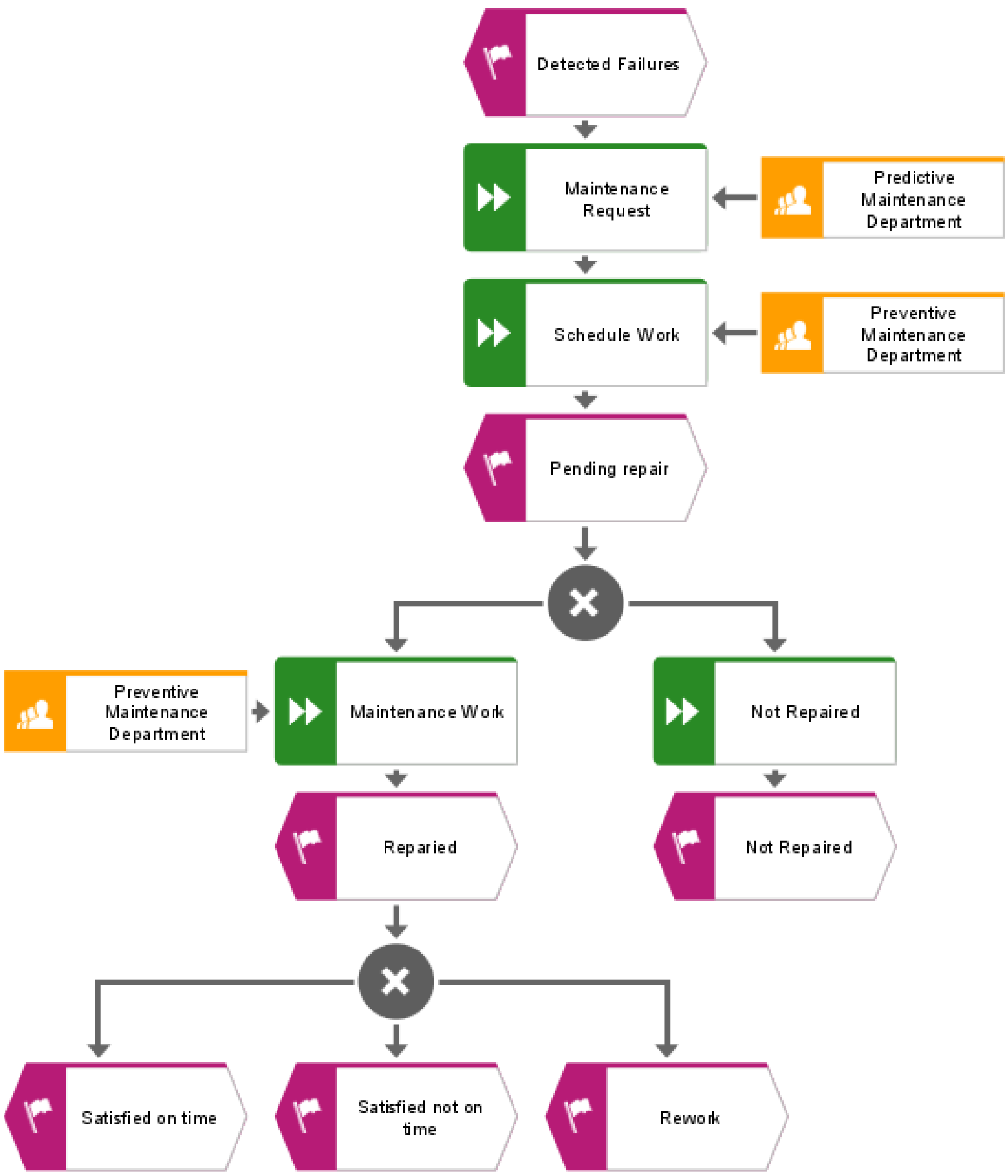


Figure 7: Preventive model diagram

Explanation of the events: The predictive maintenance department is responsible of detecting future failures as well as repair times. Once the detectable failures have been determined, a request for work order is made to the preventive maintenance department. Upon receiving the request, the department is responsible for scheduling it and, then, two events can happen: fulfil the established plan and carry the maintenance work or, on the contrary, due to lack of time, leave the work pendent. In the case that the work is done and, therefore, the request has been satisfied, it can be classified into 3 different groups: “within the pre-set time”, “out of that time” or “the machine has failed again”.

b) Corrective Model

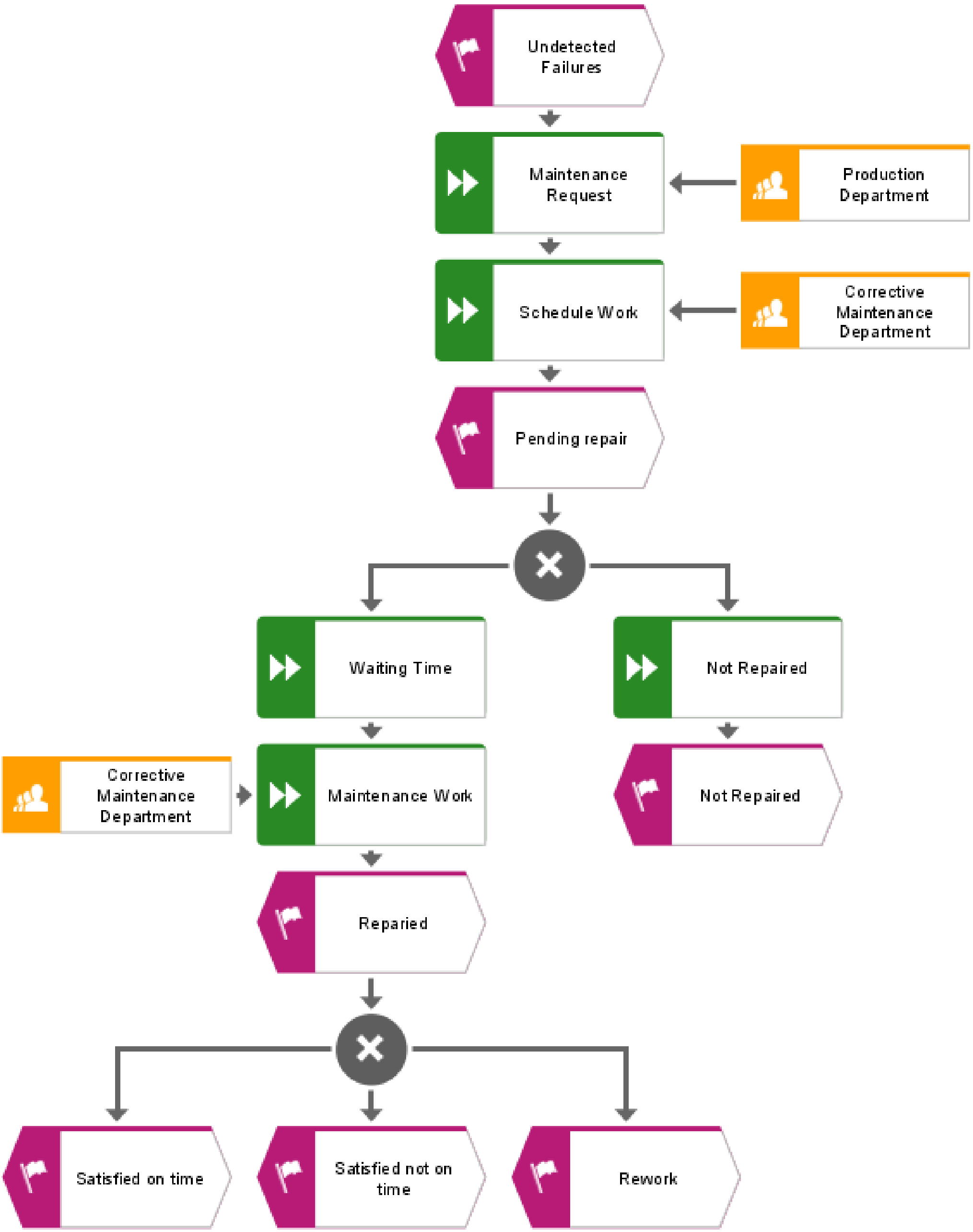


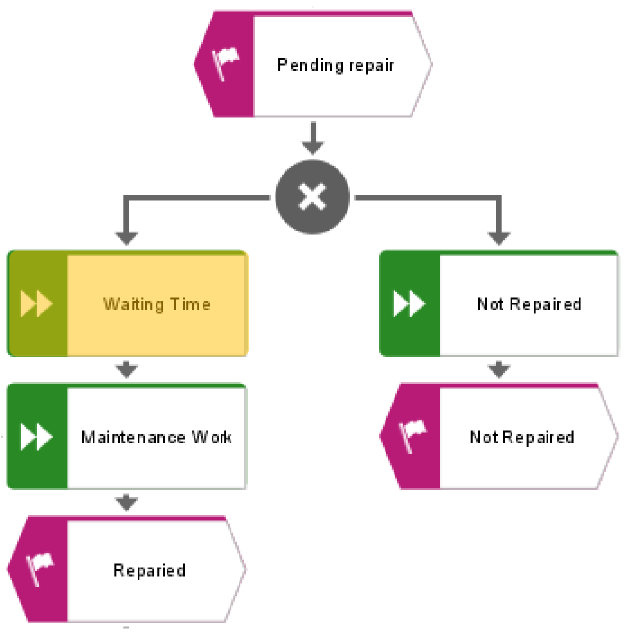
Figure 8: Corrective model diagram

Explanation of the events: An undetected failure occurs and the department in charge of production reports this and requests a maintenance work order. After receiving the request, the corrective maintenance department is responsible of programming it. At this point the same thing can happen as in the preventive maintenance model: fulfil the established plan and do the maintenance work or, on the contrary, due to lack of time, leave the work pending. As it is an unforeseen failure, the programming is not fixed and, therefore, a waiting list is created. To simulate this fact, a function is created before maintenance work that represents a waiting time. Once the work is done, as in the other model, there are 3 classifications for the satisfied requests: "within the pre-set time", "out of that time" or "the machine has failed again".

The diagrams of preventive and corrective maintenance present two groups of programmable parts:

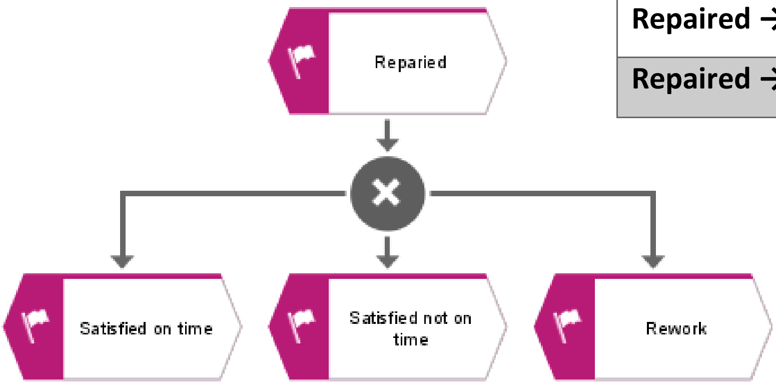
- Events probability:

The points of the model in which two events can happen next have been simulated with the XOR function, where only one of the events can happen (the sum of the different probabilities is equal to 100%). In addition, each of the roads has as an attribute the probability of occurring. Each company should determine the percentage or probability of each event.



Pending repair → Repaired	# %
Pending repair → Not Repaired	# %

Figure 9: Repair probabilities



Repaired → Satisfied on time	# %
Repaired → Satisfied not on time	# %
Repaired → Rework	# %

Figure 10: Repair type probabilities

- Functions durations:

In this model, each task or activity is represented by a function. These have a duration attribute, which can be simulated as probabilistic distributions.

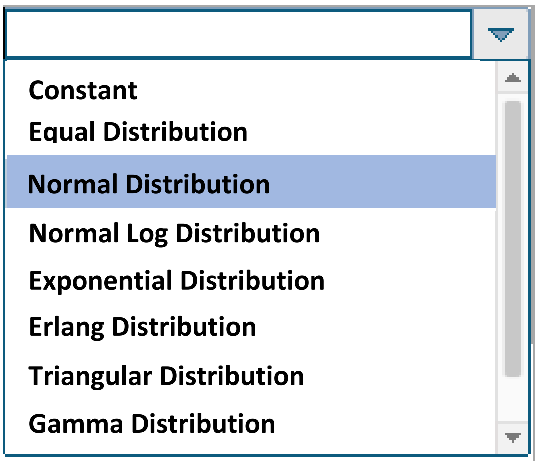


Figure 11: ARIS probability distributions

In the preventive and corrective models, the duration of each function has been represented by the normal distribution. The normal distribution or Gaussian distribution is symmetric and allows to model the times with a mean central value and a deviation. In this case, it simulates the behaviour of continuously repeated actions in the maintenance process and, therefore, the average value and its deviation can be extracted from each activity with company old data.

8.5.2. ARIS Process simulation

From the two diagrams, once the probability parameters of the XOR gates and the probability distributions of the different functions have been determined, simulations can be performed. To carry out the simulation, the steps established by the program must be followed. In order to define input and output parameters:

- Inputs:

  "Detected failures" and "Undetected failures"

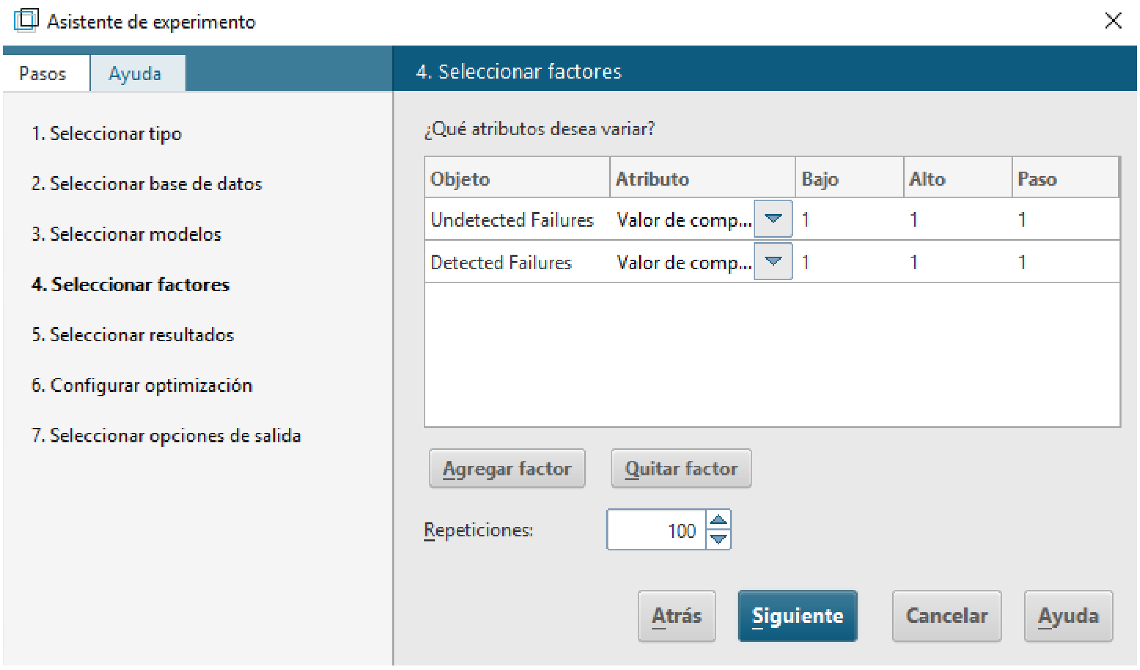


Figure 12: ARIS inputs simulation window

- Outputs:

  Event activation: “Requests on time”, “Request not on time”, “Reworks”, “Not repaired”

  Model time: “Total function time”, “Waiting time”

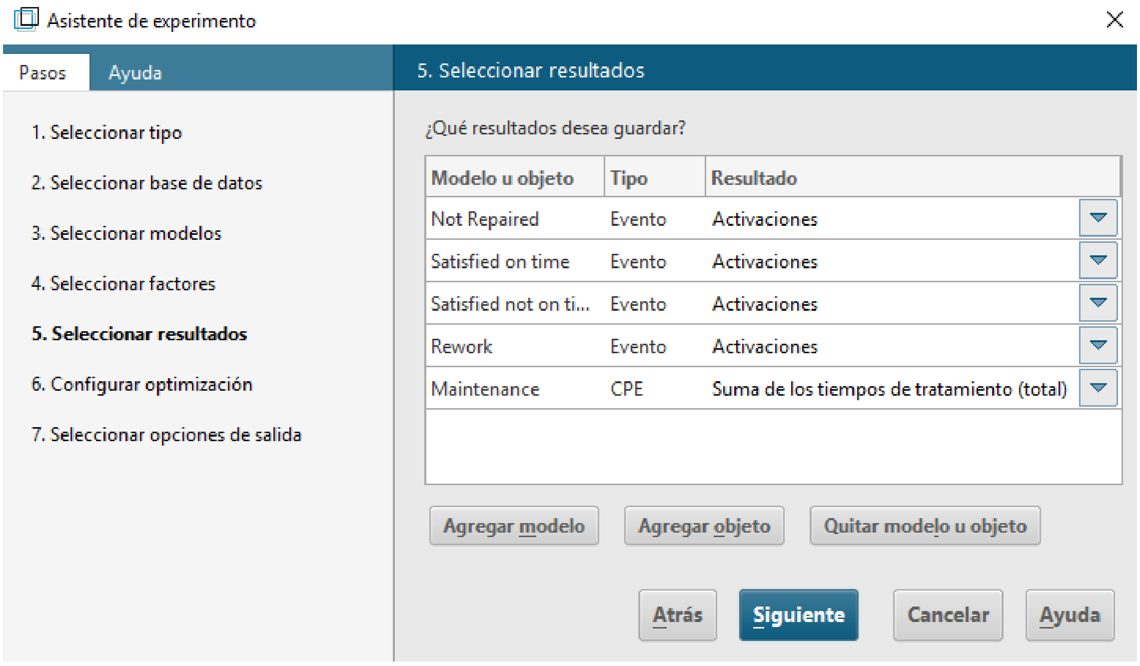


Figure 13: ARIS outputs simulation window

In simulations with ARIS, the program automatically generates 100 initial events in each simulation. The number of simulations is determined by the user and, in the designed model is set to 100. Once the simulation has been carried out, the program generates an EXCEL worksheet which displays the values of the parameters of the outputs in each of the simulations. In the model designed the number of activations of each output and the total time are shown.

Table 10: Simulation results example chart

Results				
Satisfied on time	Satisfied not on time	Rework	Not Repaired	
Activations	Activations	Activations	Activations	Total Time
81	17	0	2	152:41:47
75	20	1	4	147:10:00
79	13	2	6	145:25:07

The designed model uses two different diagrams (Preventive and Corrective) to make the extraction of the variables easier. In this way, the model is more precise and allows to determine the output values according to the type of maintenance. In the studied case, the time values of each type of maintenance are extracted separately.

8.6. INSTRUCTIONS

As previously mentioned, the designed system presents two major parts: the control chart with the indicators and the simulation model. To use it and to extract results, the guidelines defined below will be followed. Moreover, the process is divided into different stages:

STAGE 1

Enter the following data to the EXCEL table.

Table 11: Input data chart

VARIABLE	DEFINITION	UNITS	COMMENTS
TT	Total Time	[h]	Value determined by the company
DF	Detected Failures	dimensionless	Value determined by the Predictive Maintenance Department
UF	Undetected Failures	dimensionless	Undetected failures that occur
TR	Av. Failure Repair Time	[h]	Equal to MTTR extracted from the previous data period

STAGE 2

The following data is calculated automatically by the program using the previously defined formulas.

Table 12: Input calculated data chart

VARIABLE	DEFINITION	UNITS
T_{PvP}	Preventive Maintenance Time Planned	[h]
T_{CP}	Corrective Maintenance Time Planned	[h]
TM_P	Maintenance Time Planned	[h]
TP_P	Production Time Planned	[h]
F	Total Failures	dimensionless
R	Maintenance Requests	dimensionless

ETSEIB

In case of using the model as a control tool, the next step would be **STAGE 6.**

The following stages up to number **6**, show the necessary instructions to perform a simulation.

STAGE 3

Perform the simulation in the preventive and corrective models previously establishing the XOR probabilities and the normal distribution of the time of each activity. If both model simulations have been carried out successfully, the EXCEL worksheets will be generated automatically by the ARIS program. Each row of the worksheets represents one simulation with 100 events (detected or undetected failures) and shows the outputs for each one.

STAGE 4

To ensure the reliability of the study, one of the rows in each document, preventive and corrective, is randomly selected. The following values from both documents are extracted:

Table 13: Results simulation

Simulation	Satisfied on time	Satisfied not on time	Rework	Not repaired	Maintenance time	Waiting time
N	Activations	Activations	Activations	Activations	Value	Value

STAGE 5

As previously stated, each simulation performs 100 events that, in case of predictive and corrective models, match with detected or undetected failures. The values of the outputs must be corrected. Then, the results are extrapolated to the real values of the company.

Table 14: Results conversion

DF or UF	Satisfied on time	Satisfied not on time	Rework	Not repaired
K_1	$\frac{Activations}{100} \times k_1$	$\frac{Activations}{100} \times k_1$	$\frac{Activations}{100} \times k_1$	$\frac{Activations}{100} \times k_1$

SW_D	Maintenance time	*Waiting time
K_2	$\frac{Value}{100} \times k_2$	$\frac{Value}{100} \times k_2$

**Waiting time just in the corrective model*

STAGE 6

Enter the following data, to the EXCEL table. It can be original data or data extracted from the simulation.

Table 15: End of week or simulated data chart

VARIABLE	DEFINITION	UNITS
R_{ST}	Requests satisfied on time	dimensionless
R_S	Requests satisfied	dimensionless
RW	Rework	dimensionless
T_{PvR}	Preventive Maintenance Time	[h]
T_{CR}	Corrective Maintenance Time	[h]
TW	Wait Time	[h]

STAGE 7

The following data is calculated automatically by the program using the previously defined formulas:

Table 16: Output calculated data chart

VARIABLE	DEFINITION	UNITS
SW	Scheduled Work	dimensionless
R_N	Request still pending	dimensionless
SW_D	Scheduled Work Done	dimensionless
TM_R	Maintenance Time	[h]
TP_R	Production Time	[h]

STAGE 8

The EXCEL table will automatically calculate, graph and save all the values of each KPI on the present week. (Exemplary values are shown)

Table 17: KPIs values chart

KPI	Week / Optimum level	0	1	2	3	4	5	6	7	8
a) Mechanical availability	90%	98,30%	97,13%	96,21%	97,21%	99,979%	99,979%	99,979%	99,979%	99,979%
b) Maintenance type	60%	63,27%	71,62%	71,60%	73,81%	86,420%	86,420%	86,420%	86,420%	86,420%
c) Preventive compliance	95%	92,54%	95,00%	96,67%	97,20%	116,667%	116,667%	116,667%	116,667%	116,667%
d) Predictive compliance	95%	92,54%	88,33%	96,67%	98,43%	116,667%	116,667%	116,667%	116,667%	116,667%
e) Predictive plan efficiency	95%	76,92%	83,20%	87,67%	88,21%	85,714%	85,714%	85,714%	85,714%	85,714%
f) Plan compliance	90%	94,87%	92,50%	90,00%	95,12%	97,143%	97,143%	97,143%	97,143%	97,143%
g) Planning quality	5%	8,84%	5,62%	1,23%	4,76%	1,235%	1,235%	1,235%	1,235%	1,235%
h) MTTF	101,31	101,31	118,15	112,36	115,02	134,83	134,83	134,83	134,83	134,83
i) MTTR	1,26	1,26	1,15	1,93	2,05	2,31	2,31	2,31	2,31	2,31
j) MTBF	102,56	102,56	120,00	114,29	117,07	137,14	137,14	137,14	137,14	137,14
		OK	OK	Warning	Warning	Warning	OK	OK	OK	OK
k) Level service	95%	94,87%	92,50%	92,86%	95,12%	97,143%	97,143%	97,143%	97,143%	97,143%
l) Response time	80%	86,49%	94,59%	97,44%	100,00%	94,118%	94,118%	94,118%	94,118%	94,118%
m) Reworks	1%	2,70%	1,00%	0,00%	2,56%	2,941%	2,941%	2,941%	2,941%	2,941%

8.7. ANALYSIS OF DATA RESULTS

Once the results are obtained at the end of the bimester, they are analysed to observe the evolution of the maintenance indicators. The analysis is based on two aspects of each indicator: its value compared to the values given as reference or objective, and its evolution throughout the bimester, if there is any behaviour or pattern.

Below, the two analyses are developed and suitable actions to correct the indicators are proposed:

8.7.1. Maintenance indicators values

- Automate the application and planification process:

Both processes are speeded up and any type of maintenance time is diminished. In addition, the use of software to organize and plan the different activities, will greatly improve the time, especially in case of corrective maintenance. On one hand, the efficiency of the planning is increased and, therefore, increasing the fulfilment of requests, diminishing the out of time or not realized activities. On the other hand, dead hours without maintenance are avoided and the maintenance is squared in the shortest time and, therefore, it reduces the waiting time in the corrective maintenance.

Table 18: Solution 1: affected variables - improved KPIs

MAIN AFFECTED VARIABLES	TM	TW	R_{ST}

KPIs IMPROVED	Mechanical availability	Plan compliance	Planning quality	MTTF
	MTTR	MTBF	Level service	Response time

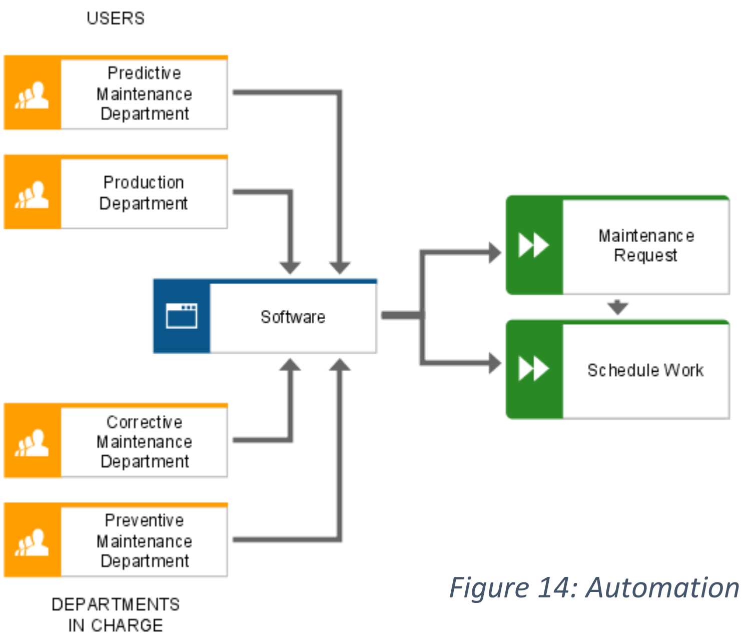


Figure 14: Automation of processes

- Increase the corrective and preventive maintenance personnel:

In this way, by augmenting the maintenance team, waiting times are reduced and the fulfilment of requests in time is increased.

Table 19: Solution 2: affected variables - improved KPIs

MAIN AFFECTED VARIABLES	TW	R_{ST}

KPIs IMPROVED	Mechanical availability	Plan compliance	MTTF
	MTBF	Level service	Response time

- Increase the skill in the predictive maintenance department:

Several possibilities can be taken into account: better software, specialized training, more personal, etc.

In-depth analysis of failures will allow the number of detectable failures to increase. Indirectly, it increases preventive maintenance and reduces the need for corrective maintenance, which shortens waiting times.

Table 20: Solution 3: affected variables - improved KPIs

MAIN AFFECTED VARIABLES	DF

KPIs IMPROVED	Maintenance type	Preventive compliance	Predictive compliance	Predictive plan efficiency

- Implement a collection of error data:

The data will be studied positively by the predicted maintenance department. This will improve the forecasts and therefore the effectiveness of preventive maintenance actions. Indirectly, it will reduce the need for corrective maintenance, which will shorten waiting times.

Table 21: Solution 4: affected variables - improved KPIs

MAIN AFFECTED VARIABLES	DF

KPIs IMPROVED	Maintenance type	Preventive compliance	Predictive compliance	Predictive plan efficiency

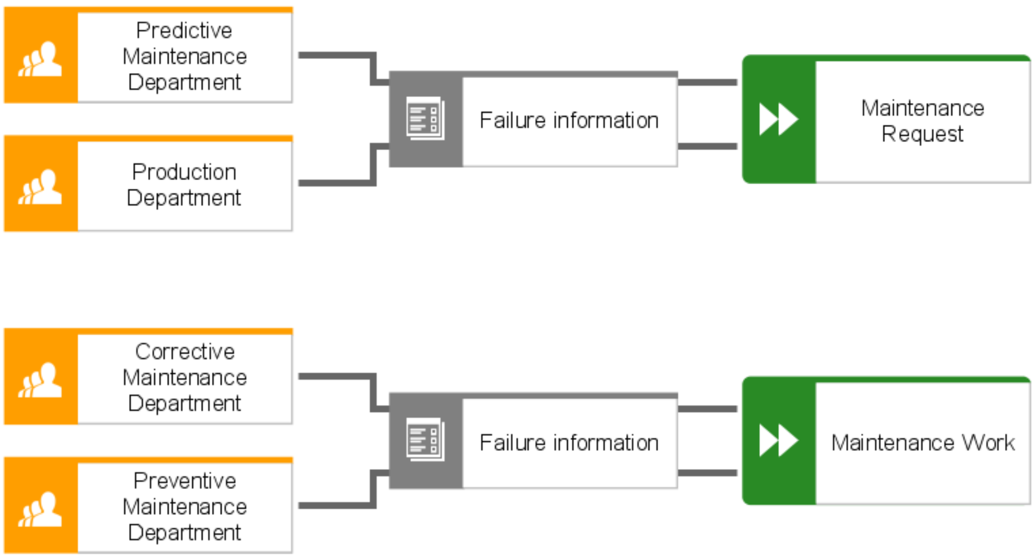


Figure 15: Process data collection

- Complementary training to the maintenance team / Contract the services of an external maintenance company:

In this way, maintenance times and number of errors are reduced. Indirectly, it affects all the other parameters by improving them.

Table 22: Solution 5: affected variables - improved KPIs

MAIN AFFECTED VARIABLES	TM	F

KPIs IMPROVED	All are improved to a greater or lesser extent.

- Best spare parts or materials:

The use of better spare parts will allow greater durability of the machines and, therefore, the reduction of errors and reworks.

A possible variant is to conduct a market study of more modern and automated machines.

Table 23: Solution 6: affected variables - improved KPIs

MAIN AFFECTED VARIABLES	F	RW

KPIs IMPROVED	Mechanical availability	MTTF	MTTR	MTBF	Reworks

8.7.2. Maintenance indicators behaviour

Change in the behaviour of the indicators are interesting for several reasons:

- Expected changes in the maintenance plan:

After making any change in the maintenance plan, like those presented previously, it is interesting to observe the evolution of the indicators. The evolution allows to assess whether the changes made meet the expectations and, therefore, the maintenance system is improving.

The variations observed in the different behaviours of the indicators must be correctly deduced, in order to not to confuse the effect of each factor.

- Unexpected changes in the maintenance plan:

In this case, the study that should be carried out is much wider. All the possible events that have produced this behaviour in the affected indicators must be tackled:

  - Company events
  - Previous changes in the maintenance plan
  - Changes in the production plan
  - Social events

9. EXAMPLE CASE

In this section a case is developed as an example in order to show in more detail the use of the system created.

Description of the problem:

A company that uses the designed control system intends to perform an operation in the maintenance department. To decide in which field they should make the investment, the following analysis is carried out:

0) Data of the previous month provided by the company:

Table 24: Initial company data

Number of machines	Daily production hours	Work days	Average maintenance time
50 machines	8h	5 days	1h 15min

T_t	T_f
2000h	1,25h

- Variables

Table 25: Last month variables values

	1st Week	2nd Week	3rd Week	4th Week
DF	25	25	25	25
UF	8	10	9	7
F	33	35	34	32
RST	20	22	22	21
Rs	10	10	9	8
RW	1	0	1	1
RN	2	3	2	2
T_{PV}	26h	25h	27h	28h
T_C	9h	13h	11h	9h
T_W	10h	11h	10h	9h

- KPIs

Table 26: Last month KPIs values

KPI	Week / Optimum level	1	2	3	4
a) Mechanical availability	90%	99,809%	99,732%	99,719%	99,694%
b) Maintenance type	70%	74,286%	65,789%	71,053%	75,676%
c) Preventive compliance	80%	83,200%	80,000%	86,400%	89,600%
d) Predictive compliance	80%	83,200%	80,000%	86,400%	89,600%
e) Predictive plan efficiency	80%	75,758%	71,429%	73,529%	78,125%
f) Plan compliance	90%	93,939%	91,429%	94,118%	93,750%
g) Planning quality	10%	-17,857%	-15,132%	-11,842%	-8,108%
h) MTTF	59,24	59,24	55,74	57,41	61,06
i) MTTR	1,06	1,06	1,09	1,12	1,16
j) MTBF	60,61	60,61	57,14	58,82	62,50
		OK	Warning	Warning	Warning
k) Level service	92%	90,909%	91,429%	91,176%	90,625%
l) Response time	75%	64,516%	68,750%	68,750%	70,000%
m) Reworks	5%	3,226%	0,000%	3,125%	3,333%

1) Analysis of the data:

By analysing the results of the previous month, several problems can be deduced:

- Predictive plan efficiency:

If the values of the failures of the month are observed, the company has defined by defect 25 detectable failures. This means that the company makes a weekly review of a half of the machines. Even so, a value around 10 non-detectable faults is observed throughout the month.

- Planning quality:

If the aforementioned indicator is observed, the values that it presents throughout the month are all negative and exceed in absolute value the optimum value pre-established by the company.

- Work times:

This issue is reflected by two points: the data provided and the indicators “Level service” and “Response time”. These problems are basically: long waiting times and little effectiveness in timely fulfilment of requests. In the corrective maintenance, the machines await the attention of the department the same time it takes to perform the repair on them. On the other hand, approximately two thirds of the requests are met on time.

2) Solutions proposal:

For each of the problems presented, several solutions are described:

- Predictive plan efficiency:

In this case, a more in-depth study should be done. First, the reason for undetected failures must be determined. Each machine is serviced every 2 weeks, so the problem could occur due to lack of maintenance quality or for other reasons. In the case that there are other reasons, it is interesting to normalize these failures, therefore, undetectable failures must be analysed. In this way, we try to include or improve the maintenance received by each machine every two weeks or, if it is not possible, the number of detectable failures and, therefore, the maintenance frequency increases.

Solution: Analyse non-detectable faults. If necessary, hire specialized personnel. Overall, it would be an investment in predictive maintenance.

- Planning quality:

From the received data, the following value can be calculated:

Table 27: Last month data calculated

Total Month Failures	Total Maintenance Hours	Actual T_f
134	148h	1,1h

The average maintenance time value presented by the company does not coincide with the average value of the month. In this case, the origin and the last update of the data provided must be consulted with the company.

In case that the value is correct, it means that the maintenance of the month has been faster than in previous months. Then, this level should be maintained and, thereafter, corrected and updated the parameter to the new value.

If the value is updated, the following evolution can be observed in the indicator:

Table 28: Evolution of Planning quality KPI

g) Planning quality	10%	-3,714%	-1,316%	1,579%	4,865%

The values are much more adjusted and within the interval ±10%.

Solution: Analyse, correct and update de T_f value.

- Work times:

In this case, the objective is to reduce waiting times and increase the number of satisfied requests on time.

Solutions: Automate the process as much as possible. Increase maintenance personnel.

3) Simulation:

From the previous solutions, the only one that makes sense to analyse by performing a simulation would be the last one, which refers to working times. To observe how the proposed solutions affect the current maintenance plan, the corresponding simulations are carried out. The results of the simulations used in the section are attached in the annexes of the document. The comparison of the results is shown at the end of the section.

To carry out the simulations, the following parameters have been defined:

- Failures: calculated by making the monthly average.

  Df = 25 UF = 9
- Maintenance time has been corrected.

  $T_f = 1{,}25\ h \rightarrow T_f^* = 1{,}1\ h = 66\ min$
- Event time distributions: provided by the company.

Table 29: Probabilities distribution of process times

	μ	σ
Maintenance time	1h	15 min
Request time	4 min	30 sec
Scheduling time	2 min	30 sec
Waiting time	1,17h	15 min

- Event probabilities:

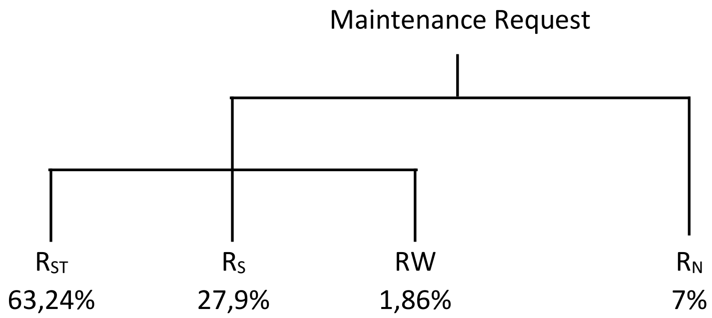


Figure 16: Event probability diagram

- 1st Simulation: Automate the application and planification process.

Of all the maintenance process, the maintenance request and the scheduling work will be automated, and then, both will be ruled out. In this way, the total maintenance time will be reduced.

Results obtained:

Table 30: Preventive maintenance results

VARIABLE	DF	RST	RS	RW	RN	Reparation time
Simulation	100	55	32	1	12	
Real	25	13,75	8	0,25	3	0:59:28

Table 31: Corrective maintenance results

VARIABLE	DF	RST	RS	RW	RN	Reparation time	Waiting time
Simulation	100	68	22	2	8		
Real	9	6,12	1,98	0,18	0,72	1:00:29	1:12:44

Table 32: 1st Simulation results

VARIABLE	F	RST	RS	RW	RN	Reparation time	Waiting time
Simulation	34	19,87	9,98	0,43	3,72		
Real	34	20	10	0	4	59:59	1:12:44

- 2nd Simulation: Increase maintenance personnel.

In this case, the maintenance team has greater capacity and, therefore, performs more work orders at the same time and reduces waiting times.

From previous data, observing how it affected the variables when increasing the maintenance team, the company provides how the variables have to be modified.

  - Event time distributions:

Table 33: New Waiting time probability distribution

	μ	σ
Waiting time	55 min	15 min

- Event probabilities:

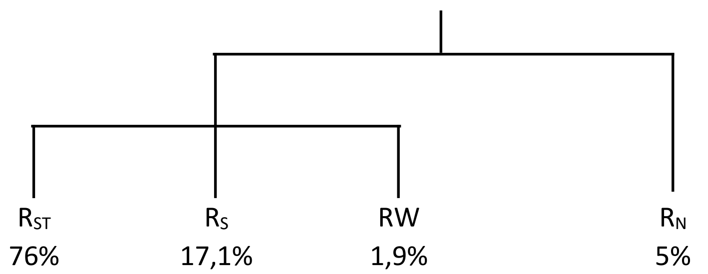


Figure 17: New event probabilities diagram

Results obtained:

Table 34: Preventive maintenance results

VARIABLE	DF	RST	RS	RW	RN	Reparation time
Simulation	100	74	22	1	3	
Real	25	18,5	5,5	0,25	0,75	1:06:18

Table 35: Corrective maintenance results

VARIABLE	DF	RST	RS	RW	RN	Reparation time	Waiting time
Simulation	100	76	18	1	5		
Real	9	6,84	1,62	0,09	0,45	1:06:10	0:56:14

Table 36: 2nd Simulation results

VARIABLE	F	RST	RS	RW	RN	Reparation time	Waiting time
Simulation	34	25,34	7,12	0,34	1,2		
Real	34	25	7	1	1	1:06:14	0:56:14

- 3rd Simulation: Automate the process and increase the personnel.

The two presented solutions are carried out simultaneously.

Results obtained:

Table 37: Preventive maintenance results

VARIABLE	DF	RST	RS	RW	RN	Reparation time
Simulation	100	77	16	1	6	
Real	25	19,25	4	0,25	1,5	1:00:05

Table 38: Corrective maintenance results

VARIABLE	DF	RST	RS	RW	RN	Reparation time	Waiting time
Simulation	100	77	19	1	3		
Real	9	6,93	1,71	0,09	0,27	0:59:45	0:55:20

Table 39: 3rd Simulation results

VARIABLE	F	RST	RS	RW	RN	Reparation time	Waiting time
Simulation	34	26,18	5,71	0,34	1,77		
Real	34	26	6	1	2	0:59:55	0:55:20

4) Results comparison

The results of the simulations are compared to observe the effectiveness of each of the solutions.

Table 40: KPIs Last month and Simulations chart

KPI	Week / Optimum level	1	2	3	4	1st Simulation	2nd Simulation	3rd Simulation
a) Mechanical availability	90%	99,809%	99,732%	99,719%	99,694%	99,983%	99,984%	99,944%
b) Maintenance type	70%	74,286%	65,789%	71,053%	75,676%	72,998%	71,183%	72,078%
c) Preventive compliance	80%	83,200%	80,000%	86,400%	89,600%	75,603%	78,336%	80,000%
d) Predictive compliance	80%	83,200%	80,000%	86,400%	89,600%	75,603%	78,336%	80,000%
e) Predictive plan efficiency	80%	75,758%	71,429%	73,529%	78,125%	73,529%	73,529%	73,529%
f) Plan compliance	90%	93,939%	91,429%	94,118%	93,750%	88,235%	97,059%	97,059%
g) Planning quality	10%	-17,857%	-15,132%	-11,842%	-8,108%	-31,314%	-23,582%	-22,532%
h) MTTF	59,24	59,24	55,74	57,41	61,06	57,66	57,56	57,64
i) MTTR	1,06	1,06	1,09	1,12	1,16	0,88	1,01	0,94
j) MTBF	60,61	60,61	57,14	58,82	62,50	58,82	58,82	58,82
		OK	Warning	Warning	Warning	Warning	Warning	OK
k) Level service	92%	90,909%	91,429%	91,176%	90,625%	88,235%	94,118%	94,118%
l) Response time	75%	64,516%	68,750%	68,750%	70,000%	66,667%	75,758%	78,788%
m) Reworks	5%	3,226%	0,000%	3,125%	3,333%	0,000%	3,030%	3,030%

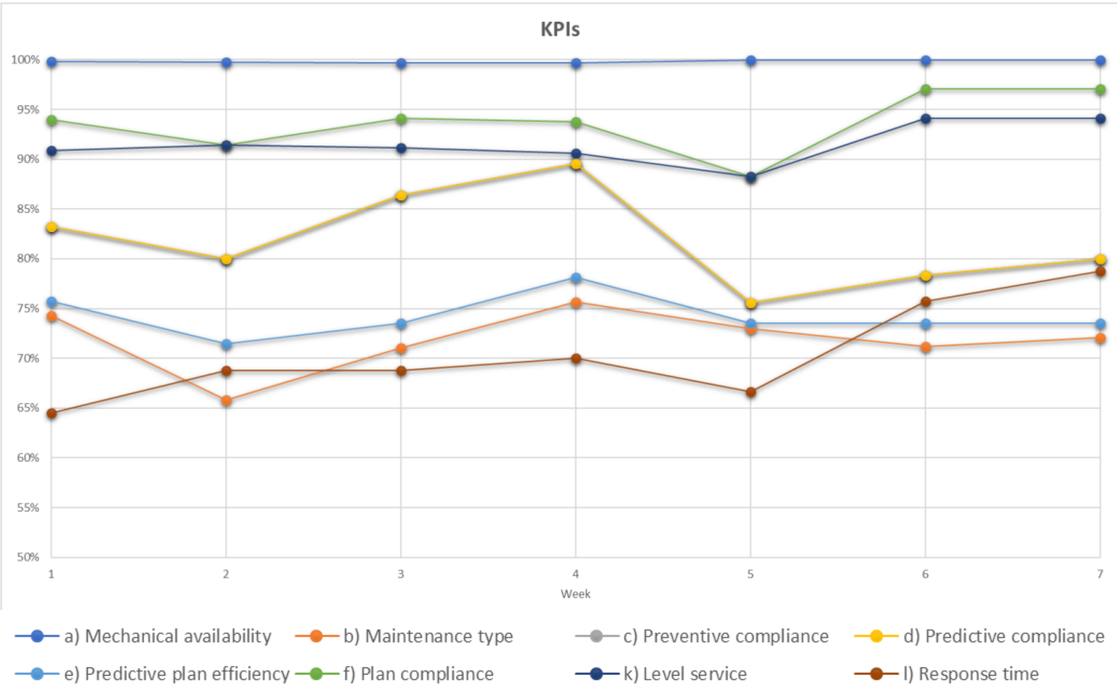


Figure 18: KPIs results graphic

Table 41: KPI changes

a) Mechanical availability	It has increased because maintenance and waiting time have been reduced.
e) Predictive plan efficiency	The indicator refers to detectable and undetectable faults. In the simulations, the predictive maintenance has not been modified, so it maintains its values. (Value equal to the 3rd week since it has the same number of UF and DF)
b) Maintenance type **c) Preventive compliance** **d) Predictive compliance** **g) Planning quality**	These indicators are dependent on the stipulated value T_f. As explained in the proposed solutions section, this value, in the of being incorrect, must be reviewed and updated. In that case, the indicators would present more adjusted values.
f) Plan compliance	This indicator reflects the increase in maintenance personnel. In the 2nd and 3rd simulations, this indicator is triggered and has a very optimal value.
h) MTTF	This indicator must be compared with the 3rd week given that it presents the same number of failures. Having increased the production time, decreasing waiting and maintenance times, the indicator increases. As a benefit, time between failures is longer.

i) MTTR	This indicator must be compared with the 3rd week given that it presents the same number of failures. This indicator reflects the decrease in maintenance times by automating part of the process.
j) MTBF	This indicator must be compared with the 3rd week given that it presents the same number of failures. As the number of failures remains constant and equal to the value on the 3rd week, the indicator does not change. In case of investing in predictive maintenance and modifying the values of detected and undetected failures, this would improve its value.
k) Level service	Having increased the maintenance staff, more requests are met, and then the service level is visibly better.
l) Response time	Having increased the maintenance staff, the waiting time is decreased and more requests are met on time, and then the response time is visibly better.
m) Reworks	This indicator has not been affected by any of the modifications. The percentage of reworks to be carried out still has a value within the margins.

5) Analysis conclusions

By observing the different proposals and the results of the comparison, a hierarchy can be defined in the solutions according to the improvement in the maintenance plan. In the event that the company could afford the budgets of the changes, they should be executed in this order:

- Analyse, correct and update de T_f value.
- Increase maintenance personnel.
- Automate the request and scheduling process.
- Invest in predictive maintenance.

The first proposal, rather than a solution itselfs, shows something that should be corrected. All the data point to the fact that the Tf has an incorrect value, at least in this last month. On the other hand, regarding the second solution, although it might be obious, looking at the simulations, it would be necessary to achieve the established values of the indicators.

10. PLANNING

The duration of the entire project is approximately 4 months. The initial date of the project is set in mid-February concurring with the beginning of the academic semester and ends with the final delivery scheduled at the end of June.

The planning of the project is divided into four phases:

- **Definition of the project:** This first stage is based on completing the concept and strategy throughout the project. Initially, the idea was to start from a case and develop the technical maintenance management model based on it. In spite of that, with all the articles and the material obtained during the search of the case, another perspective was raised: to develop a generic model.

- **Maintenance introduction**: in this second stage all the basic aspects are developed to be able to prepare the maintenance management model. The different types of maintenance are defined, as well as the parameters to control it.

- **Design of the model**: in this third phase, the two parts of the model are created: the control work sheets and the simulation model. The variables and indicators that will be used are considered and the parallel development of the two parts begins, interrelating them, creating a joint model and not two independent parts.

- **Example case**: once the technical maintenance management model is finished, an example is made to display its operation.

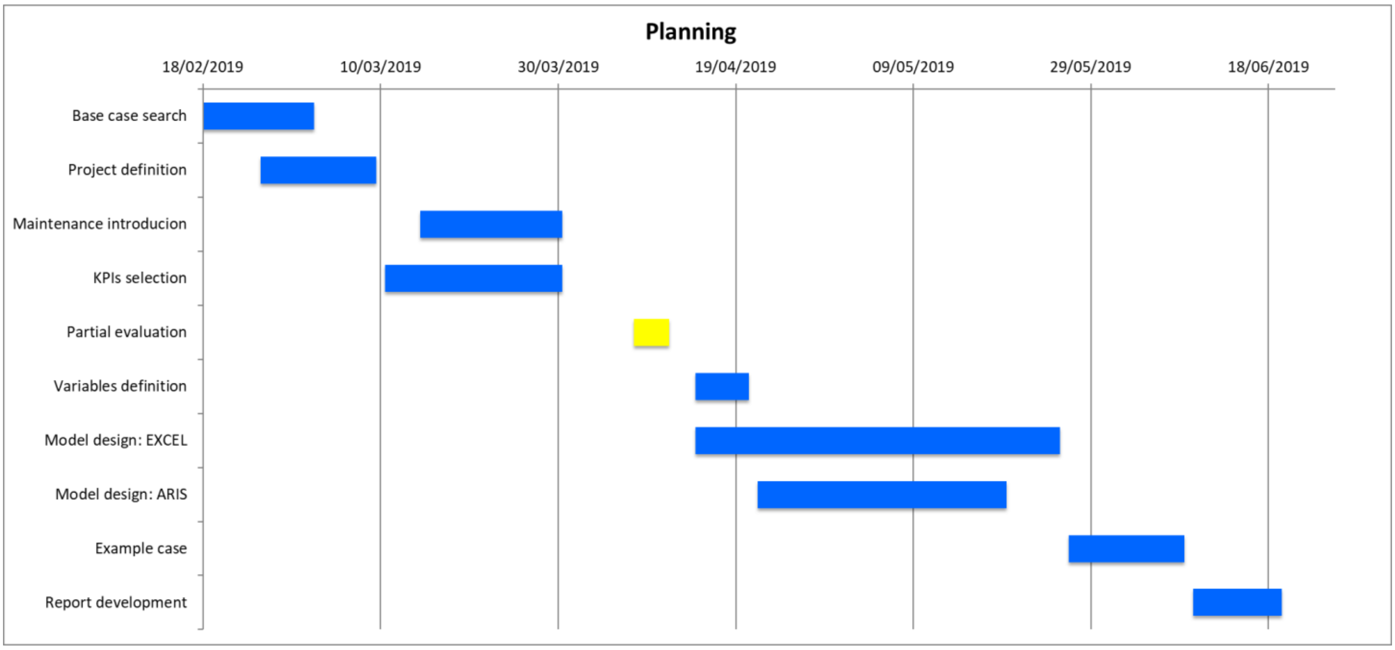


Figure 19: Gantt diagram of the project

Table 42: Project schedule

Task	Initial date	Final date	Duration (days)
Base case search	18/02/2019	03/03/2019	13
Project definition	25/02/2019	10/03/2019	13
Maintenance introducion	15/03/2019	31/03/2019	16
KPIs selection	11/03/2019	31/03/2019	20
Partial evaluation	08/04/2019	12/04/2019	4
Variables definition	15/04/2019	21/04/2019	6
Model design: EXCEL	15/04/2019	26/05/2019	41
Model design: ARIS	22/04/2019	20/05/2019	28
Example case	27/05/2019	09/06/2019	13
Report development	10/06/2019	20/06/2019	10

11. ECONOMIC ANALYSIS

For the economic analysis, the costs derived from the research and execution of the project, as well as the cost of the licenses of the software used, have been contemplated.

Different values have been assigned in the costs per hour depending on the difficulty of the work phase. In case of the first two phases, research and introduction, a cost of 10 €/h has been set. In contrast, in the last two phases, design of the model and the example case, as a consequence of its greater difficulty, the cost has been set at 20 €/h.

Furthermore, referring to the programs, in case of the EXCEL license included in the personal Office 365 pack, half of its annual value has been established as project cost. On the other hand, referring the ARIS program, the software company offers licences of the student program version for free.

Table 43: Project costs

CONCEPT	HOURS	PRICE	AMOUNT
Phase 1: Definition of the project	25 h	10 €/h	250 €
Phase 2: Maintenance introduction	40 h	10 €/h	400 €
Phase 3: Model design	180 h	20 €/h	3600 €
Phase 4: Example case	60 h	20 €/h	1200 €
EXCEL (Office 365 Personal) – License	-	70 €/year	35 €
ARIS Architect & Designer 10.0 - Student version license	-	0 €	0 €
TOTAL			**5485 €**

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12. ENVIRONMENTAL IMPACT

This project has consisted in the design and creation of a model for maintenance management. To carry out this project, only a computer capable enough to perform the different simulations has been needed. Therefore, the environmental impact of this project is null.

In the case of studying the environmental impact of the use of the technical maintenance management model, the user company should be taken into account. Based on the results obtained with the model, once the changes in the company have been defined and applied to improve maintenance, the environmental impact of these changes should be studied. In any case, the environmental impact of these changes is not directly the result of the model, therefore it is not the responsible.

13. CONCLUSIONS

Throughout the project it has been possible to develop different abilities and skills acquired in these four years of the bachelor's degree in Industrial Technology Engineering. In addition, it has led to the introduction of a small knowledge based on technical maintenance and other aspects, unknown until now.

Referring to the programs used, EXCEL and ARIS, the project has largely served as training Specifically, having a good command of the ARIS program has been a great challenge. Leaving aside the technical questions of installation, understanding the operation and the great variety of models that it has, as well as its different work objects with its attributes, has supposed a great personal development.

In addition, by using this software the importance of management has become clearer and more evident. It has shown the complexity that this implies and how good management with professionals and the right tools, gives good results.

Regarding to the main purpose of the thesis, it has been possible to create and design the technical maintenance management model, as intended.

In the first phase, after a brief introduction about technical maintenance, the topic of key performance indicators is discussed. In this study about indicators, it has been observed its great utility, not only in the field of maintenance, but in any aspect, department or process that is part of a company. The versatility that the indicators present when giving value to different aspects, allows to evaluate these processes and, therefore, to carry out certain control over them.

In addition, there is a great variety of indicators and they have great adaptability, which allows high fidelity in the processes represented of the company in question that uses them. For example, some of the indicators used in the model have undergone changes with respect to their first presentation in the general section of indicators. These changes, in general, have been changes of variables, in order to make the project model.

Furthermore, the project has developed the management model for maintenance. This model has been defined with a temporal perspective and the economic section has been left aside. That's why a selection of KPIs is initially made. Then, their variables have been defined to observe the influence of each one in the different aspects of maintenance. Once achieved this, the two parts of the model have been created simultaneously to match and share its interface. In the end, the two models have been obtained, which allow a control and simulation of the technical management.

In case of not having a scheduled deadline, the prospect of human and economic resources could have been implemented in the project. In this way, it would be much more complete and more information would be obtained in the results.

Finally, at the end of the project an exemplary case has been shown to observe the operation of the model. It is important to highlight the importance of this section, since it has been key in the development of the model. This example has allowed to calibrate and correct those errors or failures that the initially designed model presented. In short, it has put the model to the test.

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