ALMA MATER STUDIORUM-
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Modelling, Simulation and Optimization of Maintenance Considerations on Condition Based Maintenance

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presented by
GIOVANNI SCAGLIOSO

accepted on the recommendation of
Prof. Dr. Ana M.Mejìas
Prof.Dr. Juan E. Pardo
Prof.Dr. Emilio Ferrari

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ABSTRACT

Globalization has increased the pressure on organizations and companies to operate in the most efficient and economic way. This tendency promotes that companies concentrate more and more on their core businesses, outsource less profitable departments and services to reduce costs. By contrast to earlier times, companies are highly specialized and have a low real net output ratio. For being able to provide the consumers with the right products, those companies have to collaborate with other suppliers and form large supply chains. An effect of large supply chains is the deficiency of high stocks and stockholding costs.

This fact has lead to the rapid spread of Just-in-Time logistic concepts aimed minimizing stock by simultaneous high availability of products. Those concurring goals, minimizing stock by simultaneous high product availability, claim for high availability of the production systems in the way that an incoming order can immediately processed.

Besides of design aspects and the quality of the production system, maintenance has a strong impact on production system availability.

In the last decades, there has been many attempts to create maintenance models for availability optimization. Most of them concentrated on the availability aspect only without incorporating further aspects as logistics and profitability of the overall system.

However, production system operator’s main intention is to optimize the profitability of the production system and not the availability of the production system. Thus, classic models, limited to represent and optimize maintenance strategies under the light of availability, fail.

A novel approach, incorporating all financial impacting processes of and around a production system, is needed.

The proposed model is subdivided into three parts, maintenance module, production module and connection module. This subdivision provides easy maintainability and simple extendability. Within those modules, all aspect of production process are modeled.

Main part of the work lies in the extended maintenance and failure module that offers a representation of different maintenance strategies but also incorporates the effect of over-maintaining and failed maintenance (maintenance induced failures). Order release and seizing of the production system are modeled in the production part. Due to computational power limitation, it was not possible to run the simulation and the optimization with the fully developed production model. Thus, the production model was reduced to a black-box without higher degree of details.

This model was used to run optimizations concerning maximizing availability and profitability of the production system by varying maintenance strategies but also logistics factors. Those optimizations showed that there is a stringent connection between production system availability and maintenance decision variables.

This finding is a strong indicator that a joint optimization of maintenance strategies provides better results than optimizing those elements independently and highlights the need for the proposed sophisticated model.

Besides of the classic optimization criterion ”availability”, the overall profitability of the production system was investigated using a life-cycle approach coming from pre-investment analysis. Maintenance strategy was optimized over the whole lifetime of the production system.

It has been proved that a joint optimization of logic maintenance strategy is useful and that financial objective functions tend to be the better optimization criterion than production system availability.

ABSTRACT

La globalizzazione ha incrementato la pressione su organizzazioni e aziende affinché operino in maniera più efficiente ed economica. Le aziende si concentrano ormai solo sui propri core business e danno in outsourcing le funzioni meno profittevoli con l'obiettivo di ridurre i costi.

Il mercato odierno,caratterizzato da personalizzazione dei prodotti sempre più spinta, mix produttivi più ampi, crescente importanza della qualità e necessità di avere ridotti Time To Market e costi produttivi, spinge le aziende a collaborare con i propri fornitori e formare lunghe e complesse supply chains.

La complessità della catena del valore genera alti livelli di stock in magazzino e relativi costi. Infatti, per rispondere al mercato in maniera veloce ed efficiente le aziende sono costrette a sovradimensionare le scorte per non perdere potenziali profitti, generando però alti costi di immobilizzo finanziario.

A queste caratteristiche del contesto competitivo le compagnie rispondono con il Just-in-Time logistico, principio che punta a minimizzare le scorte e simultaneamente a massimizzare la disponibilità di prodotti.

La produzione dei beni viene realizzata solo quando c'è una effettiva richiesta da parte del cliente; si passa quindi dalla logica *push* in cui si produceva a prescindere dal fabbisogno del cliente ad una logica *pull* in cui è il mercato a "tirare" la produzione. Per perseguire questi due obiettivi di minimizzare le scorte e massimizzare la disponibilità dei prodotti, è necessario che il sistema produttivo abbia una disponibilità molto alta, in modo che quando c'è un picco di richiesta, questi possa adempiere alla domanda.

La disponibilità di un sistema produttivo dipende oltre che da come è stato concepito e progettato, anche dalla manutenzione e dal modo con cui viene realizzata. Questi sono i principali motivi che hanno trasformato la manutenzione da semplice attività "cuscinetto" della produzione ad attività oggetto di studio e ottimizzazione.

Nell'ultimo decennio si sono susseguiti numerosi studi aventi l'obiettivo di determinare un modello in grado di definire la migliore strategia manutentiva in funzione delle caratteristiche del sistema.

Nell'elaborato sono stati studiati più modelli matematici che puntano alla ricerca della strategia manutentiva che minimizzi l'indisponibilità. Un approccio più innovativo considera però anche i costi, e deve avere come obiettivo la massimizzazione dei profitti che il sistema genera.

Per questo motivo, nell'elaborato vengono presentate prima le diverse politiche manutentive note ed in seguito viene descritta la realizzazione di un modello simulativo realizzato con l'ausilio del software Arena. L'obiettivo del modello è stato quello di realizzare delle considerazioni su come le diverse caratteristiche del sistema oggetto di studio possano influire sulla definizione della migliore politica manutentiva.

Il modello è stato suddiviso in tre sotto-modelli, uno che simula la produzione,uno la manutenzione e un terzo modulo di connessione tra i primi due. Tale scelta è dettata dalla ricerca di generalità e modularità che si è voluto dare al modello. In questo modo infatti i concetti chiave dello studio possono essere applicati a più ambiti solo con il cambio di alcune variabili.

Sono stati ipotizzati diversi scenari, costruiti cambiando le variabili di input del modello, e si sono studiati gli effetti, dal punto di vista economico, che il sovradimensionamento o il sottodimensionamento della funzione manutenzione genera.

Il sottomodello della produzione è stato simulato come una “scatola chiusa” in cui entrano materie prime ed escono prodotti finiti, sia per i limiti dovuti alla versione student del software Arena sia perché l’oggetto dello studio è quello di ottimizzare le politiche manutentive e non gli aspetti legati alla produzione.

Il modello si limita a mostrare come vari la disponibilità del sistema produttivo in funzione delle variabili di input che caratterizzano la manutenzione.

In seguito al lancio di più simulazioni,è stato valutato come variano i costi totali della manutenzione in funzione del rapporto tra costo di un’azione correttiva e di una preventiva, nel caso in cui un fallimento del sistema generi dei costi indotti.

In questo modo il modello considera oltre alla disponibilità anche gli aspetti puramente economici.

L’output finale dell’elaborato sono diverse matrici che in funzione di alcune variabili chiave che caratterizzano la produzione determinano la migliore strategia manutentiva.

È chiaro quindi che produzione e manutenzione siano strettamente inter-connesse e lo studio congiunto tramite software simulativi può aiutare a massimizzare la profittabilità e la disponibilità del sistema.

Abbreviations

CMB	Condition Based Maintenance
CF	Cash Flow
CFR	Constant Failure Rate
CM	Corrective Maintenance
PM	Preventive Maintenance
MTBF	Mean Tima Before Failure
MTTF	Mean Time To Failure
RCM	Reliability-Centered Maintenance
TPM	Total Production Maintenance
Cpm	Cost preventive action
Ccm	Cost corrective action
ttf	Time To Failure

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5.Final Consideration

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Appendix 2-Application example of the mathematical model

Chapter 1

Introduction

This relation shall give a brief introduction into subject of maintenance, its associated areas of conflict and trends in the industries. In addition to present the most important maintenance strategies and maintenance selection procedures, their impact on industry and company level is discussed.

Through a simulation model showed how is possible to identify the best maintenance strategies. The study of a mathematical model determined which are the more common features that a production system presents.

These features have been convert in variables that represent the data input of simulation model.

The simulation model has been build with the software Arena Rockwell, a discrete events simulation software.

The final considerations are based on the output that the simulation model produces, in fact we studied only the trend of the costs and how they change in function on the most important variables of the production system. In this way it is been possible to identify which are the features of the system that have more impact on the maintenance strategies.

In particular we studied the features that make a Condition Based Maintenance convenient for a production system.

Finally we built more matrices with these variables that show visually the best maintenance strategies in function of the most important characteristics of the system.

1.1 Objectives Of Investigation

The objectives of study have been to build a simulation model that present two important features: the generality and the modularity.

The generality because the model represents only a way to make considerations about the costs in function of the input variables . Through repeated analysis with change of variables has been possible to determinate which are the parameters that influence the selection to achieve a type of maintenance.

The modularity because with student's version of Arena was impossible to build a model with high number of entities. The present model, described in the following pages, represents only a module of the real production system(e.g. one machine), but with a change of the input variables it can be implemented in a real context. In fact, a system is defined in the following mode : "a group of interacting, interrelated, or interdependent elements forming a complex whole"[1] , so the objects constituting a system can be referred to as subsystems, namely as part of a system corresponding to the definition already given system (1), or as components, that are as primitive entities characterized by proper parameters that, for a given end, not it is necessary to consider further divided. For example, the articulated connecting rod-crank handle mechanism may be a system if it wants to study the dynamics; becomes a sub-system if you want to perform the analysis of the entire motor; and this is in turn a sub-system if, for example, it is analyzing the machine on which the engine is operating.

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[1] http://www.merriam-webster.com/dictionary/system

1.2 Diagram of the objectives

The diagram of features of the simulation model is shown in the following figure (1).

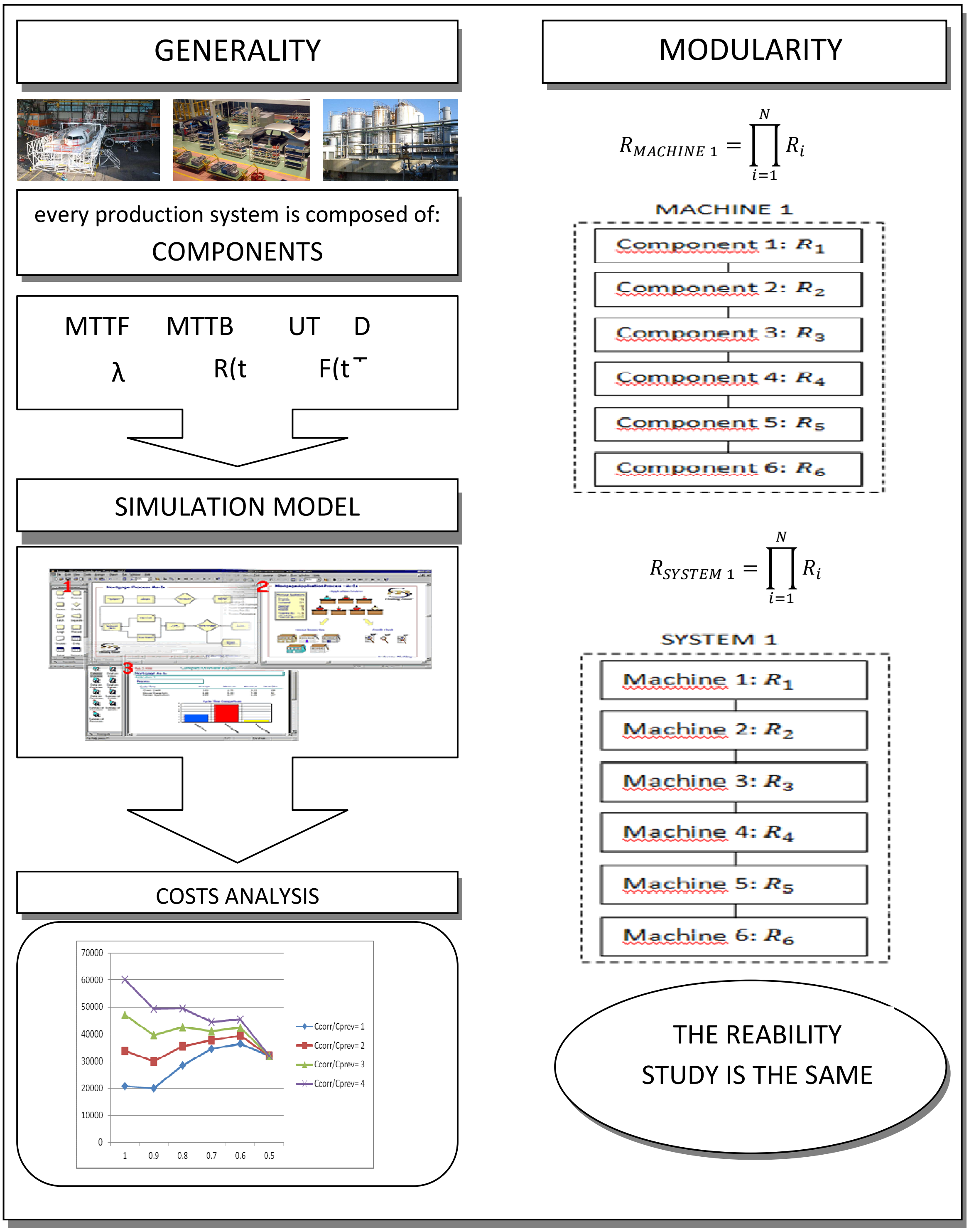

Figure 1

1.3 The Importance Of Maintenance

MAINTENANCE ENGINEERING is the discipline and profession of applying engineering concepts to optimization of equipment, procedures, and departmental budgets to achieve better maintainability, reliability, and availability of equipment.

The importance of maintenance is growing in every industries because the current market, where the companies must to compete, is characterized:

- increase product customization;
- increase mix productive;
- increase of variability;
- increase importance of quality;
- decrease of Time to Market;
- decrease of sales prices.

For these features, actually the companies try to increased the interest for three parameters: productivity, safety and quality. The maintenance affect every three parameter because is a discipline cross a many function.

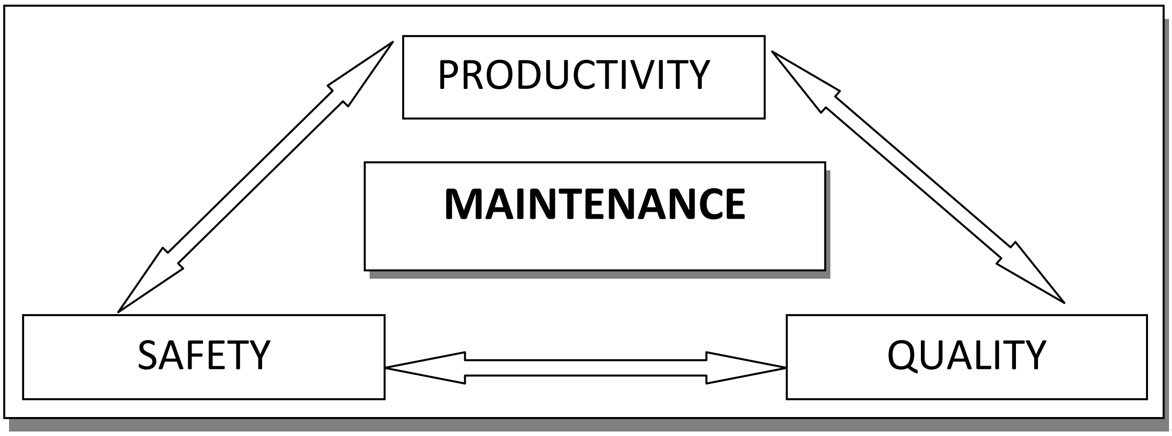

Figure 2

Although the economic contribution of maintenance to the company profitability is beyond dispute, many companies regard maintenance and the maintenance department as expense factor only. Maintenance is a significant cost factor in many companies and is under constant pressure of cost reduction. Among others, the tendency to highlight costs and disregarding the benefit of maintenance is fostered by the difficulties to rate and estimate the contribution of maintenance to the company's profit. Even though many rating and optimization approaches (e.g. Reliability Centered Maintenance[2] and Total Productive Maintenance[3]) have been developed, they still lack of reliable quantitative measurands and impede a cost-benefit consideration between different maintenance strategies but also among other investment ventures A new approach that considers not only the availability of the system but also the productivity and the quality of the output is needed. In this way is possible to indentify every variables of the system that has an impact on total cost of maintenance. In fact if the availability is high but the quality of the output is low, increases the total cost of maintenance, and in the same way an induced cost will originates if the productivity is low.

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[2] Moubray, 1991

[3] Nakajima,1988

Chapter 2

Strategies Of Maintenance

Breakdowns and holdups in production systems can seriously impacting system availability and usability, both putting profitability of a production system at risk.

Idle production systems cause a negative shift regarding the ratio between fixed costs to production output. In combination with the reduced production output due to breakdowns, this has a double negative effect of the cost-effectiveness of the production system[4].

Moreover, sophisticated production systems often need significant start-up time after an interruption. During this time, scrap or goods of minor quality are manufactured that either cannot be sold or only at reduced prices. Thus, efficient operation of a production system claims only few interruptions and fast recovery from breakdown.

We can have mainly two type of maintenance:

- Corrective Maintenance
- Preventive Maintenance

In the first case the maintenance function intervenes when a failure occurs in the production system. Instead when the company employs a preventive maintenance also, the maintenance function has a proactive role to try to intervene before that a failure occurs.

The other types of strategies derive from these two type.

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[4] Seiler,2000

In the following figure (3) is shown different strategies of maintenance.

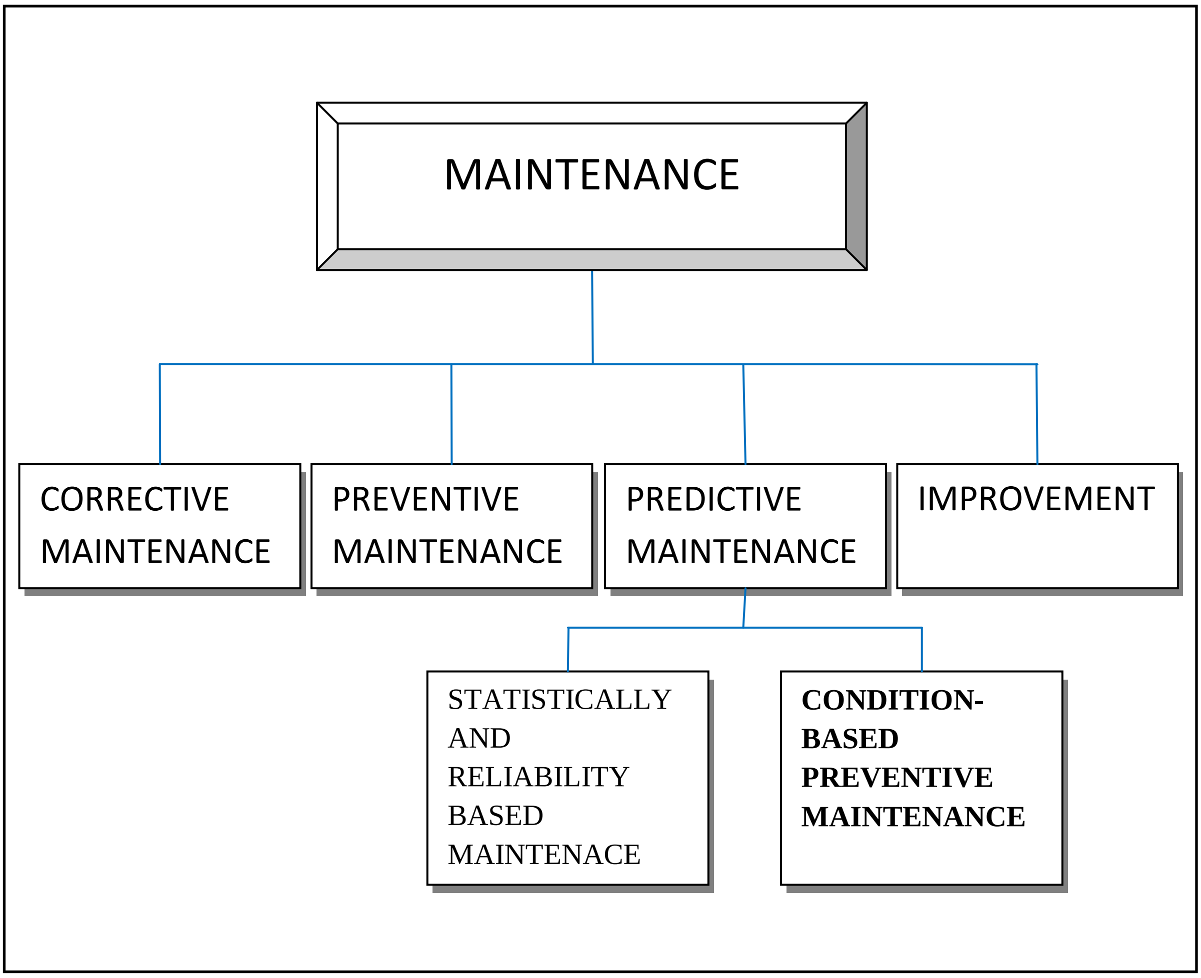

Figure 3

In this paper we have examined in depth the Condition Based Maintenance, because when the production system has certain characteristics, this strategy produces the higher benefits.

2.1 Corrective Maintenance

Corrective maintenance (CM) is initiated after a failure occurs and is intended to reset system into a failure-free state[5].
Often, corrective maintenance is named repair or restoration and involves the actions repair and replacement of failed components, figure (4).
This type of maintenance can be applied in systems where:

- the failures do not cause costly and dangerous situations;
- the components have a constant failure rate (expose purely stochastic failures);
- systems with built-in redundancy.

Benefit of corrective maintenance is the maximum exploitation of the wear-out reserve of the components. However, CM is, in some form, an integrative part in any maintenance strategy, since unplanned breakdowns can never be excluded.

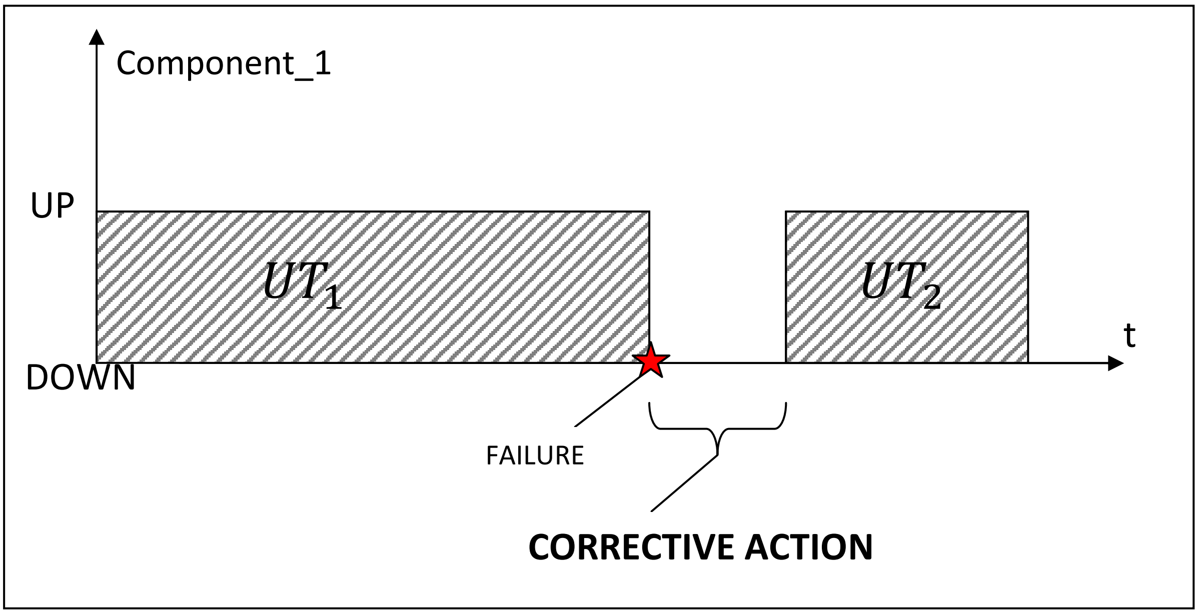

Figure 4

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[5] DIN-13306, 2001

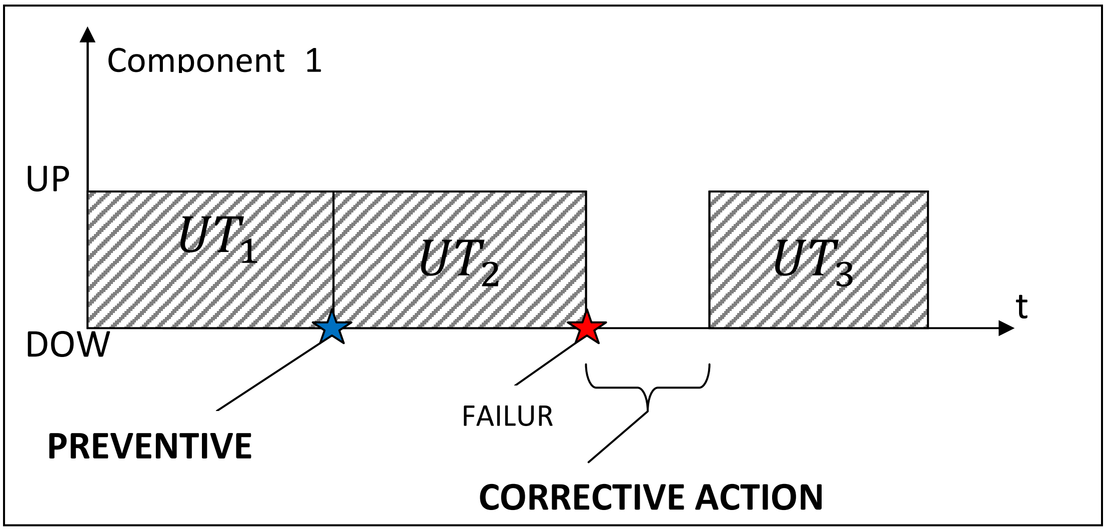
2.2 Preventive Maintenance

Preventive maintenance (PM) encompasses all activities geared towards reducing or preventing deteriorating tendencies by anticipating possible future failures[6].

Preventive maintenance makes sense when:

- the failure rate of a component increases in time;
- the costs for preventive maintenance are lower than the overall costs of a breakdown strategy(CM);
- a breakdown could lead to severe accidents.

Although preventive maintenance is designated to prevent the system from failure, some failures may still occur. Those stochastic failures are covered with corrective actions. Thus, a preventive maintenance strategy incorporates always reactive (CM) and proactive (PM) tasks.There are production system where is possible to make a preventive action without stop the machine, as shown in figure (5).In this case if it is known the failure rate of component, there are more advantages because the preventive action does not induce a stop of production.



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[6] Wu, S. and Zuo, M.J. (2010). *Linear and nonlinear preventive maintenance*

Instead in the systems where to make a preventive action is needed the stop of production, there are economic advantages only if the failure rate of a component is certainly known.
In fact, in this case, is possible to replace the component when it has a residual service life lesser than the overall costs of breakdown.

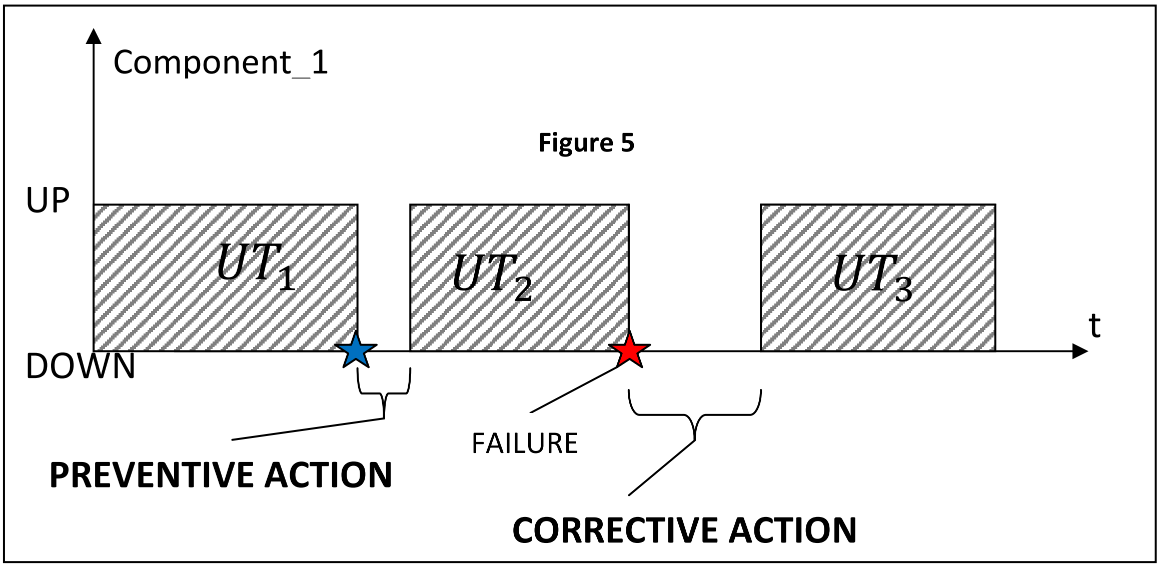


Figure 6

2.3 Condition Based Maintenance

The maintenance of the condition is the present and the future of maintenance because through knowledge of the technological process and goods to keep promoting the necessary response actions maintenance achieving the minimum overall cost.

Incorporates inspections of the system in predetermined intervals to determine system condition. Depending on the outcome of an inspection, either a preventive or no maintenance activity is performed.

Thus, CBM is a variety of a PM strategy with the difference, that the triggering event to perform a preventive maintenance activity is the expiring of a maintenance interval in the PM case, respectively the result of an inspection in CBM. Unlike in planned scheduled maintenance (PM), where maintenance is performed based upon predefined scheduled intervals, condition based maintenance is performed only when it is triggered by asset conditions. Compared with preventative maintenance, this increases the time between maintenance tasks, because maintenance is done on an as-needed basis.

Apparently, CBM is only applicable when wear-out reserve is measurable.

The goal of CBM is to spot upcoming equipment failure so maintenance can be proactively scheduled when it is needed - and not before. Asset conditions need to trigger maintenance within a long enough period before failure, so work can be finished before the asset fails or performance falls below the optimal level.

The guidelines for implementing a CBM system are explained in the following figure (7).

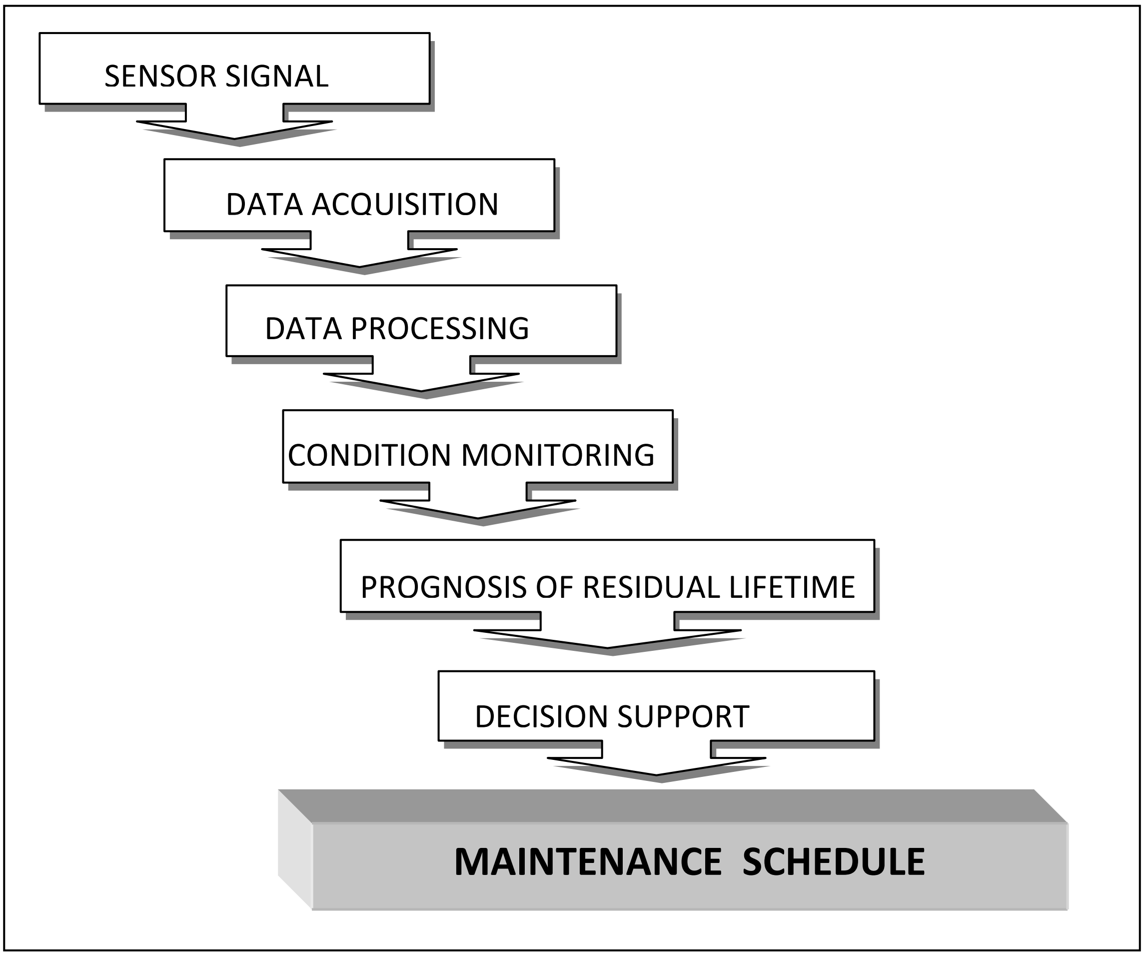


Figure 7

Condition Based Maintenance allows preventive and corrective actions to be scheduled at the optimal time thus reducing the total cost of ownership. Today, CBM methods are becoming more mature and improvement in technology are making it easier to gather, store and analyze data for CBM. In particular, CBM is highly effective where safety and reliability is the paramount concern such as the aircraft industry, semiconductor manufacturing, Nuclear, Oil and Gas.

2.4 Data Input in Condition Based Maintenance

Acquisition of data is done by observing the state and condition of the production system with monitoring tool and devices.
Among others, some of the monitoring tools are:

- Vibration monitoring;
- Lubrication monitoring;
- Thermography;
- Acoustic sound source localization;
- Non-destructive thickness measuring with ultrasonic.

In the following figure (8), it shown the diagram about the data input.

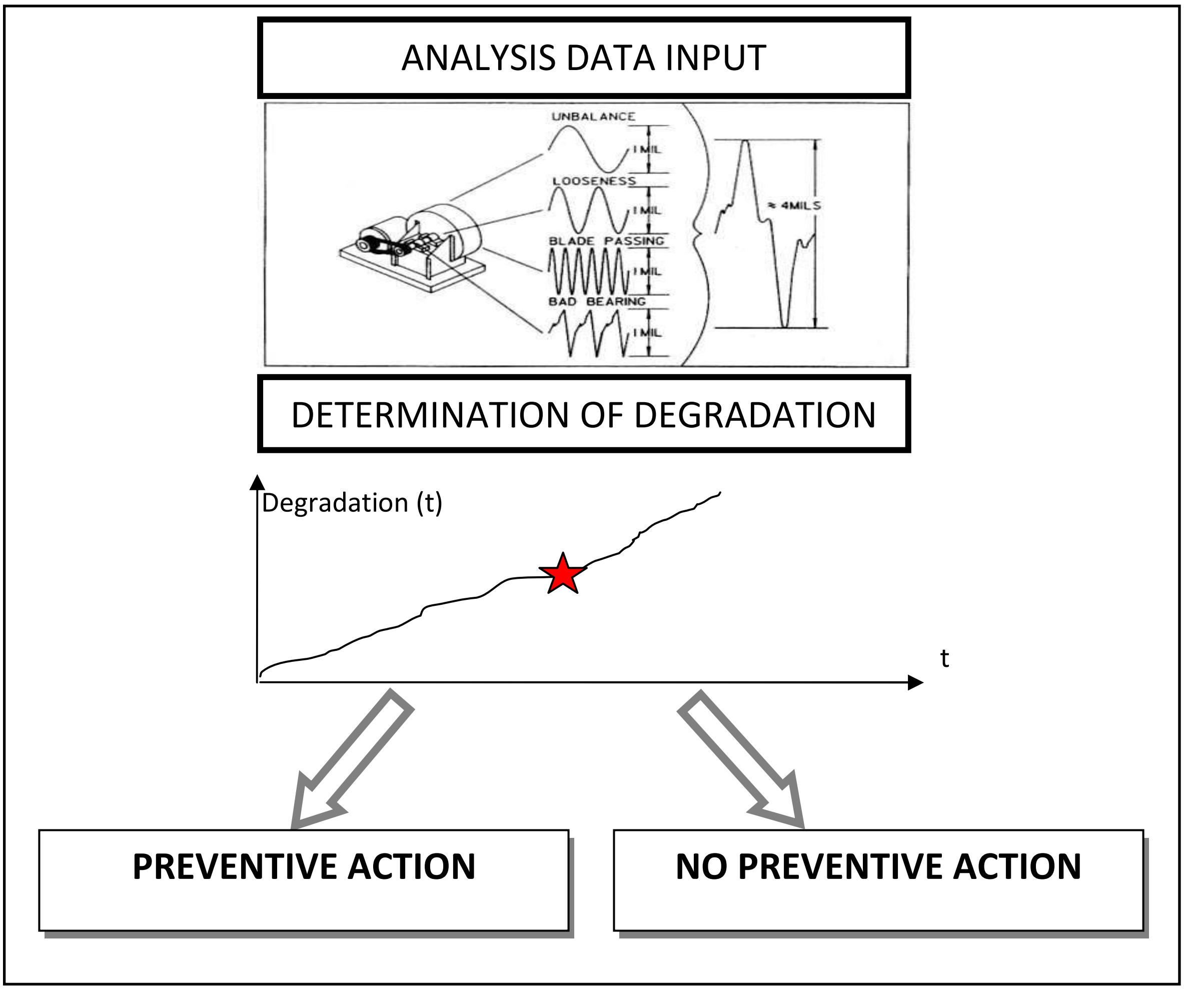


Figure 8

2.5 Advantages Of Condition Based Maintenance

The advantages that the implementation of a CBM policy on maintenance could bring are:

- CBM is performed while the asset is working, this lowers disruptions to normal operations;
- Reduces the cost of asset failures;
- Improves equipment reliability;
- Minimizes unscheduled downtime due to catastrophic failure
- Minimizes time spent on maintenance;
- Minimizes overtime costs by scheduling the activities
- Minimizes requirement for emergency spare parts;
- Optimized maintenance intervals (more optimal than manufacturer recommendations);
- Improves worker safety;
- Reduces the chances of collateral damage to the system.

But this advantages are compensated for the following disadvantages:

- Condition monitoring test equipment is expensive to install, and databases cost money to analyze;
- Cost to train staff – you need a knowledgeable professional to analyze the data and perform the work;
- Fatigue or uniform wear failures are not easily detected with CBM measurements;
- Condition sensors may not survive in the operating environment;
- May require asset modifications to retrofit the system with sensors;
- Unpredictable maintenance periods.

2.5 Vibration Monitoring

Rotating equipment such as compressors, pumps, motors all exhibit a certain degree of vibration. As they degrade, or fall out of alignment, the amount of vibration increases. Vibration sensors can be used to detect when this becomes excessive.

The vibration monitoring can have different goals:

- to evaluate if a mechanical system respects the safety standards;
- to shape the suspension of a machine, is needed take the measurement of excitatory actions that arise when the machine works .
- to find an adequate mathematical model of the mechanical system vibrant, is needed before the measure of its response to a known excitation.

The equipment to detect the vibrations comprises a transducer, an amplifier and an indicator.

2.5 Trade-Off Maintenance Costs

The first step of this project has been to evaluate if is possible to estimate a best level of the maintenance in a production system. In fact, there is a trade-off between the costs of maintenance and the costs of down time system. The sum between maintenance costs (connected to the realization of maintenance) and induced costs (which are related to the unavailability of system) is the total cost of the maintenance function.
There will a minimum in this curve, and the goal is to find it.

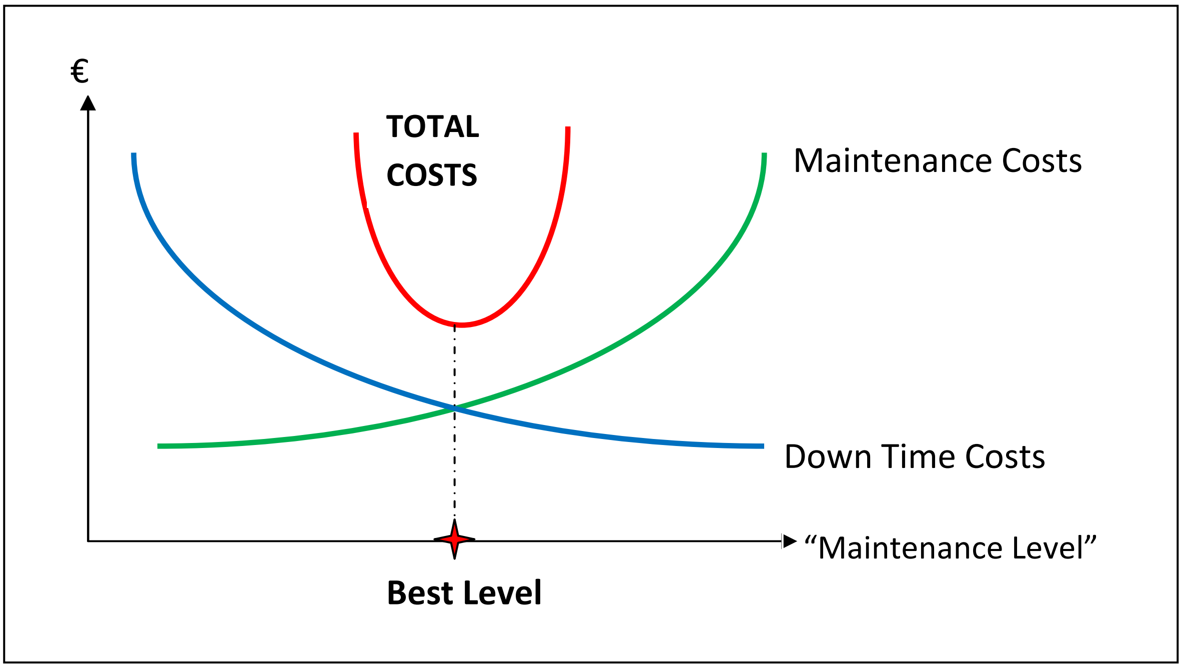


Figure 9

Chapter 3

A Condition Based Maintenance Model

Scientific research has shown a great interest for this type of maintenance. In fact many studies propose different approaches for apply a CBM.

A feature common to all models analysed, both in the case of mathematical or simulative approaches and in case of discrete or continues models, is the evaluation of thresholds maintenance that identify the value of the wear parameter in which should be done a certain action (inspection, preventive maintenance, etc.).

It was studied a polity of Condition Based Maintenance because it turned out to be the most innovative.

The CBM maintenance is becoming increasingly important because the development of advanced sensor and ICT technology makes the remote acquisition of condition monitoring data less costly, and condition data can improve diagnostics and prognostic of failures, which helps to reduce maintenance related costs further.

Furthermore this maintenance strategy, in the scientific publications analyzed, turned out to be applied in the industries of advance capital goods (e.g., aviation, renewable energy and chemical process) due to the convenience of static intervals for the operations planning and coordination of maintenance resources (e.g., service engineers, maintenance equipments, spare parts).

3.1 Degradation Analysis

The most innovative aspect of this type of maintenance, is to suppose that there is a link between degradation and failure of component.

This is certainly true and it is confirmed from many studies that showed how the bathtub curve is true only for a little percentage of all components, but the problem is how can evaluate the degradation of the component.

Assuming that is possible to determine at any given time a parameter(e.g. temperature of engine, wearing of a brake, vibrations of a FMS, etc.) that describes the wear of component, is possible to have with this type of maintenance many economical advantages.

As said before, the tools for evaluate these parameters are expensive, so this type of maintenance is possible only in some industrial business.

In a CBM maintenance the reliability of the system is studied in function of a parameter linked with the time and other characteristic aspects of the production system.

Assuming that is possible to determinate a deterioration threshold, when the wear exceeds this threshold the component enters in a period where is better to make a preventive maintenance than wait the failure, because the residual safety life of the component is lower than the overall costs of breakdown.

The following figure (10) is shown a stochastic process of degradation of a generic component prone to preventive maintenance.

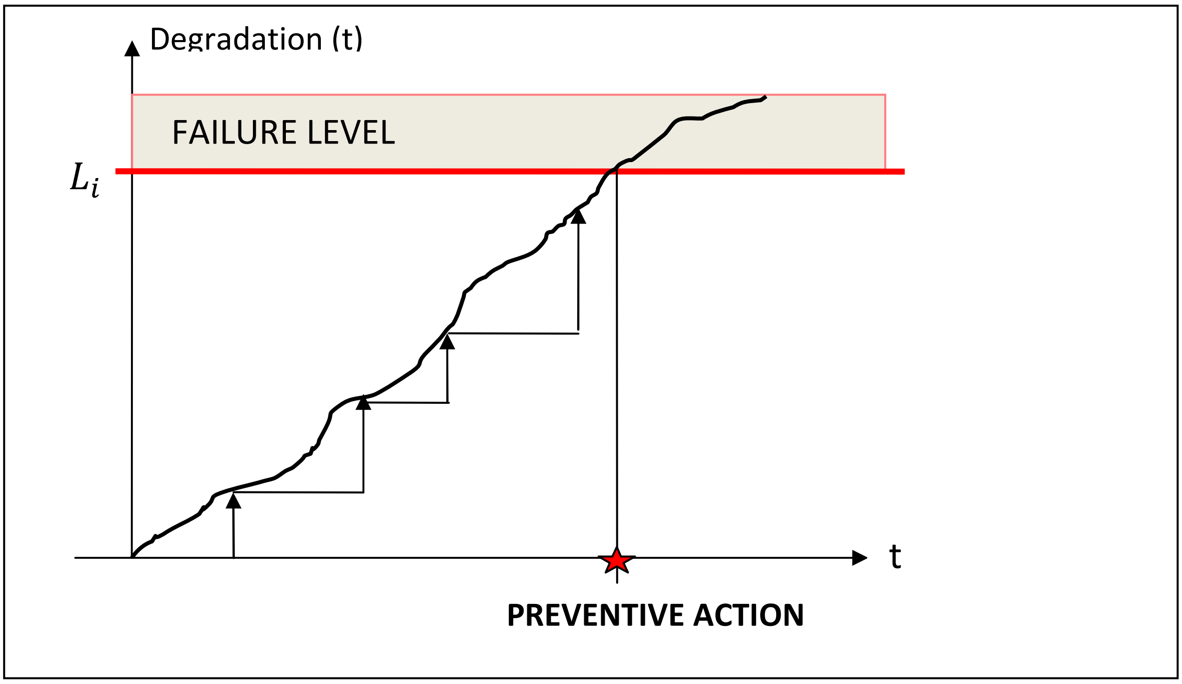


Figure 10

As in the figure (10) showed, the process of increasing of wear is a stochastic process.
In fact:

$$\Delta X(0, t_i) \neq \Delta X(t_i, t_{i+1}) \qquad \text{if } (0, t_i) = (t_i, t_{i+1}) \qquad (1)$$

The increase of wear in the same time intervals is different.

This is obvious because the increase of degradation depends mainly from two aspects:

- work condition of machine;
- work load of machine.

Namely that degradation of a system depends from the condition where it works, there will be nominal conditions that the constructor identifies where the degradation process of the machine is known. But if the machine works in different condition, the degradation process is not can be determined.

The same is for the production rate, if the machine works at the nominal rate has a degradation process known, but if it works with other rate, the degradation will be different.

In this paper the approach used is to assess the failure of a device based on the characteristics of the process that caused its failure, normally a degradation process. Such an approach is common in assessing the amount of crack, the amount of erosion, and creep, and amount of contamination. Since many devices fail because of degradation, the degradation process is some type of stochastic process.

For this reason the mathematical model that it was used to define the behaviour and the characteristics of the simulation model is a model that examines a stochastic degradation process.

3.2 Mathematical Model

The mathematical model that was studied is: “ *A CBM policy for stochastically deteriorating*” of Grall, Berenguer and Dieulle, a continuous and mathematical model that studies how is possible to apply a CBM maintenance in a system consisting of N components in series.
$I = \{1,2,3 \ldots \ldots N\}$ denotes the set of components that composed the system as shown in figure (11).

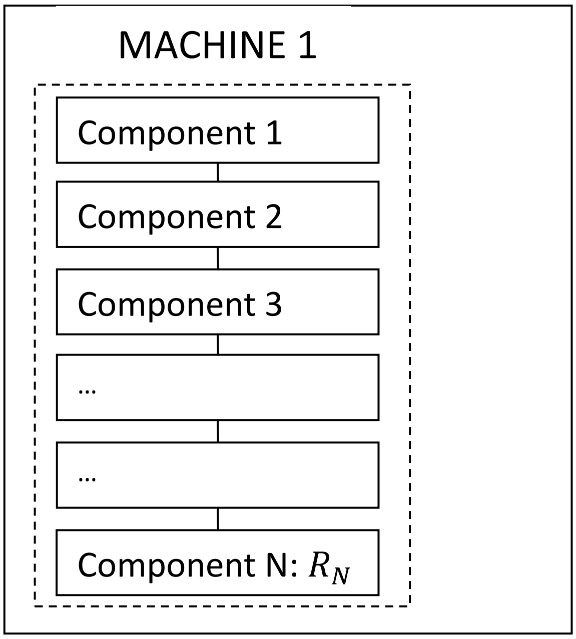


Figure 11

The reliability of a general machine composed of N components in series can be studied as a system composed of N machines in series. In the elaborate has only been studied the series because this configuration presents the greatest interdependencies between the components and the system.
In fact in this type of system when there is a failure of a component , the whole system fails.

Through this initial research, it have been possible to determinate which are the most important features that the simulation model must have.

The mathematical formulation, given in appendix (2) , provides the determination of minimum maintenance cost in function of two variables:

- τ: time interval between two inspections;
- L_i: threshold of wear for change the part.

is possible to determinate τ and Li that give me the minimum cost in function of these two variables.

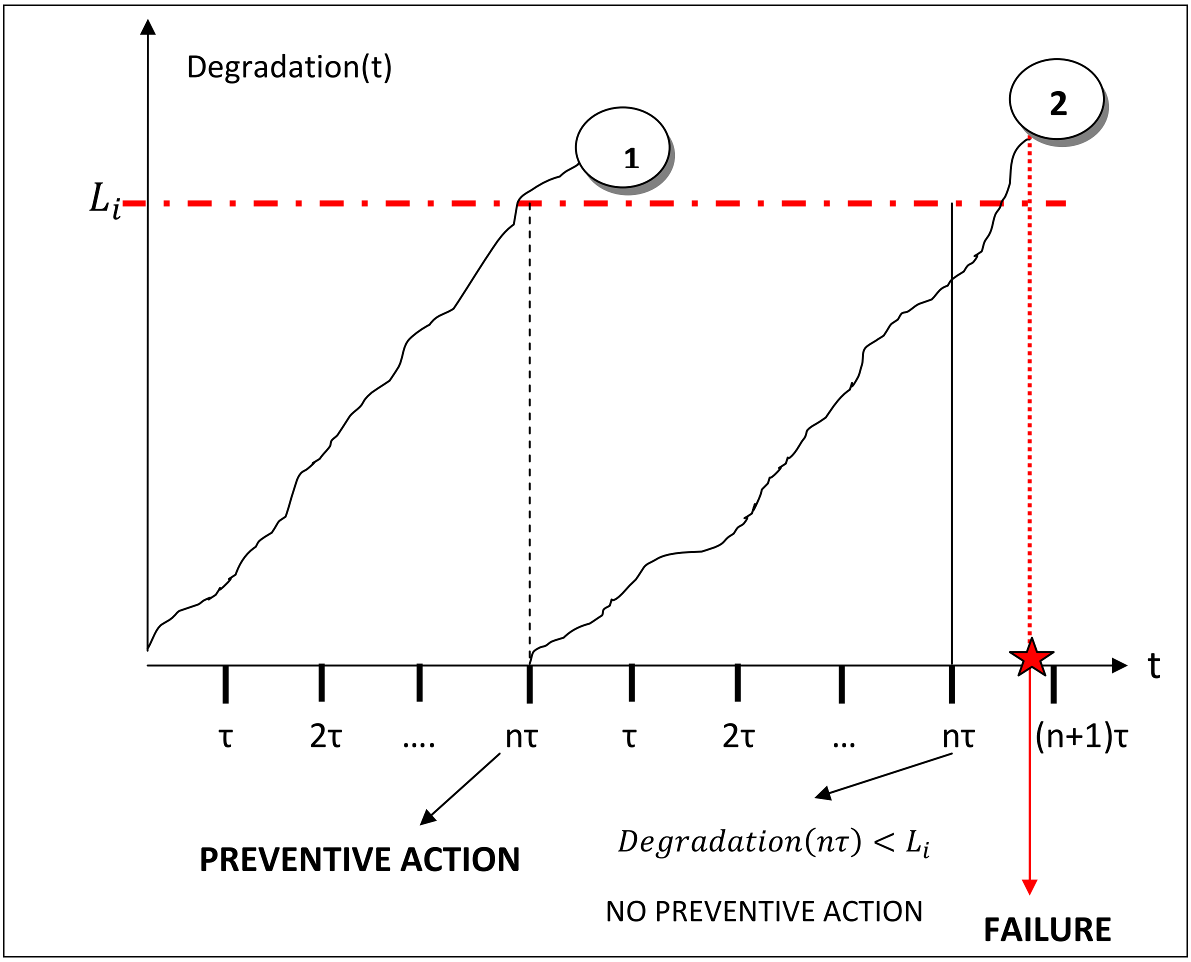


Figure 12

So is possible to indentify two case:

1. When at the inspection in nτ the degradation is higher than the threshold L_i, a PREVENTIVE ACTION will be taken in nτ.
$$Degradation(n\tau) \geq L_i \rightarrow Preventive\ Action$$

2. When at the inspection in nτ the degradation is lower than the threshold L_i , but it increases fast in the interval [nτ,(n+1)τ] and exceeds both the thresholds L_i and the threshold of failure before the next inspection at the time: (n+1)τ, a CORRECTIVE ACTION will be taken.
$$Degradation(n\tau) < L_i \rightarrow NO\ Preventive\ Action$$

The figure (12) shows two aspects:

1. When is carried out a PM action, the component has a residual service lifetime but it is substitute before the failure. In this case it is lost money related to the residual service lifetime of the component which is not used.
2. When is carried out a CM action, the component has not a residual service lifetime, but there will be an overall cost of breakdown.

In fact to determinate the threshold L_i, it must to solve a trade-off between the residual service life of the component in money and the overall cost of a breakdown, as the following figure(13) shows.

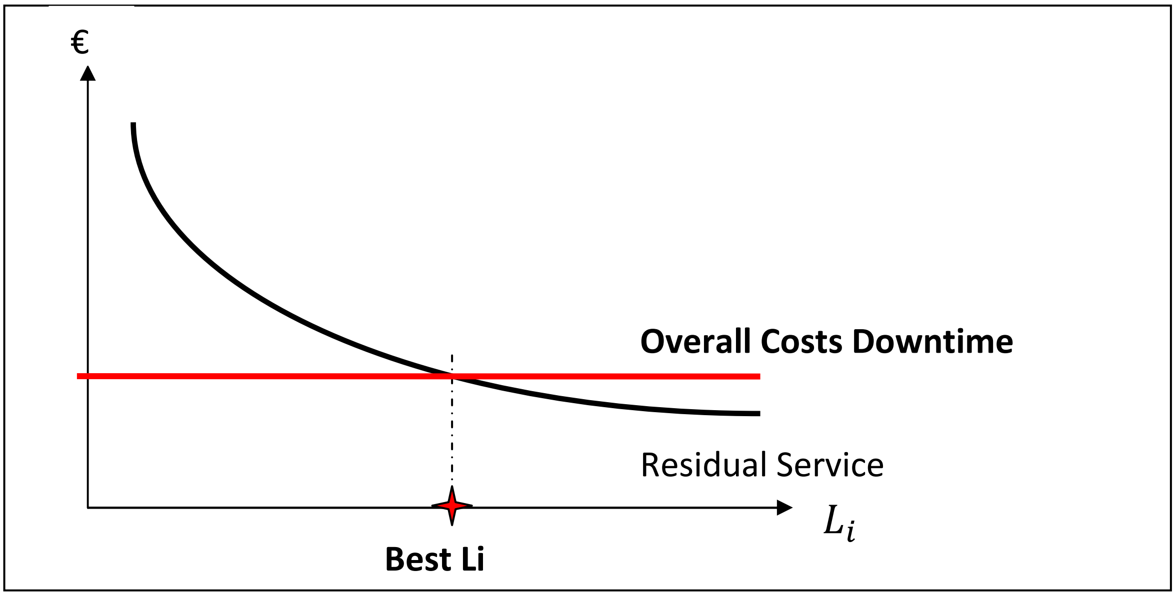


Figure 13

The value of L_i is function of the overall cost of downtime. More is high the overall cost downtime and lower is the value of L_i, and therefore the component is changed when it have yet high residual service lifetime.

As explained in the previous pages, the most important parameter that influences which type of maintenance have to realise, is the overall cost of downtime.

For overall cost of downtime :

•high→PREVENTIVE MAINTENANCE;

•low →CORRECTIVE MAINTENANCE.

For Overall Costs Downtime is defined the total cost that we have more if the production system have a stop.

Chapter 4

SIMULATION IN MANAGEMENT DECISION MAKING

In today’s competitive business climate, careful planning and analysis of alternative strategies and procedures are essential. In an effort to derive maximum benefit from available resources , engineers and business planners have made mathematical and computer modelling an important part of their planning activities. Among these modelling techniques , simulation has experienced a particularly dramatic increase in popularity because of its broad range of applicability.

Simulation is simply the use of a computer model to “mimic” the behaviour of a complicated system and thereby gain insight into the performance of that system under a variety of circumstances.

Simulations are often used to determinate how some aspect of a system should be set up or operated.

The discrete-event simulation describes system that are assumed to change instantaneously in response to certain sudden or discrete events or occurrences.

When we choose to model a real-world system using discrete-event simulation, we give up the ability to capture a degree of detail that can only described as smooth continuous change. In return, we get a simplicity that allows us to capture the important features of many system that are too complex to capture with continuous simulation.

Simulation Model

Create a model that reproduces the behavior of a complex production system subject to maintenance on condition represents a test, whose complexity is linked to the presence of many variables associates and employees , such as for example:

- Wear parameters of the system components,
- Deterioration's laws of the components, and trend of this parameters in time;
- Number and relationships of physical and logical connection between the components,
- Relationship between the wear and failure,ect.

In this dissertation, the simulation approach was preferred at the mathematical approach, because with a simulation software is possible to realize a complex model that has a behaviour closer to the reality.

The wear is identified as parameter of aging characterized by a continuous and non-decreasing trend in the time. It was decided to model the wear with different distributions, in order to identify which was the one that reflects the real behavior. It is supposed that a component can be considered fault if the wear parameter exceeds a certain threshold. This hypothesis appears to be significantly distant from experience, because the fault is an event that can be linked to the wear of the component but whose time of occurrence is a random variable. Therefore, the probability of failure has been patterned by a distribution of Weibull, not linked to the time, but to the parameter of wear, as appears more correct from logical point of view.

4.1.1 Metamodel

In this model, it was studying a general system composed of N components.

The main objective of the work was to build a model that was valid to more industrial areas. For do this, it was studied a system composed of N components in series. It was studying only the series because it is the most important from the point of view of reliability.

The difficulties found concern the fact that it is impossible to perform a simulation with Arena and a consequent optimization leaving not fixed, but variable, a number N of elements. For this, we thought to build a modular model that represents only one general system, but changing some variables is apply to many production system.

In the model it was evaluated the production logic and the maintenance logic together.

It was impossible to build only one model for simulate the both logics because the entities in the production system model are work pieces while in maintenance model are preventive or corrective maintenance requests.

For this it was build a model formed by three sub-models, how shown in the figure (14):

- one to simulate the maintenance system;
- one to simulate the production system;
- and one to link the two previous sub-models, that we called sub-model of connection.

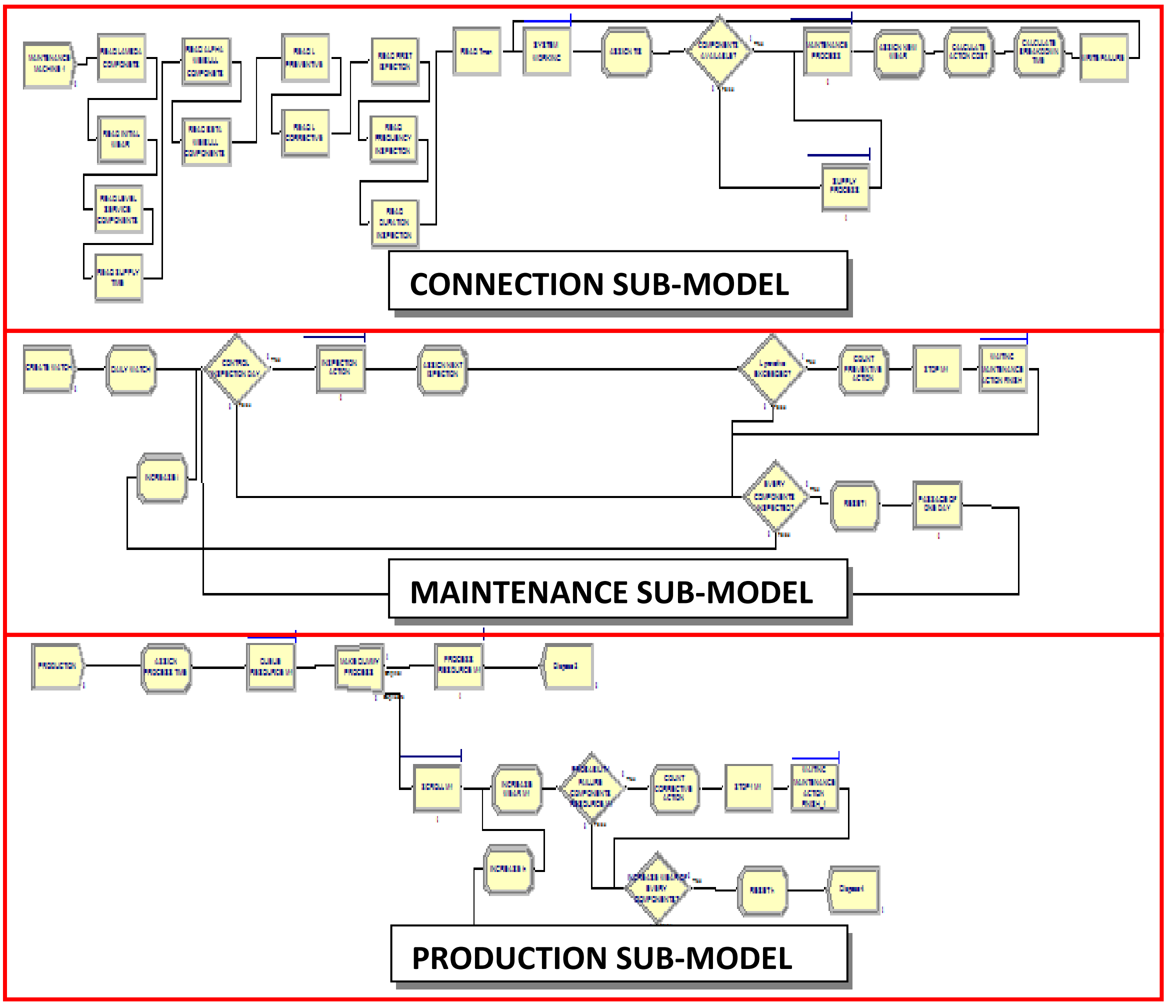


Figure 14

4.2 .1 The Logic Of The Model

As already mentioned, the model is split in three sub-models. For each of them, the entities that flow in the logic are different.

In fact in the connection sub-model there is only a entity that representing the machine, in the maintenance sub-model there is only a entity that representing an inspection request, while in the production sub-model there are more entities that representing work pieces. In sub-models of connection and maintenance there is only a entity that flow in a closed loop. This choice has permitted to have a model more simply and less “heavy" in the computational point of view.

In the following figure (15) , it was showed the model’s logic.

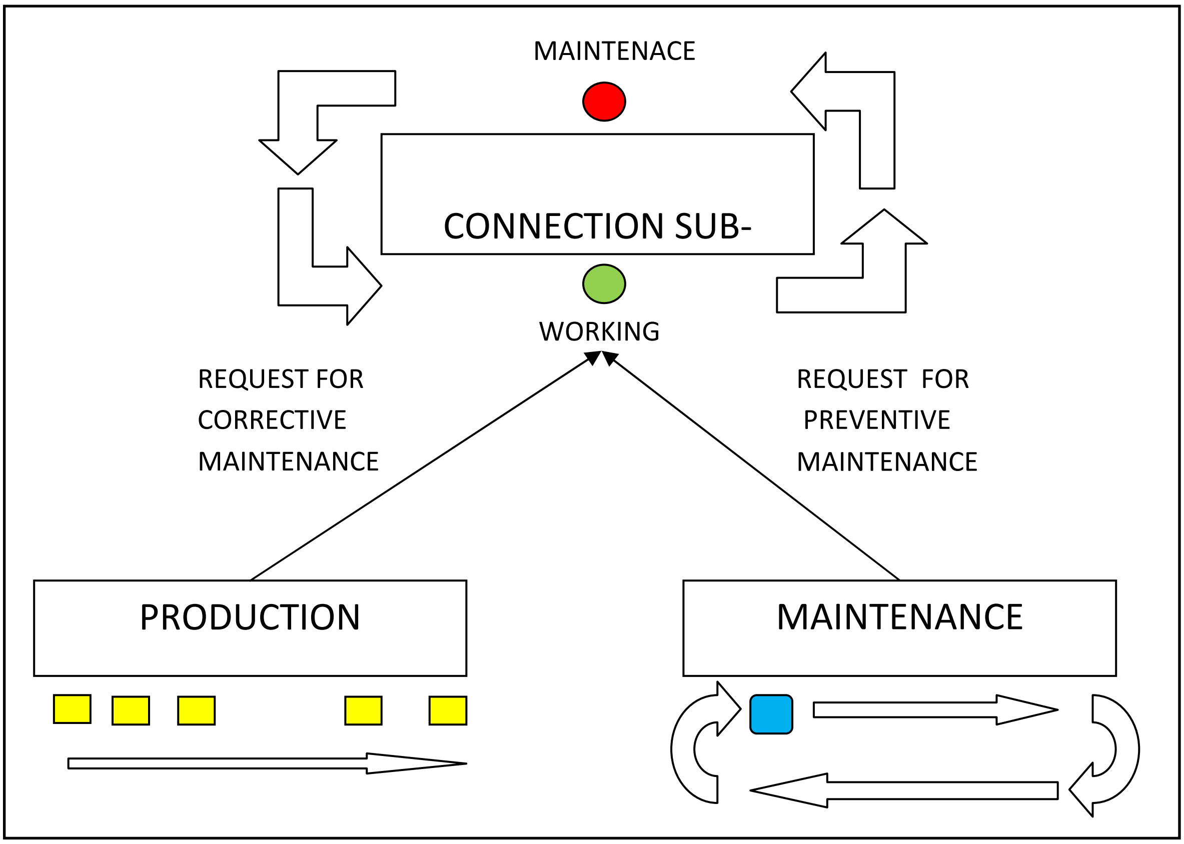


Figure 15

The production sub-model is in open loop, where with a rate of arrival known, the entities flow from a *Create* module to a *Dispose* module after have been passed the production logic.

When a failure occurred, this sub-model throws a signal to the sub-model of connection that handles the request.

At the same way, the maintenance sub-model, that have a closed loop logic, when after an inspection determines a degradation level higher than threshold L_i, throws a signal to the sub-model of connection.

The signal derived from the maintenance is a preventive action request, while the signal derived from production is a corrective action request. Both the requests generate a state change of the entity, that from the working state passes to the maintenance state.

When finishes the maintenance action , the entity returns to the working state. So it flows in a closed loop, changing its state from working to maintenance and from maintenance to working.

4.2.2 Connection Sub-Model

This sub-model have a “closed loop” logic, where only an entity flows in the modules. This entity represent the machine or the system object of study.

There are two possible state of this entity:

- Machine WORKING;
- Machine MAINTENANCE;

In the initial state, it supposed that the machine is working. This choice simplifies the model and permits a study more realistic.

When after an inspection, the degradation level is higher than the threshold L_i, the maintenance sub-model send a signal to the connection sub-model, that handle the maintenance process. When instead after the inspection, the degradation is less than L_i , the control logic does not make nothing and the machine continues to work.

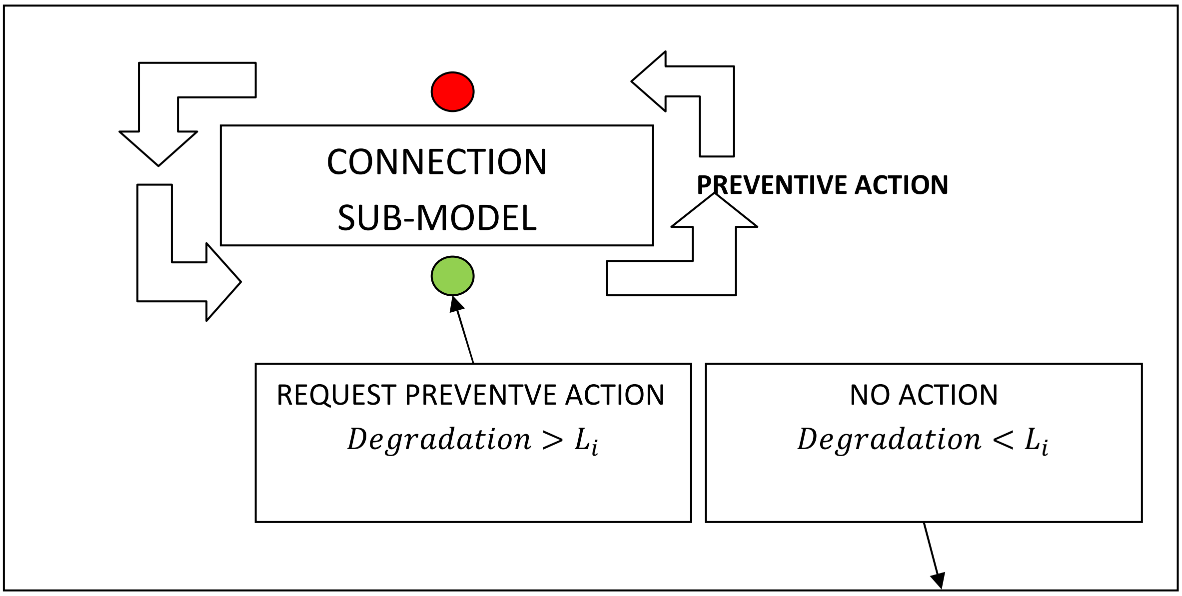


Figure 16

In this way, after an inspection is possible to indentify two case:

•If $Degradation < L_i$ →No ACTION.
•If $Degradation \geq L_i$ →PREVENTIVE ACTION.

The request of maintenance can arrive:

1. after an inspection;
2. when the degradation exceed the threshold of failure before of an inspection;
3. when a random failure occurs.

When arrive a request of maintenance from the production sub-model, it is a corrective maintenance action.

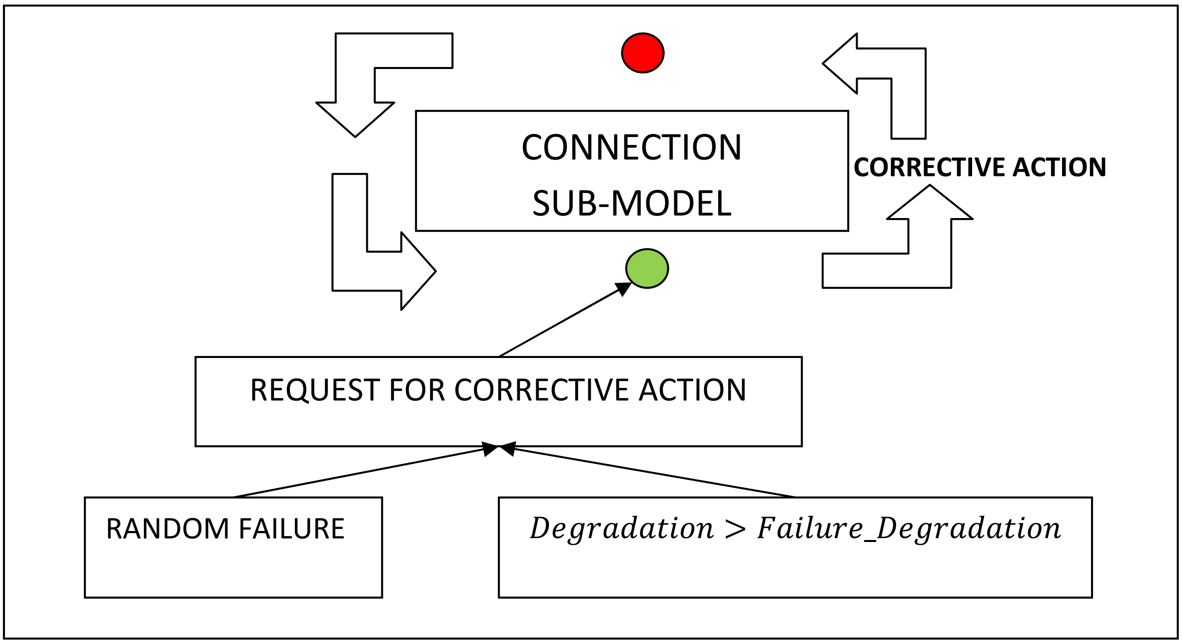


Figure 17

4.2.3 Maintenance Sub-Model

In this sub-model the entity symbolizes an inspection request, and it is recycled for all time of simulation. In a real context it is impossible, but in this way it was possible to overcome on the limits of the student version of Arena(limit about the number of entity).

Through *Decide* modules this entity produces inspection requests in function of a scheduling read from an external file of Excel.

After an inspection if the wear exceeds the threshold L_i , a signal has sent to the connection sub-model, which it provides to replacement the part, while if the wear is lower of the threshold, the entity flows into the closed loop and evaluates the next inspection defined in the scheduling.

This sub-model reads the scheduling of inspections, performs the inspection in function of the schedule, and carries out a request of maintenance after an inspection when the wear of the component has a value higher of the threshold of preventive maintenance.

Therefore the goals of this sub-model are:

- count the time and evaluate when is the moment to achieve an inspection, in function of the schedule,
- read the wear parameter and determine if is necessary a preventive action or not;
- send a signal to the sub-model of connection if the wear is higher of the preventive threshold;
- wait that preventive action is finished before to make a new inspection of one other component.

4.2.4 Production Sub-Model

In the production sub-model the entities flow in a open-loop and arrive with a ratio that is given from an external input.

This ratio is the production rate of the system.

The production is simulated with a module *Process* that takes up the machine for the production time.

If the logic control,determines a value of degradation higher than the value of failure of the component, it throws a signal to the connection sub-model and the production is stopped.

The same is made when arrives a random failure.

When the machine is in maintenance, the work pieces enter in a module *Hold* that representing a queue.

When the maintenance process is finished, a signal from the connection sub-model is threw to the production, that can restart to work.

In this way it was been possible to shape the input buffer in function of:

- production rate of the system;
- time of maintenance of the system.

As explained in the previous pages, the objective of the study it was been to build a model more general possible that was applicable in different business companies.

In this mode we defined a general simulation model that with the change of the input variables it could be apply to make many considerations about the initial planning of the factory.

Description Data Input

In this chapter we were described the input data of the simulation model. All inputs data are read from an external file to give generality and modularity at model.

4.3.1 Failure Rate

To build a general model that was applicable to many different industrial areas,all inputs are read from an external file of Excel.
In this way, it was possible to make a general model that with a change of the variables can be applied to solve many problem.
It was assumed that in some way is possible to calculate the Rate Failure of each components. Is possible to have this data if the company have a management software like a CMMS: Computer Maintenance Management System, with it the company can have track of every failures of the system. In fact with a CMMS, the information about every failure of production system are tracked in the software.
It was supposed that when the production system has a failure,is possible to input in CMMS the istant of failure,namely the parameter:

- ttfi: time to failure component it

Then with many different algorithms, present in many scientific publications , can be determinate the parameter: λ(Rate Failure) for every components.

The following figure(18) shows the scheme of application three different algorithms:

1. DM: Direct Method ;
2. IDM: Improved Direct Method ;
3. RM: Ranked Method .

The explanation of these three methods is beyond the scope of this study.
It have been study these alghoritms only to build a procedure to determinate a maintenance plan.

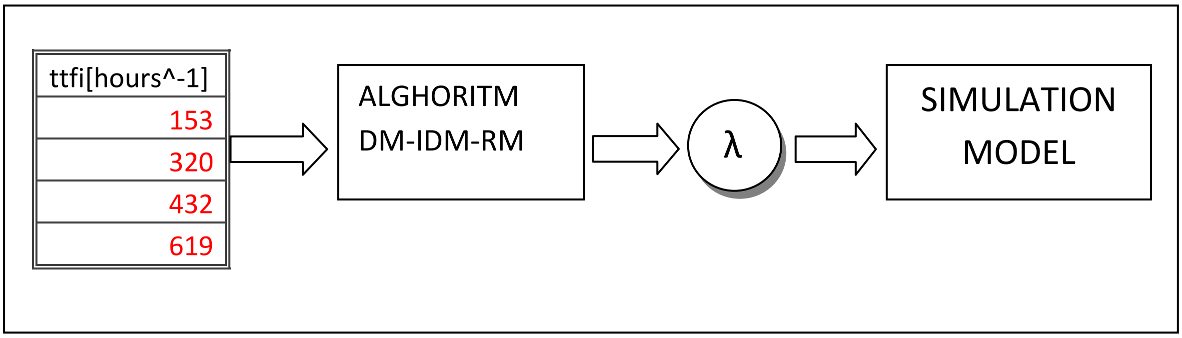


Figure 18

In the appendix (1) is shown an example of application of these three algorithms.
The parameter λ is used like a input data to simulate the random failures of the system. In fact, from the probability theory[7]:

$$\begin{cases} MTTF = \frac{1}{\lambda} \quad \text{[hours]} \\ \quad \text{If } \lambda\text{=constant} \end{cases}$$

---

[7] Statistical Theory of Reliability and Life Testing: Probability Models (1975)

So if the component is in service life and it has a failure rate constant, the MTTF: *Mean Time To Failure* is defined in this mode.
In this way, there will a logic in the production sub-model that will generate a failure every MTTF hours.

In the following table(1) it is showed how is possible to calculate the parameter λ.
In fact, if the company have a CMMS that tracks of the failures of each component, is possible to estimate λ.

$$MTTF = \frac{AVAILABLE\ TIME\ production\ system}{FREQUENCY\ of\ failure\ component} \left[\frac{\frac{hour}{year}}{\frac{failure}{year}}\right] = \left[\frac{hour}{failure}\right]$$

$$\lambda = \frac{1}{MMTF}[hour^{-1}]$$

CODEX COMPONENT	sum duration stops [min]	sum duration stops [hours]	frequency of the stops	MDT: mean down time [min]	MTTF[hours]	λ[h^-1]=1/MTBF
M1-01	159	2.65	11	14.45	727.27	0.0014
M1-02	234	3.9	9	26.00	888.89	0.0011
M1-03	74	1.23	6	12.33	1333.33	0.0008
M1-04	103	1.72	3	34.33	2666.67	0.0004
M1-05	127	2.12	6	21.17	1333.33	0.0008
M1-06	245	4.08	11	22.27	727.27	0.0014
M1-07	121	2.02	15	8.07	533.33	0.0019
M1-08	21	0.35	7	3.00	1142.86	0.0009
M1-09	36	0.60	5	7.20	1600.00	0.0006
M1-10	45	0.75	9	5.00	888.89	0.0011
M1-11	78	1.30	13	6.00	615.38	0.0016
M1-12	95	1.58	11	8.64	727.27	0.0014
M1-13	36	0.60	1	36.00	8000.00	0.0001
M1-14	258	4.30	24	10.75	333.33	0.0030
M1-15	301	5.02	23	13.09	347.83	0.0029

Table 1

4.3.2 Frequency Of Inspection

Same as the failure rate λ, the frequency of inspection and the date of first inspection are read from an external file of Excel.

The maintenance sub-model reads the date of the first inspection and when the simulation's watch arrive to this date, it makes an inspection.

At the same way , for every time interval equal to the frequency of the inspection, repeats the inspection for the component.

CODEX COMPONENTS	Date FIRST ispection	Day of year of FIRST ispection	Frequency inspection [days]	Tisp [min]
1	07/01/2015	7	7	10
2	08/01/2015	7	7	10
3	09/01/2015	7	7	10
4	10/01/2015	7	7	10
5	11/01/2015	7	7	10
6	12/01/2015	7	7	10
7	13/01/2015	7	7	10
8	14/01/2015	7	7	10
9	15/01/2015	7	7	10
10	16/01/2015	7	7	10
11	17/01/2015	7	7	10
12	18/01/2015	7	7	10
13	19/01/2015	7	7	10
14	20/01/2015	7	7	10
15	21/01/2015	7	7	10

Table 2

So in the maintenance sub-model , the entity flows in a closed-loop, and it becomes a request of inspection when arrive the date of inspection for the component.

When for one day , there are not inspections to make, the entity flows in a loop and go to the next day.

4.3.3 Degradation Parameter

To evaluate the degradation of the component, the model reads from an external file, shown in table (3) , the following parameters:

- Initial wear →the initial degradation of the component.
- L preventive → the threshold of preventive action.
- L failure →the threshold of corrective action.

The initial wear is supposed equal to zero, therefore the component is new , when start the simulation.

λ costant	**L preventive (% wear)**	**L failure (% wear)**	**Initial Wear**	**Num hours for exceed Lp**	**Num days for exceed Lf**	**ρ=Lp/Lf**
0.0013	**0.9**	**1**	**0**	**692.307**	**32.05128205**	**0.9**
0.0013	**0.9**	**1**	**0**	**692.308**	**32.05128205**	**0.9**
0.0013	**0.9**	**1**	**0**	**692.308**	**32.05128205**	**0.9**
0.0013	**0.9**	**1**	**0**	**692.308**	**32.05128205**	**0.9**
0.0013	**0.9**	**1**	**0**	**692.308**	**32.05128205**	**0.9**
0.0013	**0.9**	**1**	**0**	**692.308**	**32.05128205**	**0.9**
0.0013	**0.9**	**1**	**0**	**692.308**	**32.05128205**	**0.9**
0.0013	**0.9**	**1**	**0**	**692.308**	**32.05128205**	**0.9**
0.0013	**0.9**	**1**	**0**	**692.308**	**32.05128205**	**0.9**
0.0013	**0.9**	**1**	**0**	**692.308**	**32.05128205**	**0.9**
0.0013	**0.9**	**1**	**0**	**692.308**	**32.05128205**	**0.9**
0.0013	**0.9**	**1**	**0**	**692.308**	**32.05128205**	**0.9**
0.0013	**0.9**	**1**	**0**	**692.308**	**32.05128205**	**0.9**
0.0013	**0.9**	**1**	**0**	**692.308**	**32.05128205**	**0.9**
0.0013	**0.9**	**1**	**0**	**692.308**	**32.05128205**	**0.9**

Table 3

In the file there is the parameter ρ that is defined as:

$$\rho = \frac{L\ preventive}{L\ corrective}$$

It is reported because in the optimization of the model, it was studied how changes the total cost in function of this parameter.

4.3.4 Service Level

Service level measures the performance of a system. Certain goals are defined and the service level gives the percentage to which those goals should be achieved.

In this case the service level determinate how many times there is the spare part in the warehouse after a failure.

So it can be defined for each component in the following mode:

•Service Level: probability to find the spare part in the warehouse, after the breakdown of the component.

CODEX COMPONENT	SERVICE LEVEL [%]	SUPPLY TIME [min]
1	90.0000	100.00000
2	90.0000	100.00000
3	90.0000	100.00000
4	90.0000	100.00000
5	90.0000	100.00000
6	90.0000	100.00000
7	90.0000	100.00000
8	90.0000	100.00000
9	90.0000	100.00000
10	90.0000	100.00000
11	90.0000	100.00000
12	90.0000	100.00000
13	90.0000	100.00000
14	90.0000	100.00000
15	90.0000	100.00000

Table 4

In the table(4) it shown the data input related to the Service Level and the Supply Time. In fact in the simulation model when a component fails, with a percentage equal to the SL, the spare part is in the warehouse, and with a percentage equal to (1-SL) it is not in the warehouse and a supply time is needed.

The table(4) is only an example, in fact is impossible that all components have the same SL and supply time.

In a real context and in a company with an innovative way to make the maintenance, there will be a study for each component of the system (or for each machine) and the Service Level will be defined in function of:

- cost of component (if it is high ,the spare part in the warehouse is an fixed financial asset);
- supply time (if it is high, is better to have it in the warehouse the spare part);
- induced failure on the system (if when a failure of the component induces the failure of system whole, is better to have a spare part).

4.3.5 Data Input Diagram

As already definite in the previous paragraphs, the input data of the model are:

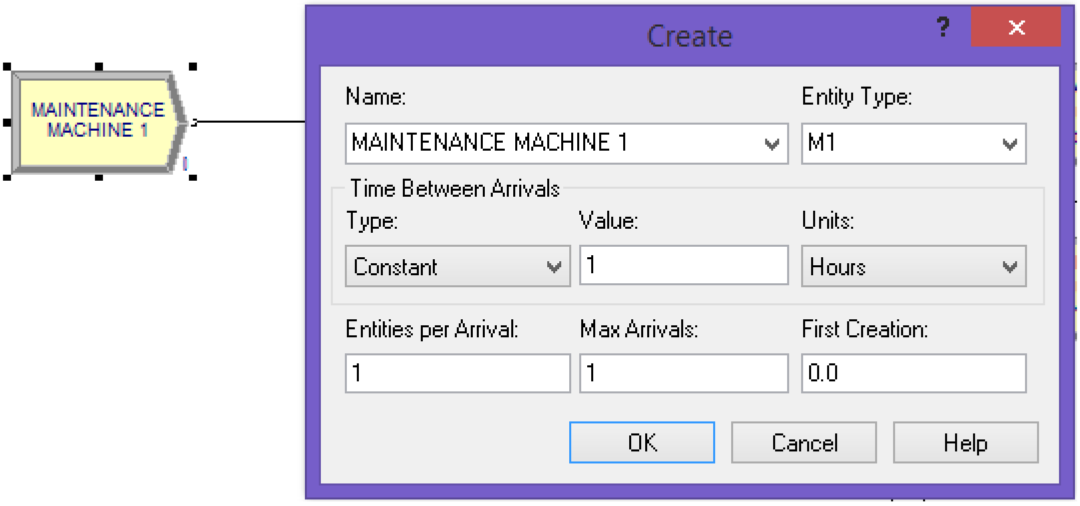
- λ : Failure rate;
- day of the first inspection;
- frequency of inspections;
- initial degradation;
- L preventive;
- L failure.
- Service Level.

In the simulation model it was evaluated how changes the output in function of the input.
Especially the objective of the dissertation it has been to check on which variables have more impact in the choice of the maintenance strategies.
In fact without a real application, the goal of the research was to determinate which characteristics are important for apply a CBM policy.
With repeated analysis in Arena, it was been possible to investigate how changes the total cost of maintenance in function of the inputs previously described.

4.3.6 The Creation Of The Entities

The creation of the entities is an input that is possible to insert from an external command in Arena.

It has been assumption that the first entity that enters in the system is the machine, that flows through more module ReadWrite in the connection sub-model and determines the features of the system.



Name: MAINTENANCE MACHINE 1
Entity Type: M1
Time Between Arrivals
Type: Constant
Value: 1
Units: Hours
Entities per Arrival: 1
Max Arrivals: 1
First Creation: 0.0

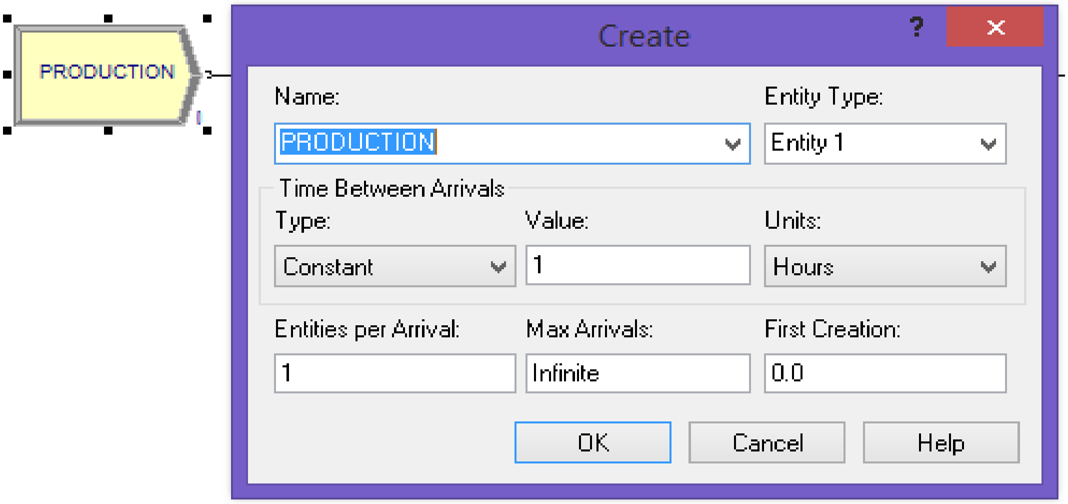
It is create only one entity when the simulation start.

The entity is called M1.

The parameter First Creation is set to 0.0 and Max Arrivals is set to 1, so when start the simulation, the model create the entity machine that flows in a closed loop for all time of analysis.

In the same way, we have in the maintenance sub-model only one entity that flows in a closed loop.

While in the production sub-model, we have more entity that flow in logic. In fact in this sub-model, the entities are a work pieces.



Name: PRODUCTION
Entity Type: Entity 1
Time Between Arrivals
Type: Constant
Value: 1
Units: Hours
Entities per Arrival: 1
Max Arrivals: Infinite
First Creation: 0.0

In production sub-model, the entities are created in fixed intervals of time equal to 1 hour and the parameter Max Arrivals is set to Infinite, so a entity is created each hour for all simulation time.

The reason to insert an inter-arrival time between two consecutive entities will be more clear when we will describe the degradation increase process.

In fact, with the goal to investigate only the maintenance of the production system, we have supposed that the degradation of the component increases every hour of work of the machine.

In this way we can examine the degradation process of the component and we can pass the limits of student version of Arena.

4.4.1 Simulation Model Description

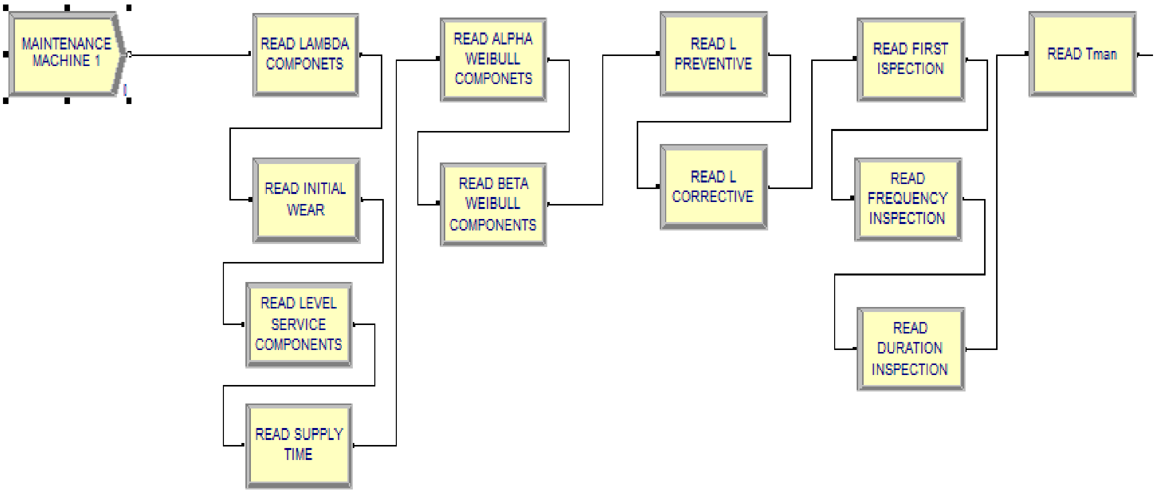
To have a more easy definition of the simulation model built with the Arena software,we divided it in more sections, each one with a different logic.
Is possible to define 6 different sections, that we describe in the following mode:

1. Reading external file;
2. System control;
3. Daily watch;
4. Phase of inspection;
5. Production logic;
6. Degradation process.

In the following pages it was illustrated each section for have a more complete description of the simulation model.
Each section have a own logic, but it is linked with the others through Boolean variables that change own value when an entity flows in the *Assign* modules.

4.4.2 Reading External Files

When the entity “machine” is created, it flows through more module ReadWrite in the connection sub-model and determines the features of the system.

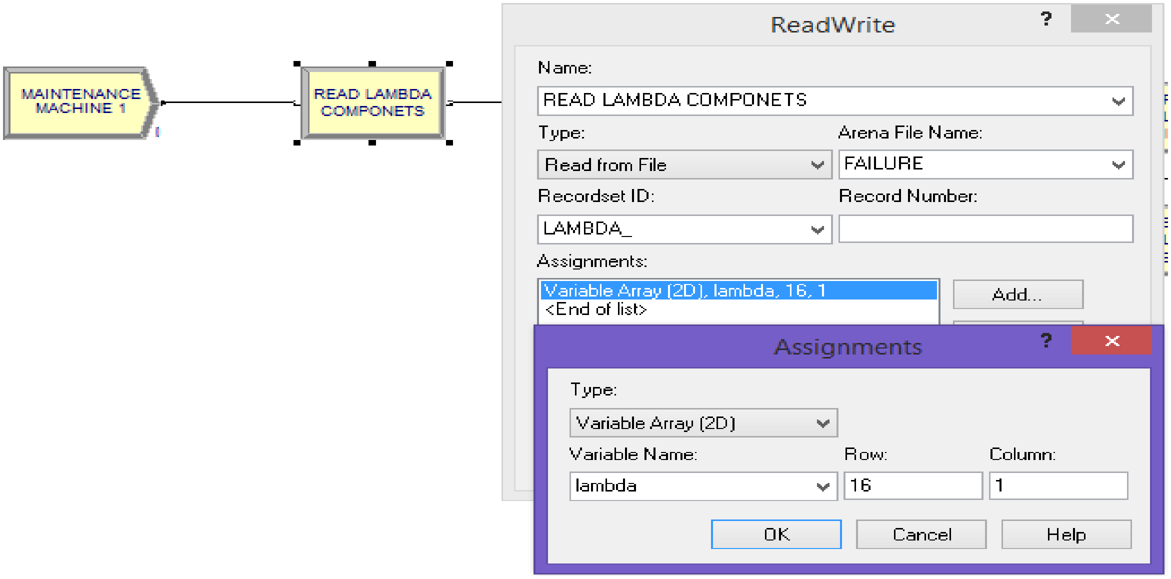


The entity reads for each components of the system, the following parameters:

- λ: failure rate of the component [hour^-1];
- Initial degradation;
- Service Level of the component [%];
- Supply time [hours]
- α and β of the Weibull Distribution of the degradation process;
- L preventive and L corrective [%];
- Date of first inspection;
- Frequency of inspections [days],
- Duration of inspection [hours];
- Duration of maintenance action [hours].

When the entity flows in the ReadWrite module, reads the parameters and writes them in an array that is used in the model.

How showed in the following figure, Arena reads the parameter λ from an external file and writes it in one array with 16 lines (the number of the components) and one column(the number of parameters).

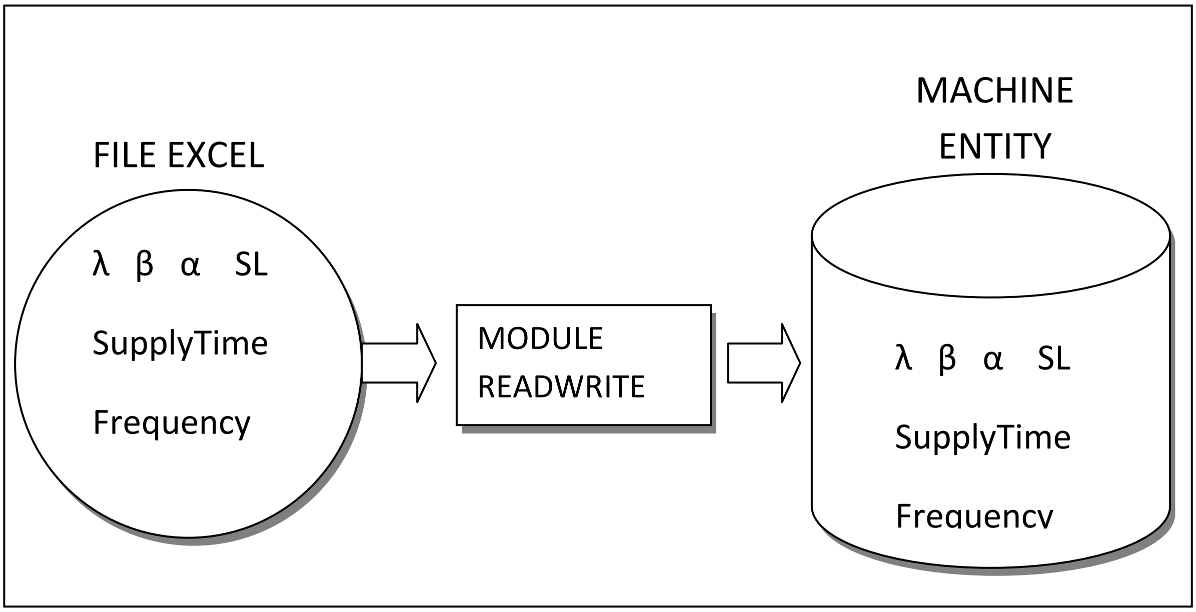


Name: READ LAMBDA COMPONETS
Type: Read from File
Arena File Name: FAILURE
Recordset ID: LAMBDA_
Record Number:
Assignments:
Variable Array (2D), lambda, 16, 1
<End of list>

Type: Variable Array (2D)
Variable Name: lambda
Row: 16
Column: 1

The software read sixteen values for each variables, but it work with only fifteen because there are problems with the last value of the array. In the input we put fifteen values, but it is possible to introduce more values in function of the number components of the system. This is possible only with a change of variable because, how explain previously, the goal of the research has been to build a general model that is possible to apply in different context.

Therefore we can definite the entity machine like a bin that contain every features of the production system.



In this way if a system has different features or if certain values are not available, the model remain valid.
Is needed to change the path of the entity, and add or remove the ReadWrite modules in function of the data inputs available.

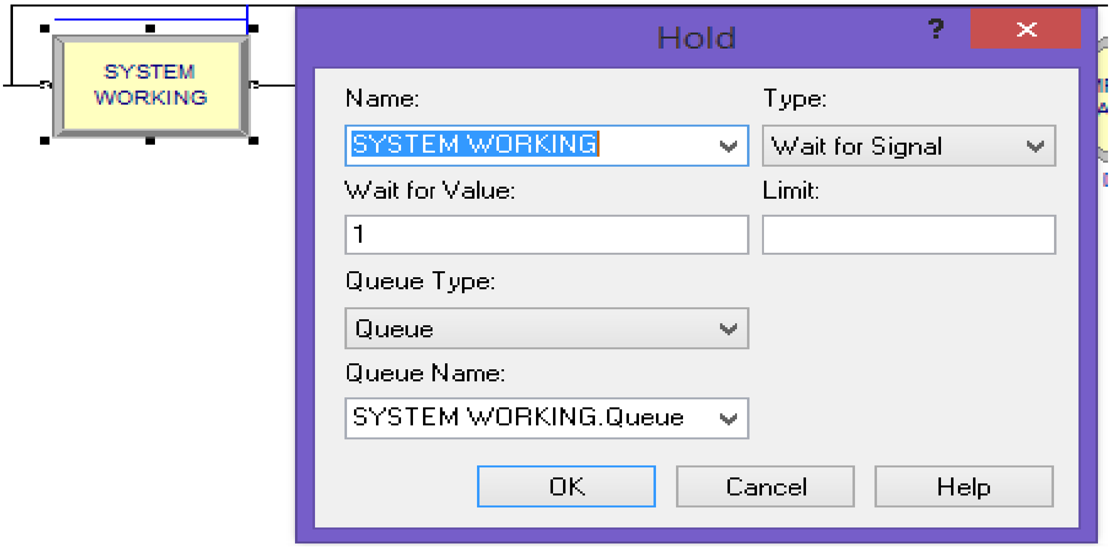
4.4.3 Control System

This section of the model is the most important because it handles the connection logic between the production and the maintenance.

When the entity *Machine* exits from the last *ReadWrite*, it flows in a *Hold* module.

When the entity is in this module it means that the machine is working, while if it exits of this module it means that the machine is failure.

This module *Hold* is set of *Wait a Signal*, so it waits a signal from the production(if there is a failure) or from the maintenance (if after an inspection is need to make a preventive action).



Name: SYSTEM WORKING

Type: Wait for Signal

Wait for Value: 1

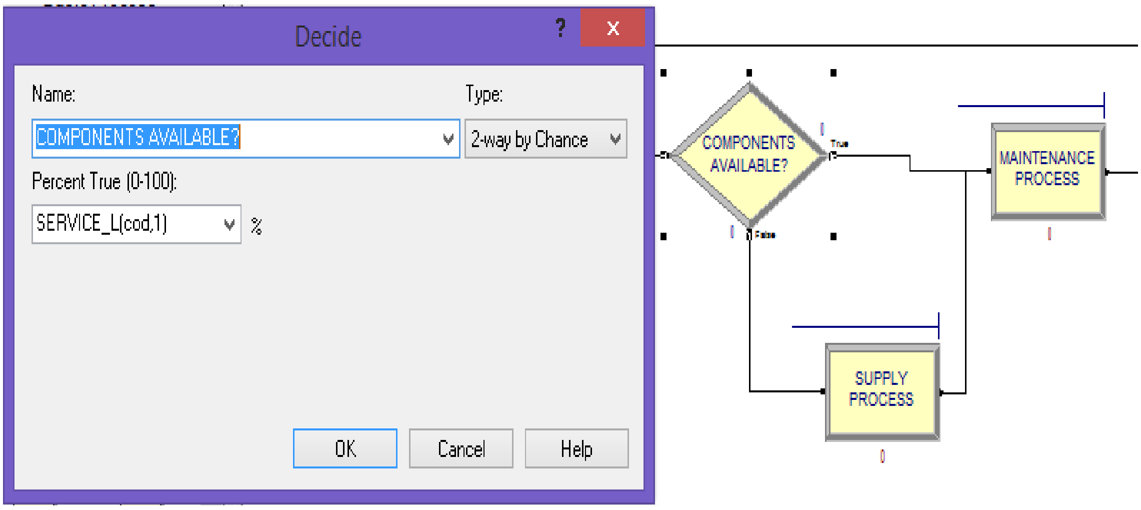
Limit:

Queue Type: Queue

Queue Name: SYSTEM WORKING.Queue

When the entity *Machine* exits from the module called *System Working*, it means that there is a preventive or corrective maintenance request. At this point the entity flows through more *Assign* module that are needed for determine the final statistics.

In this logic we have a *Decide* module that reads the probability to find in the warehouse the spare part, after a failure. If with probability equal to Service Level the spare part is in the warehouse, the system handles the maintenance action, while if the spare part there is not in the warehouse ,with probability equal to (1-SL) the system waits to finish the supply process before, and then it handles the maintenance action.



Decide

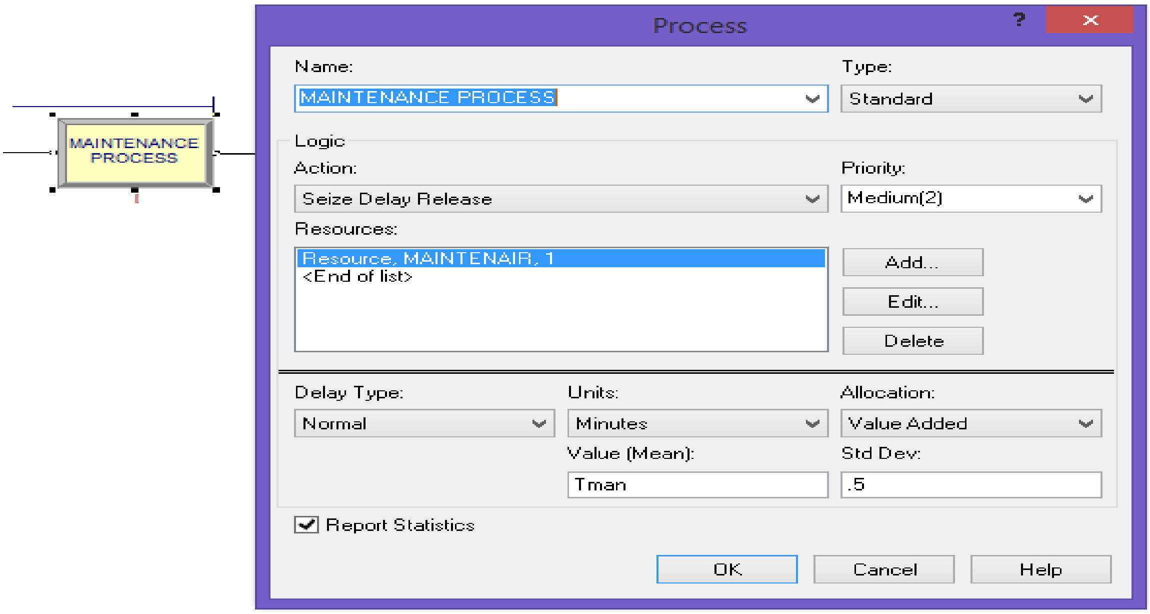
Name: COMPONENTS AVAILABLE?

Type: 2-way by Chance

Percent True (0-100): SERVICE_L(cod,1) %

In this way it has been possible to evaluate how changes the breakdown time of the system in function of the Service Level of each component. As said previously, the Service Level for each component is a value that is possible to determinate only after a specific study on your features.

The maintenance action is simulated with a *Process* module that seize a *Maintenair* resource for a time equal to *Tmain*. This last parameter is different for each component, and representing the time to change the component. It is read from an external file and is characteristic for each component.

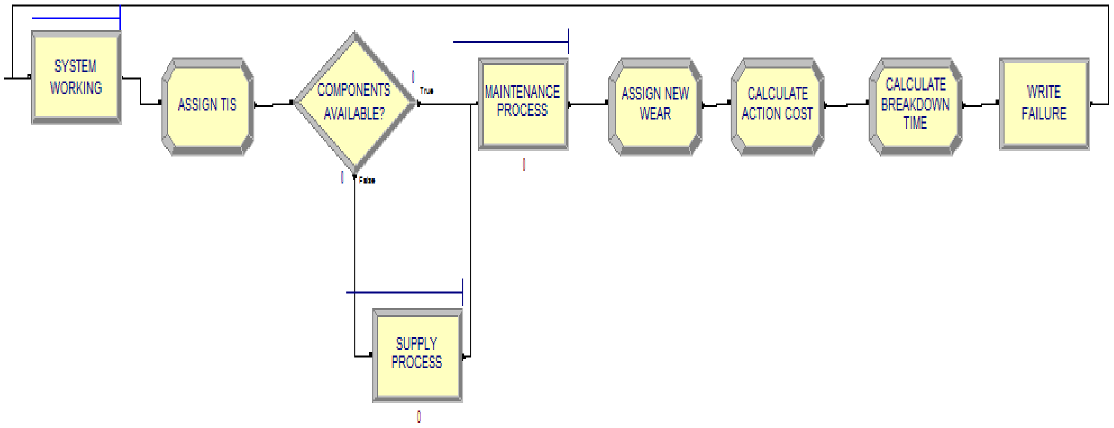


Name: MAINTENANCE PROCESS
Type: Standard
Logic
Action: Seize Delay Release
Priority: Medium(2)
Resources:
Resource, MAINTENAIR, 1
<End of list>
Delay Type: Normal
Units: Minutes
Allocation: Value Added
Value (Mean): Tman
Std Dev: .5
☑ Report Statistics

We have inserted a standard deviation to simulate that the replacement time is not a fixed time but it can change in an interval.

So when the entity exits from this module it means that the maintenance action is finished, so the Machine flows in more Assign modules, writes the data about the failure, and then returns in the Hold module that simulates machine working.

In the following figure, it is showed the complete logic of the system control.

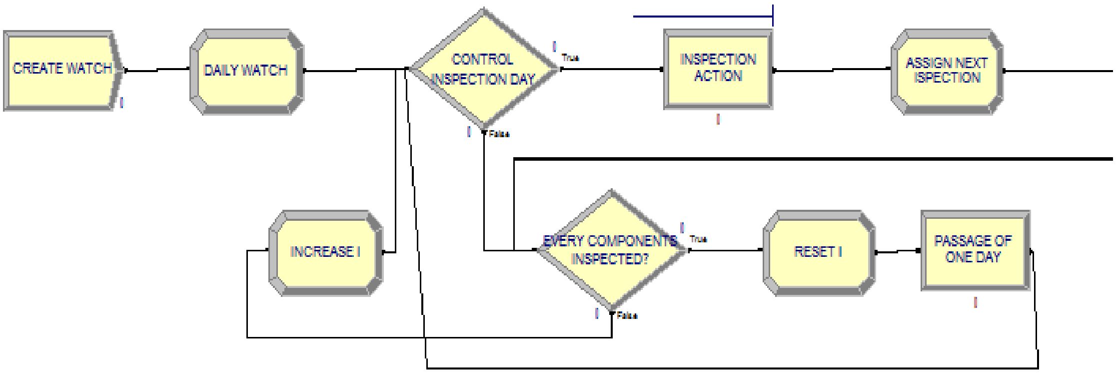


There are many Assign modules that are needed to write the final report.

In these modules more variables change the own value when the entity pass.

4.4.4 Daily Watch

This section of the model handles the inspections on the production system. The date of first inspection and the frequency, are read for each component from an external file, as before we are explained.



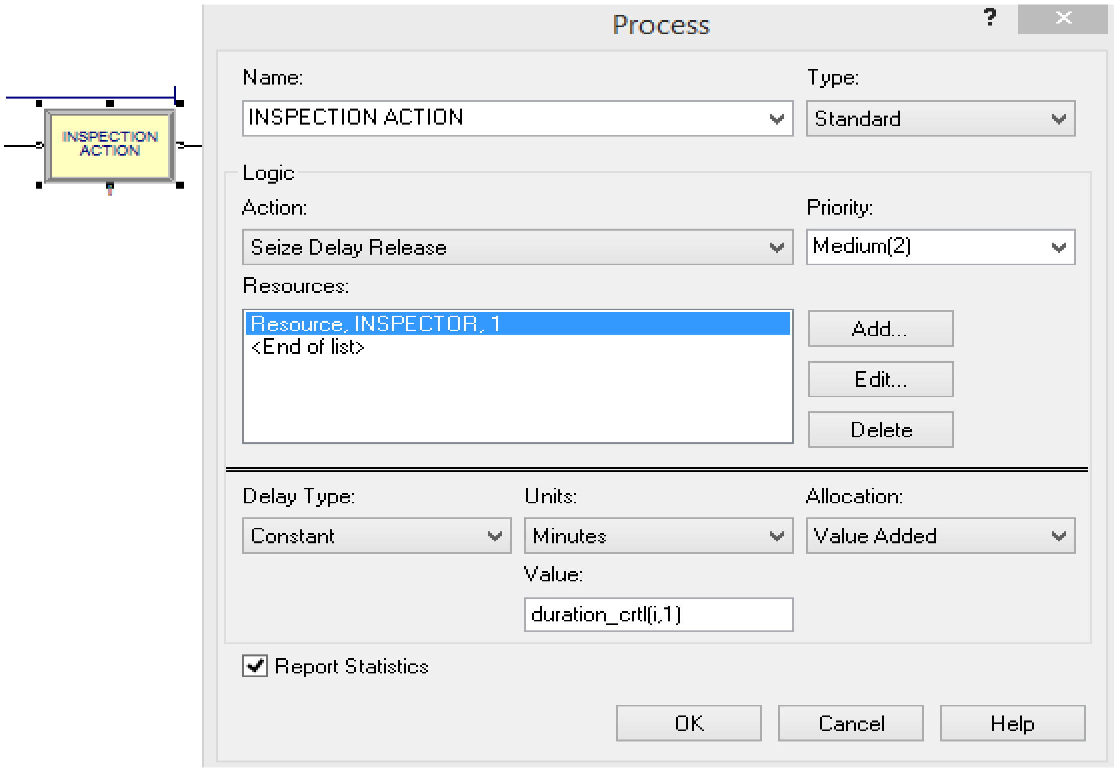
There is only an entity that flows in a closed loop. It passes across more *Deci*de module, and it evaluates if it is the day of the control for each components.

The simulation's watch calculates the time, in fact there are in Arena more variables that determinate the minute, the hour, and the day of simulation's time.

We used these variables to determinate when is the day of one inspection.

So for each day, this logic checks if there is inspection to make with a *Decide* module.

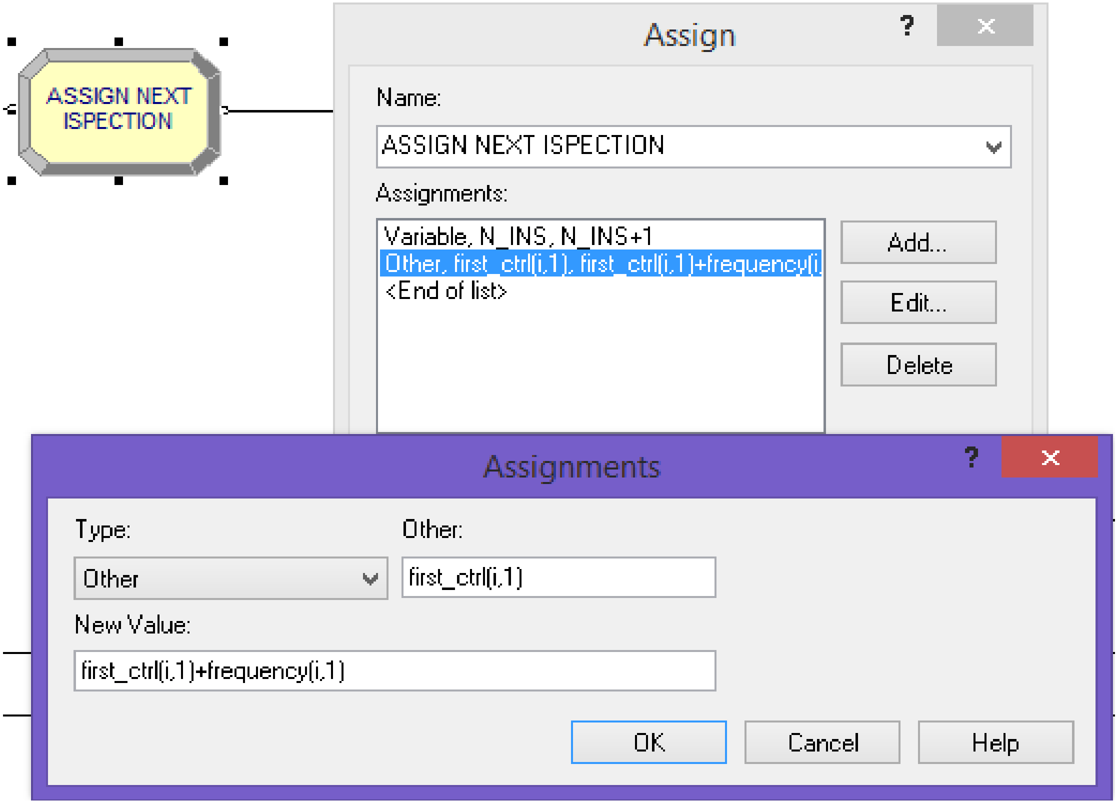
When arrive the day of the inspection on the component i, the logic simulates the control of the system with a *Process* module, as *Inspection Action*. It is a process that seize a inspector resource for a time equal to the time needed to make that action. This time is read from an external file.



Name: INSPECTION ACTION
Type: Standard
Logic
Action: Seize Delay Release
Priority: Medium(2)
Resources:
Resource, INSPECTOR, 1
<End of list>
Delay Type: Constant
Units: Minutes
Allocation: Value Added
Value: duration_crtl(i,1)
☑ Report Statistics

We use two different resource for the inspections and for the maintenance actions because in final we want to do considerations about the costs and about the workers needed to the production system. If instead it is not the day of the control of the component i, the logic evaluates the next component. When the dates of every component are checked and every action of the day are processed, the logic pass to the next day and repeat the control.

Besides when a inspection is finished, the system assign the next date of the inspection with a *Assig*n module.



Name: ASSIGN NEXT ISPECTION

Assignments:

Variable, N_INS, N_INS+1
Other, first_ctrl(i,1), first_ctrl(i,1)+frequency(i
<End of list>

Type: Other

Other: first_ctrl(i,1)

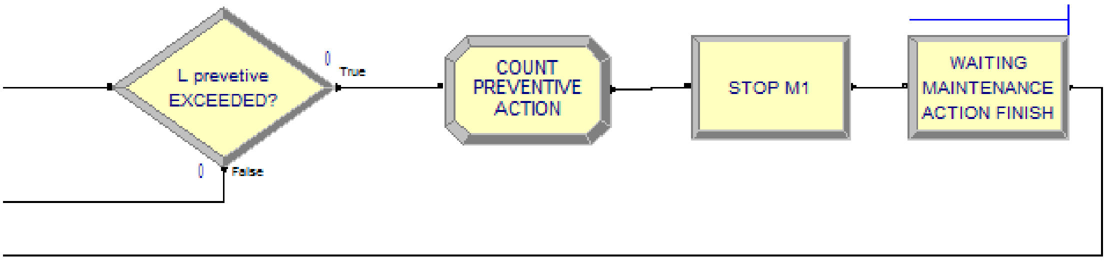
New Value: first_ctrl(i,1)+frequency(i,1)

Every data input are read from an external file because we want to built a general model, that is possible to apply in more business only with the change of the variables.

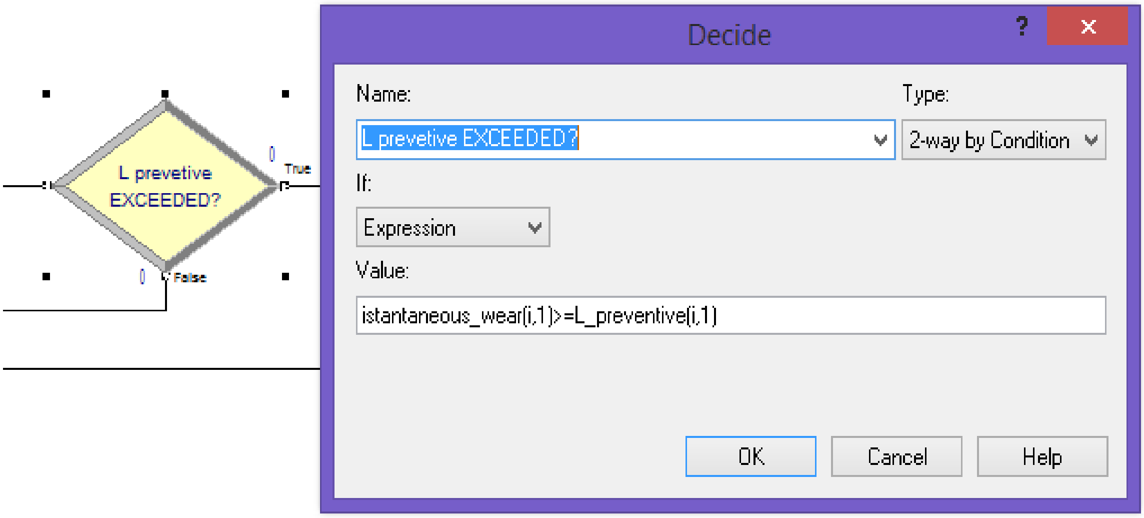
How shows the figure the new value of the variable (type *Others*) is equal to *first_control+frequency*. In this way when an inspection is finished this variables is updated at the next control day. For each variable is specified the index *i*, that defines which component is.

4.4.5 Phase Of Inspection

When the simulation's watch determines the day of the inspection of component i, the system makes this inspection. We already have explain that an inspection is simulated with a process that seize a resource.
After an inspection if the instantaneous degradation of the component exceed the preventive threshold, a signal is throw to the connection sub-model that handles the request.



With a *Decide* module the logic evaluates if the instantaneous degradation of the component exceed the threshold.



Name: L prevetive EXCEEDED?

Type: 2-way by Condition

If: Expression

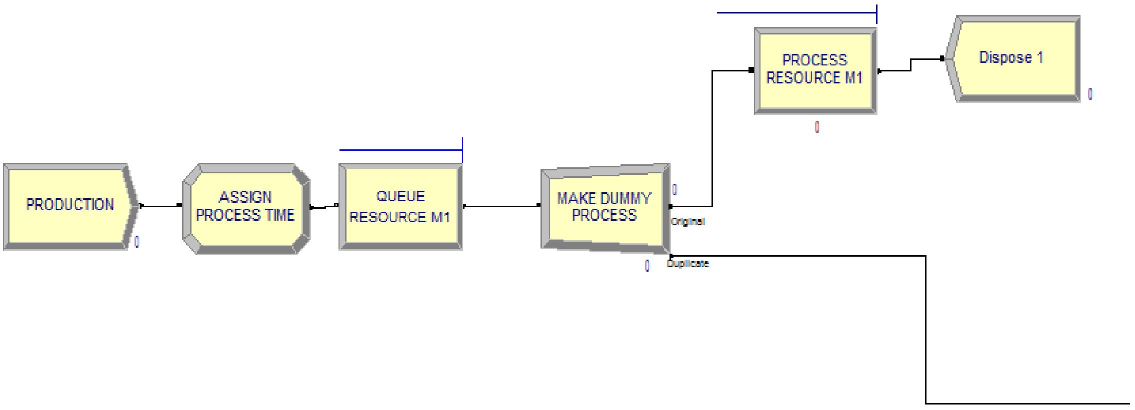
Value: istantaneous_wear(i,1)>=L_preventive(i,1)

Then we have a *Assign* module that changes the variables needed to write the final report and a *Signal* module that throws a signal to the connection sub-model.

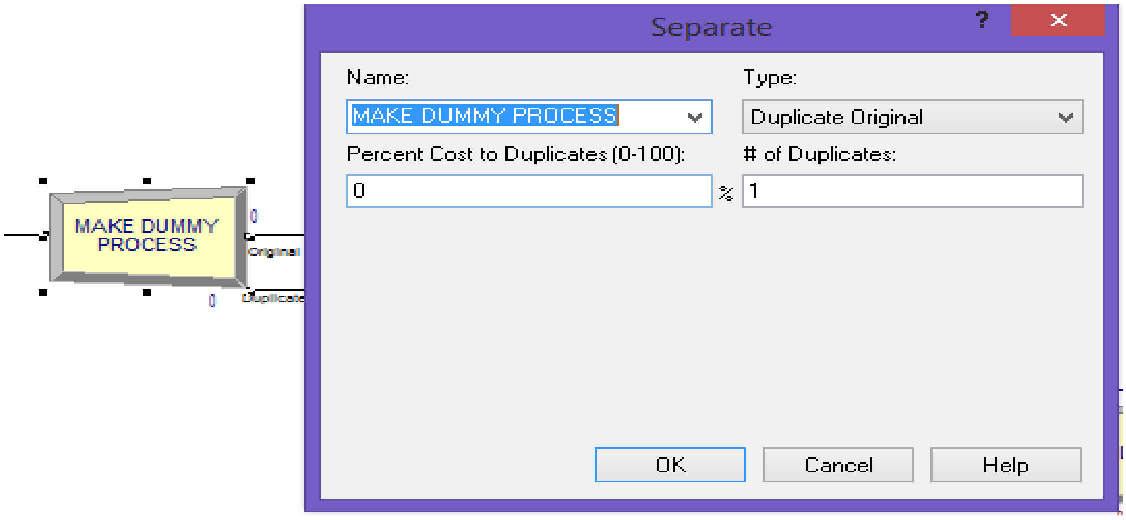
This signal arrive to the connection sub-model, it handles this request while the maintenance sub-model waits for the time need to finish the preventive action.

4.4.6 Production Logic

This section of the model simulates the production system.
In this sub-model,the entities flow in a open loop and simulate the work pieces.



There is a queue that simulates the input queue of the production system. Here the work pieces wait if the machine is not available.
Then we have a *Separate* module that duplicates the work pieces.



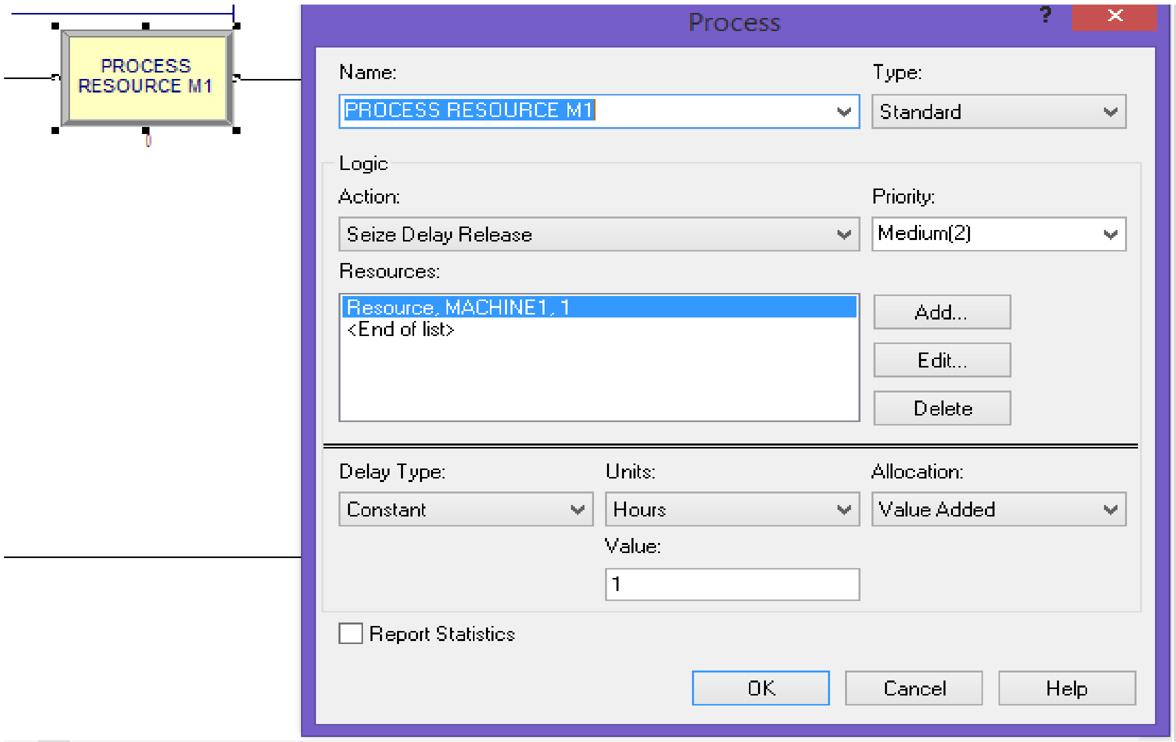
Name: MAKE DUMMY PROCESS
Type: Duplicate Original
Percent Cost to Duplicates (0-100): 0 %
# of Duplicates: 1

We use this module to duplicate the processes. There will be the original work piece that flows in the production process and a other duplicate that flows in other section to increase the degradation of the machine.

In this way it was simulated the production system and the degradation process, so that the wear of the machine increase only if the system works.

We have been supposed that the degradation increases every hour of work, so the production time is set to one hour. This choice permitted to simulated a more realist degradation process.

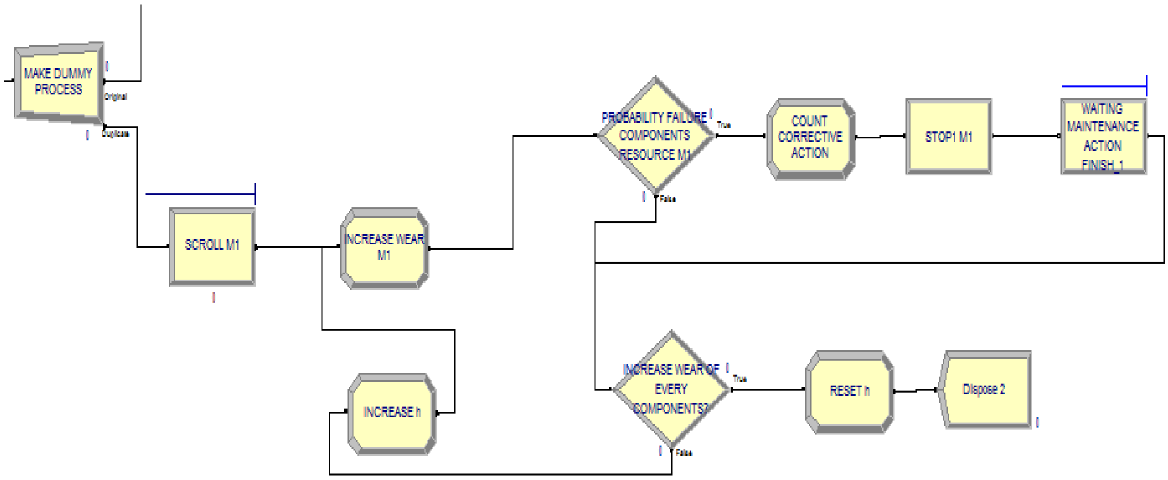
The production is simulated with a *Process* module that seize the machine resource.



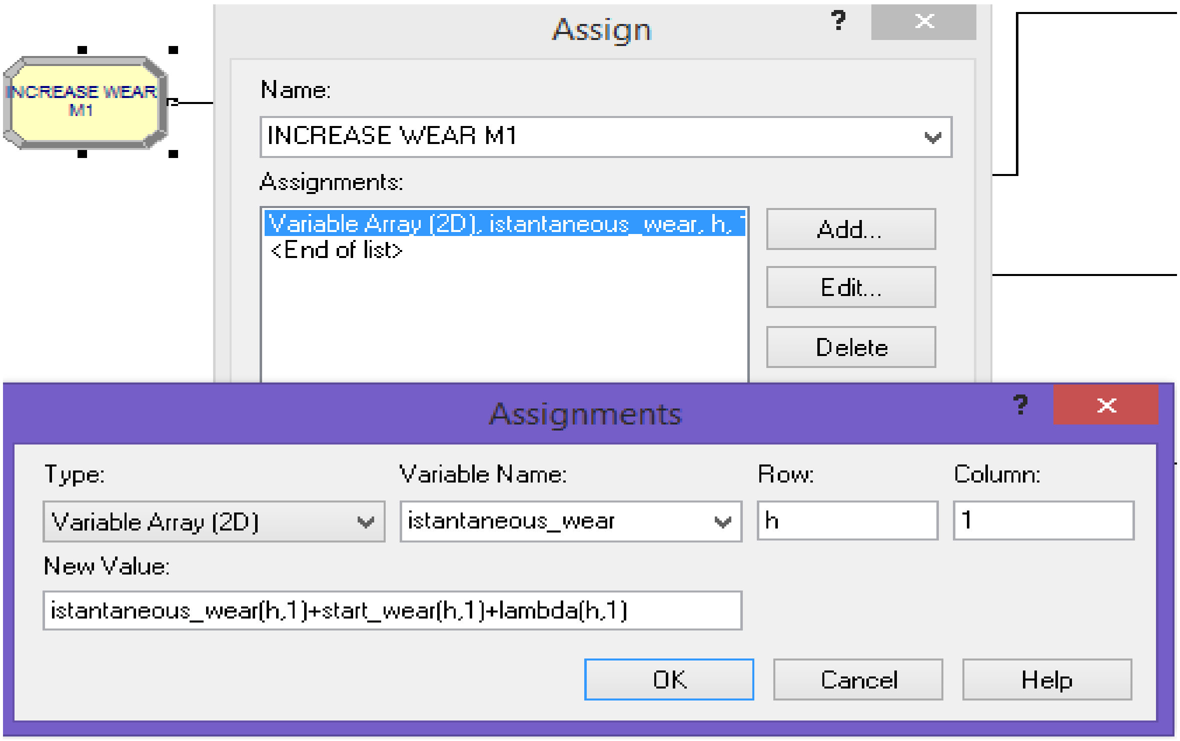
Name: PROCESS RESOURCE M1
Type: Standard
Action: Seize Delay Release
Priority: Medium(2)
Resources:
Resource, MACHINE1, 1
<End of list>
Delay Type: Constant
Units: Hours
Allocation: Value Added
Value: 1
☐ Report Statistics

4.4.7 Degradation Process

The degradation process is simulated with a dummy entity that flows in a *Process* module to increase the wear of the component.



There is a *Hold* module called *ScrollM1* where the dummy entity waits the finish of the production time. When it is passed the production time, the degradation of each component is increased with an *Assign* module.



Name: INCREASE WEAR M1

Assignments:
Variable Array (2D), istantaneous_wear, h,
<End of list>

Type: Variable Array (2D)
Variable Name: istantaneous_wear
Row: h
Column: 1
New Value: istantaneous_wear(h,1)+start_wear(h,1)+lambda(h,1)

For each component it was defined a variable called *instantaneous_wear*.

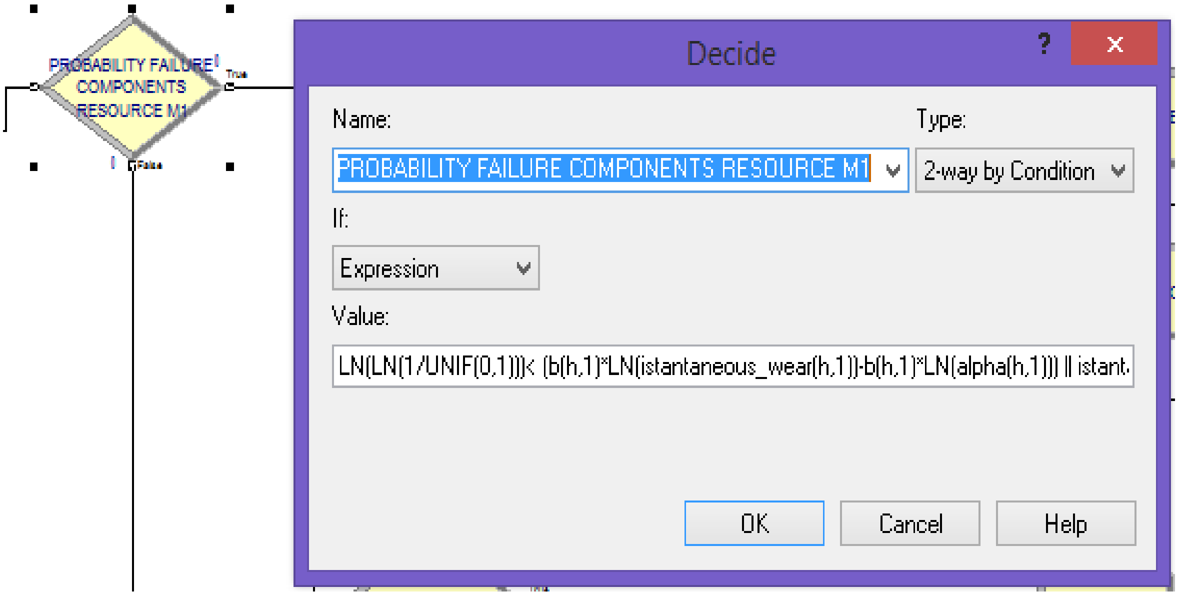
This variable is increased every hour for a value equal to parameter lambda, previously defined.

Then we have a *Decide* module that evaluates the instantaneous wear of each component. This *Decide* handles the random failure of the system also.

In fact it throws a signal to the connection sub-model if occurred two event:

•when the instantaneous degradation of the component exceed the threshold of corrective action;

•and when the a random failure occurs.



Name: PROBABILITY FAILURE COMPONENTS RESOURCE M1

Type: 2-way by Condition

If: Expression

Value:

```
LN(LN(1/UNIF(0,1)))< (b(h,1)*LN(istantaneous_wear(h,1))-b(h,1)*LN(alpha(h,1))) || istant
```

In this *Decide* we use the following expression:

$$Log\left[Log\frac{1}{UNIF(0{,}1)}\right] < \{[b(h,1) * Log(instantaneous_{wear}(h,1)] - b(h,1) * \log[a(h,1)]]\}$$

With this expression it is simulated the probability that a random failure occurs.

It is supposed that the random failure of each component follows a Weibull distribution.

In fact, if we want to study the probability that a component has a random failure before of a known time, we have to study the cumulative function of the distribution.

The cumulative function of the Weibull distribution[8] is:

$F(t) = 1 - e^{-(\frac{t}{\alpha})^{\beta}}$: probability that the component has a failure before the time t.

With this expression, Arena had a problem to calculate an exponential function, so we solved the same expression with the logarithms.

$1 - F(t) = e^{(\frac{t}{\alpha})^{\beta}} \rightarrow$

$\log[1 - F(t)] = \log\,[e^{-(\frac{t}{\alpha})^{\beta}}] \rightarrow$

$\log[1 - F(t)] = -(\frac{t}{\alpha})^{\beta} \rightarrow$

$-\log[1 - F(t)] = (\frac{t}{\alpha})^{\beta} \rightarrow$

$\log[1 - F(t)]^{-1} = (\frac{t}{\alpha})^{\beta} \rightarrow$

$\log\left[\frac{1}{1-F(t)}\right] = (\frac{t}{\alpha})^{\beta} \rightarrow$

$$\log\,[\log\left[\frac{1}{1 - F(t)}\right] = \beta \log t - \beta \log \alpha$$

In the expression inserted in Arena we have:

- b(h,1): parameter β of the component i;
- alpha(h,1):parameter α of the component i;
- UNIF(0,1): random parameter $\in [0,1]$;
- instantaneous_wear: parameter t for simulate the time.

This is the expression for simulate the random failure.
Instead to simulate the failure when the degradation exceed the threshold of corrective action we use the following formula:

$$instantaneous_{wear(h,1)} > L_{corrective(h,1)}$$

---

[8] Weibull, W. (1951)

This sub-model does these two controls every hour of production and for each component. When one of these expressions is true a signal is throws to the connection sub-model.

As for the maintenance sub-model, also in this there is an Assign module for change of the variables needed to write the final report and a Hold module for wait the finish of the maintenance action.

5.1 Final Report

The final report shows how the key performance indices of the production system in function of the input variables change.
Through more Assign and Write modules we determinate the diary of failures.
The format of the failure diary is showed in the following table(3) and it change for every simulation.

CODEX COMPONENTS	ISTANT FAILURE	TYPE ACTION [1:Preventive;2:Corrective]	BREAKDOWN TIME
12	49620	2	10.31449526
11	49670	1	9.887851741
14	49709.88785	1	9.478516378
3	55630.3145	2	10.16732162
6	80329.36637	1	10.50765707
7	80349.87403	1	10.33308891
12	99260.48182	2	9.95961022
14	99510.44143	2	10.35298101
9	100840.2071	1	9.428141099
11	100869.6353	1	10.0209164
3	111029.6562	1	10.1664712
13	111139.8226	1	9.78436937
10	121349.607	1	9.839624196
2	131509.4466	1	8.671332813
12	148918.118	2	9.692903761
14	149347.8109	2	9.646422067
11	152068.118	1	9.368372042
3	162227.4863	1	109.400235
6	162366.8866	1	10.10916755
7	162386.9957	1	9.422776016
12	198636.8866	2	10.34947275
14	199247.236	2	8.864165881
9	203336.4185	1	109.8714488
11	203466.29	1	10.15130041
3	213626.4413	1	9.168704408
8	223915.61	1	9.938691805
13	223975.5487	1	10.70310963
6	244376.2518	1	109.8010498
7	244496.0528	1	9.492363444

Table 5

For each simulation that we throw, we evaluate this diary and determinate how the key performance indexes change.
In this diary the model writes:

- which component fails;
- the instant of the failure;
- the type of the action;
- and the total breakdown time.

Then using a macro in Excel we calculated the total cost of the maintenance function. In particular the total cost is calculated in the following mode:

$$BreakDownCost = \sum_{j=1}^{M} BreakDownTime * BreakDownCost \quad [min] * [\frac{€}{min}]$$

This is the cost for the breakdown of production system.
Then we add the cost for every action of maintenance that it is made on the system.

$$TotalCost = BreakDownCost + CostPreventive * Npreventive \\ + CostCorrective * Ncorrective$$

Where:

- CostPreventive: is the cost of a preventive action;
- CostCorrective: is the cost of the corrective action;
- N: is the number of the corrective or preventive actions.

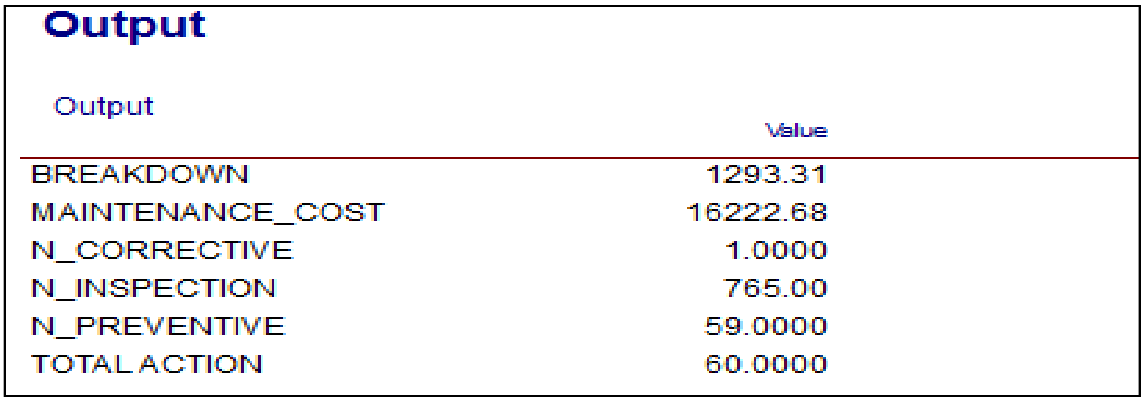
In this study we supposed to evaluate a production system where there is different cost between a corrective and preventive action. If we want inspect a system where there is not this distinction, every considerations made here is not true.

5.2 Output Of Arena

The final considerations have been done in function of the diary of failure and of the statistics that have been defined in Arena.
In particular for each simulation, Arena calculates the following parameter:

- Total Breakdown time of the production system;
- Total actions of maintenance;
- Total inspections;
- Number of preventive action;
- Number of corrective action;
- Total cost of the maintenance function.

An example of the output of Arena, is showed in the following figure(20).



```
Output

 Output
                                        Value
BREAKDOWN                             1293.31
MAINTENANCE_COST                     16222.68
N_CORRECTIVE                           1.0000
N_INSPECTION                           765.00
N_PREVENTIVE                          59.0000
TOTAL ACTION                          60.0000
```

Figure 19

This output is related to a simulation of one year with a low threshold of preventive action. In fact in this case, we have only one corrective action, while all other actions are preventive.
This is only an example, during the research we made many different analysis changing every time the input data.
The output of each simulation it was put in an Excel file, and it has been the input for the following considerations about the advantages of a CBM policy.

Final Considerations

With this model we have been determined some general considerations about the economic convenience of a CBM polity. In particular we evaluated the change of the costs in function of the input variables.

5.3 Input Variable ρ

We determined the variable ρ, defined in the following mode:

$$\rho = \frac{Lpreventive}{Lcorrective} \qquad with\ \ \rho \in [1; 0{,}5]$$

In particular when ρ is equal to:

- 1 →there are not preventive actions, the threshold of the preventive action is equal to the corrective action, and the system does only corrective maintenance.
- 0,5 → there are not corrective actions because the threshold of the preventive action is low, so the system replaces the components when it still have half residual service life. In this case a corrective action is made only if a random failure occurs.

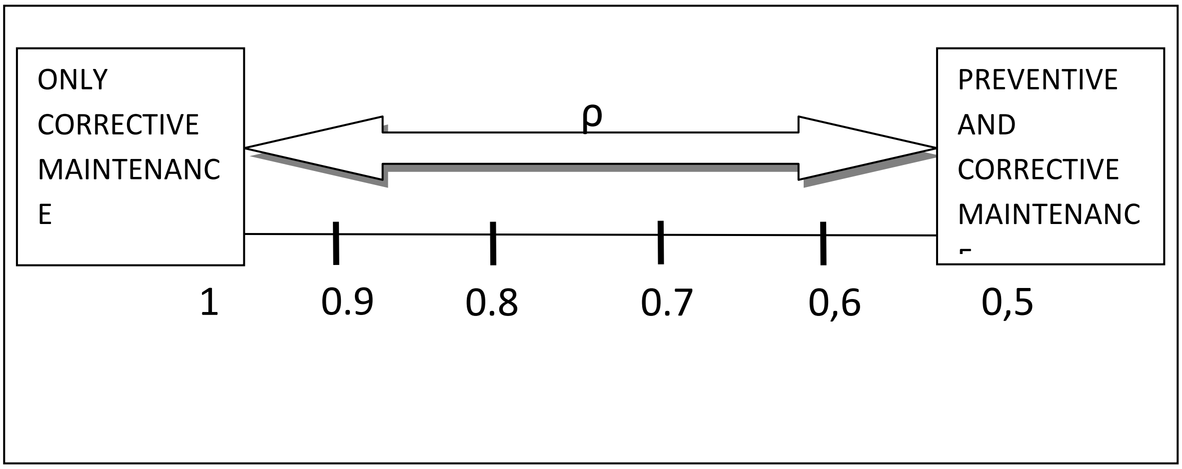


Figure 20

We have studied the changing the total actions in function of this variable.

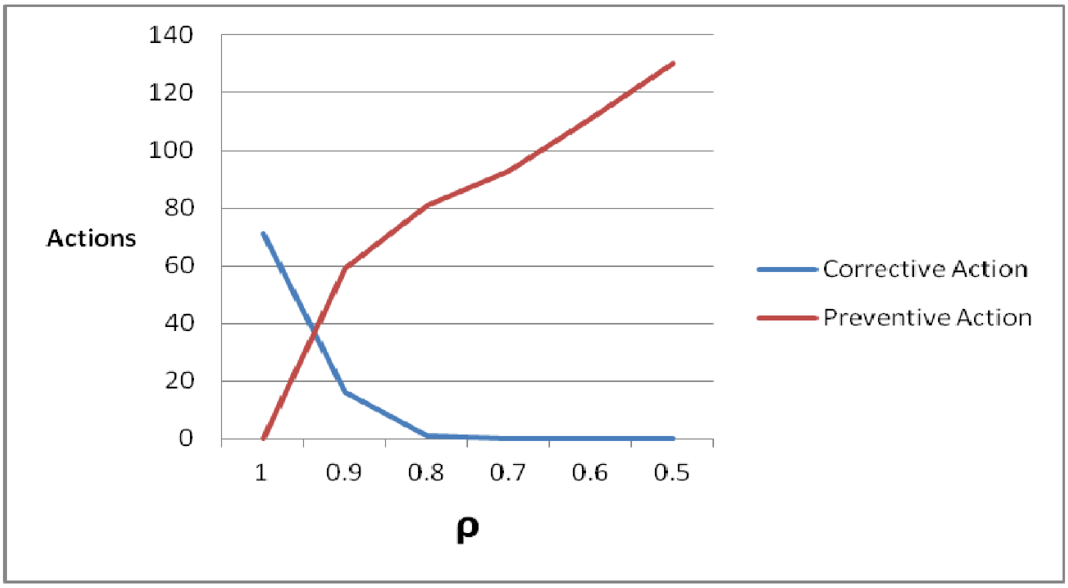


Figure 21

The figure (22) shows how the actions types change in function of ρ.

As was to expect the corrective actions increase when there is a decrease of parameter ρ , because the maintenance function replaces the component when it have service residual life still.

While the preventive actions decrease when ρ increases because it means that the components are replaced when have little service residual life .

5.4 Input Variable ω With Weekly Inspection

We determinate the variable ω, defined in the following mode:

$$\omega = \frac{C\ corrective}{C\ preventive} \quad with\ \omega\ \in [1;4]$$

It is the relation between the cost of a preventive action and of a corrective action.

Higher is the value of this variable and higher is the overall cost of a breakdown of the production system. We have supposed that the cost of a corrective action is possible to be four time the cost of the preventive action.

In function of this variable and of ρ,we studied the changing of the total cost of the maintenance if we have weekly inspections on the components.

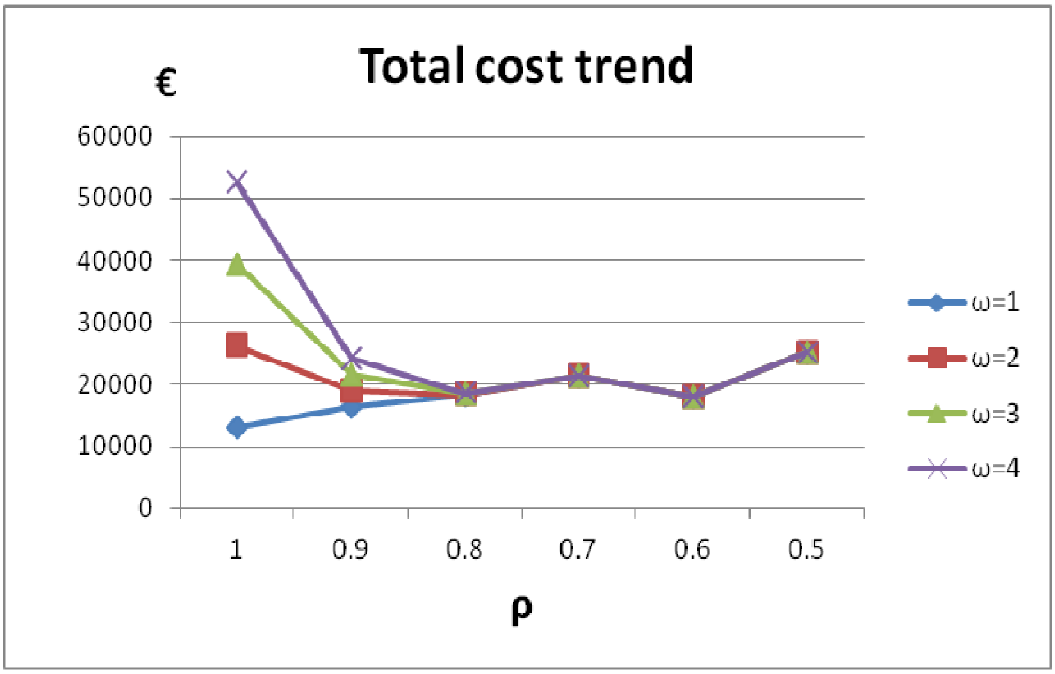


Figure 22

In the figure is possible to evaluate that:

- when $\rho=1$, namely when there is only corrective maintenance in the system, the increase of total cost is proportional at the variable ω increase. It was predicted because if we have only corrective maintenance, when increase the cost of a corrective action increases also the total cost.
- when $\rho=0,9$, we have corrective and preventive maintenance. In this case the total cost for every value of ω is lower than the total cost that we have in case of only corrective maintenance. The total cost with $\rho=0,9$ is higher than the cost of the corrective maintenance only if $\omega=1$,namely if there is not an overall cost of the breakdown.
- when $\rho=0,8$ or values lower, we have only preventive maintenance, so the total cost does not change in function of ω.

For values of ρ lower than 0,8,there is only preventive maintenance, and the total cost fluctuates in function of the number of the preventive action. In fact lower is ρ and more preventive action on the system are needed.

The most important considerations that is possible to determine with this graphic is that with $\rho=0,9$, the total cost is lower than all others case. So if is possible to evaluate the degradation of the component and replace it when it has service residual life low, this type of maintenance policy can give economic advantages.

5.5 Input Variable ω With Monthly Inspection

Besides we studied the change of total costs when there are monthly inspections in the production system.

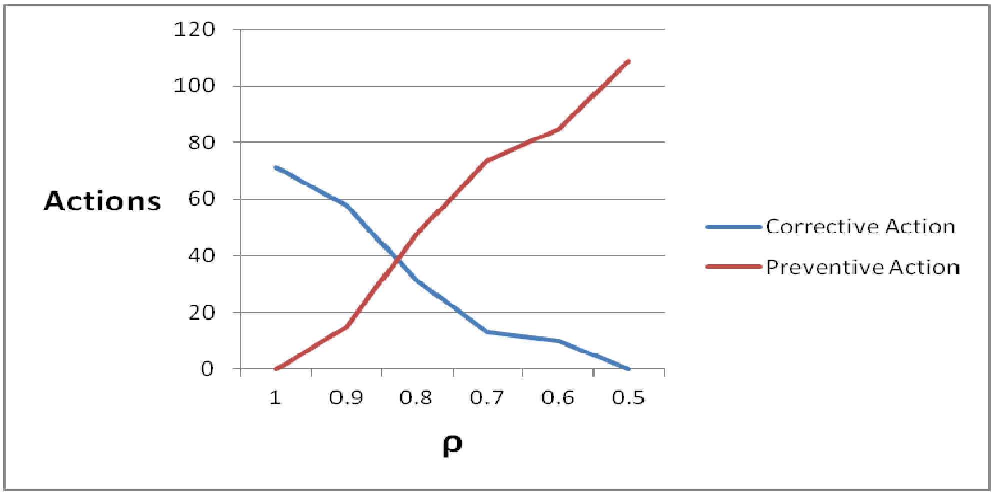


Figure 23

In this case we have only preventive maintenance, if the system replaces the components when it still have half residual service life, namely when ρ=0,5.

So with monthly inspections the threshold when there is only preventive maintenance is lower respect to previous case.

The trend of the total cost in function of ω and ρ is showed in the following figure (25).

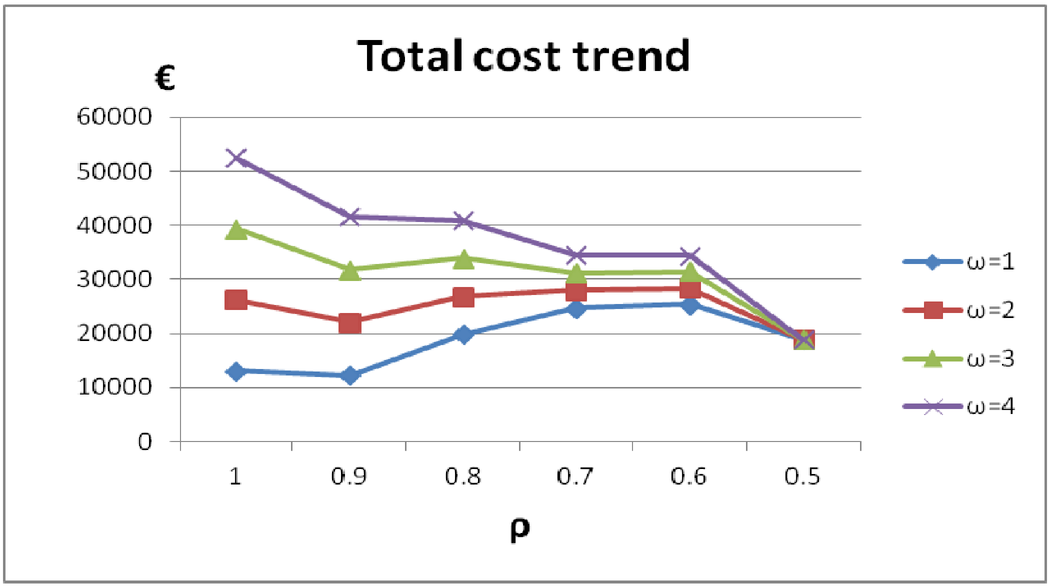


Figure 24

In this case the total cost in function of ω is higher variable, it means that is possible to determine the best maintenance policy because there is a minimum.

Also in this instance the minimum for each trend in function of ω there is when ρ=0,9, this means that for each value of the data inputs, is possible to determinate the best strategies of maintenance only when there is a parameter linked to the degradation that is possible to evaluate.

If is impossible to determinate this parameter is better to make only corrective maintenance because the equipment to study the degradation of the component is expensive.

5.7 Matrices To Find The Best Policy Of Maintenance

In particular the trend of the costs when the inspections are monthly, is always decreasing, so in this case is possible to have more economic advantages.
These are general considerations in function of the initial hypothesis,these outputs can be different if the input changing.
But the goal of the elaborate was to determine general matrices where in function of more variables is possible to identify the best maintenance policy for the company.
In particular is possible to make an ABC analysis and make a cluster of components in function of the following variables:

- ratio between the costs of a preventive action and a corrective action: $\alpha = \frac{C_{prevetive}}{C_{corrective}}$
- probability of failure induced;
- costs induced of downtime;
- knowledge of degradation trend.

These information are in the data base of the company if a management software ,like a CMMS, is used from the maintenance function. In fact with this equipment is possible to have track about the failure of each component. In factories highly evolved, is possible to insert in a CMMS software many information, for example ttf (TimeToFailure of the component), instant of last failure, cost of replaces, breakdown cost of the production system, supply time, etc.

In the following figure(26), we clustered the components in function of the first two parameters α and probability of induced failure. This analysis shows that:

•the PREVENTIVE MAINTENANCE is cost-competitive if the parameter α is low and the probability of induced failure is high. In fact:
→if $\alpha \in (0,1]$; (because the maximum cost of preventive action can't be higher than the cost of corrective action) is low means that the $C_{prev} << C_{corr}$, so is better to make a preventive action than a corrective action because there is an economic advantage.
→if the probability of induced failure is high means that a failure can induce other failures,by increasing the downtime cost.

•the CORRECTIVE MAINTENANCE, instead , is cost-competitive if α is high and the probability of induced failure is low. In fact:
→if $\alpha \in (0,1]$; is high means that the $C_{prev} \approx C_{corr}$, so there aren't many difference between the costs of a corrective action and an a preventive action.
Is better wait the failure and after change the part.
→if the probability of induced failure is low means that a failure doesn't induce others failures in the system.

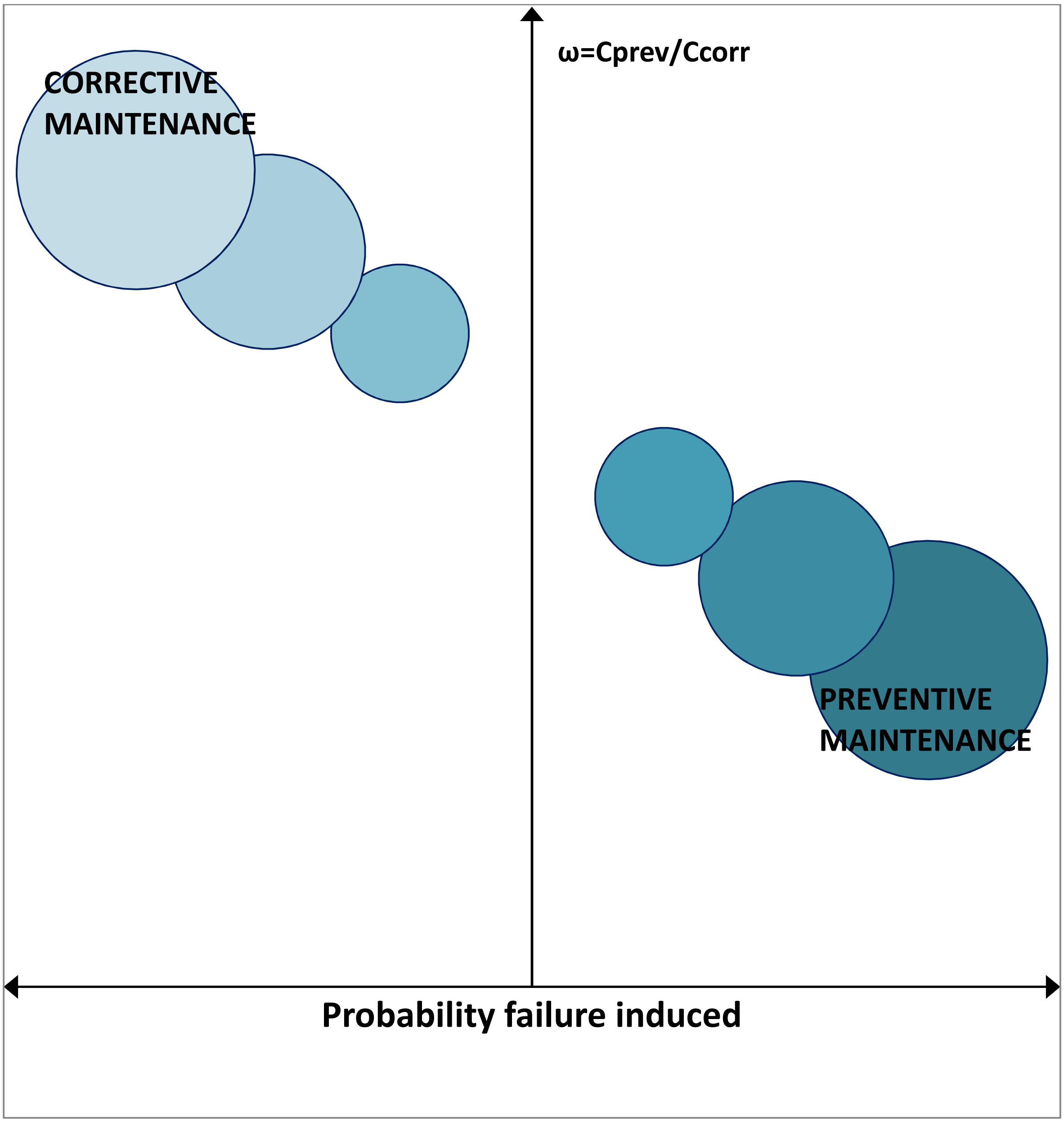

ω=Cprev/Ccorr
CORRECTIVE MAINTENANCE
PREVENTIVE MAINTENANCE
Probability failure induced

Figure 25

Instead in the following figure(27), we clustered the components in function of the others two parameters, the costs induced of downtime and the level of knowledge of degradation trend.

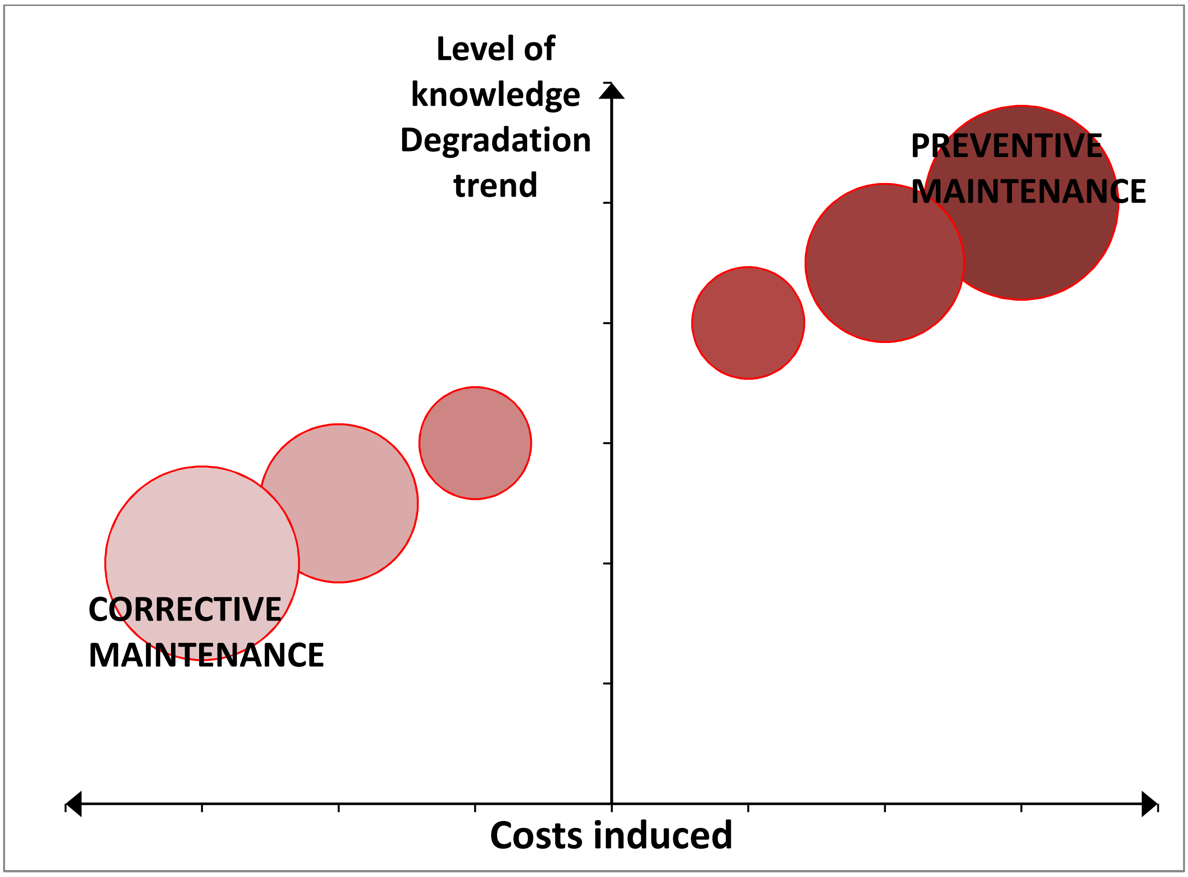


Figure 26

In this case, we are showing that:
•the preventive maintenance is competitive cost if is known the degradation trend in the time and the induced costs of downtime are high. This because:
→if is known the degradation's trend means that is possible change the part when it arrive to have a degradation near to the failure, so we know more or less when the components can fail and we make a preventive action before.
→if the induced costs of downtime are high means that when a component has a failure there is a high induced cost on the machine, so is better change the part before that it has a failure.

•the corrective maintenance is more competitive than the preventive maintenance when the knowledge of degradation's trend is low and the induced costs are low, because:
→if the degradation's trend is not known,means that the components have a high lumpyness, so it have a useful life very variable and it’s impossible to estimate when is convenient change the part.
→if the induced costs are low means that when a component has a failure isn’t a problem because the machine do not have a failure, so is better to wait the failure.

In the following figure (28) it is showed the matrix to indentify the best maintenance polity in function of all variables previously considered.

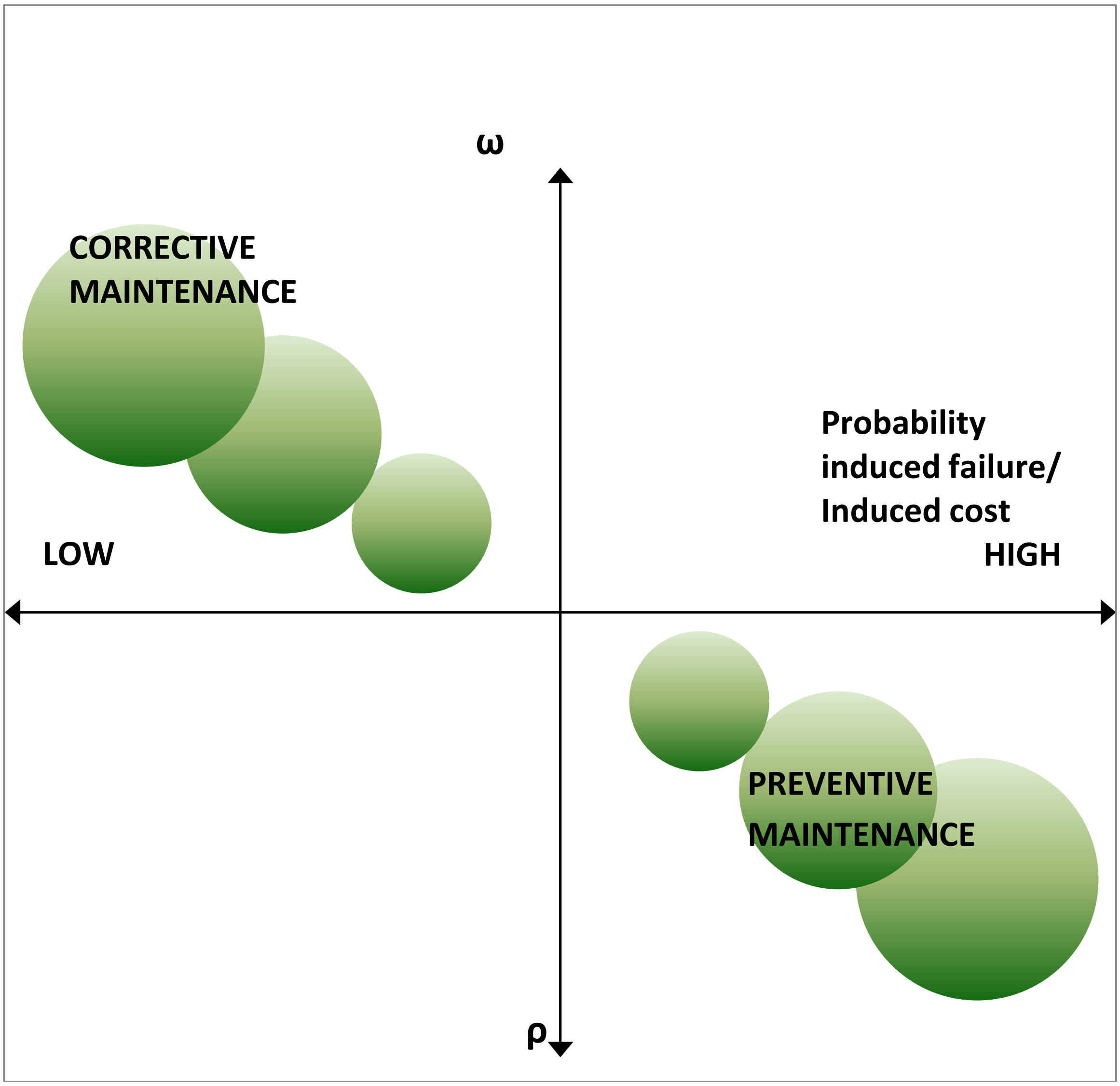
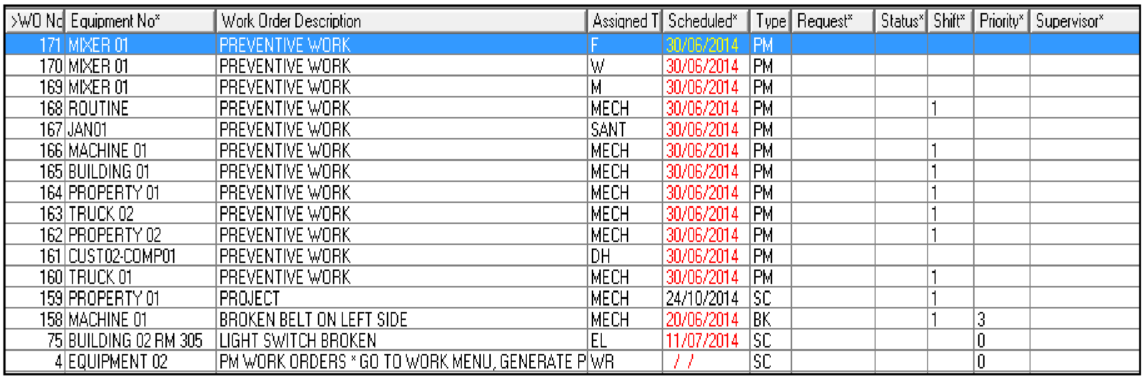


Figure 27

5.9 CMMS Software

A CMMS software package maintains a computer database of information about an organization’s maintenance operations. This information is intended to help maintenance workers do their jobs more effectively (for example, determining which machines require maintenance and which storerooms contain the spare parts they need) and to help management make informed decisions (for example, calculating the cost of machine breakdown repair versus preventive maintenance for each machine, possibly leading to better allocation of resources). CMMS data may also be used to verify regulatory compliance.

During the research the software CMMS that it has been possible to analyse has an application of input as that of the following figure ( ):



>WO Nc	Equipment No*	Work Order Description	Assigned T	Scheduled*	Type	Request*	Status*	Shift*	Priority*	Supervisor*
171	MIXER 01	PREVENTIVE WORK	F	30/06/2014	PM					
170	MIXER 01	PREVENTIVE WORK	W	30/06/2014	PM					
169	MIXER 01	PREVENTIVE WORK	M	30/06/2014	PM					
168	ROUTINE	PREVENTIVE WORK	MECH	30/06/2014	PM			1		
167	JAN01	PREVENTIVE WORK	SANT	30/06/2014	PM					
166	MACHINE 01	PREVENTIVE WORK	MECH	30/06/2014	PM			1		
165	BUILDING 01	PREVENTIVE WORK	MECH	30/06/2014	PM			1		
164	PROPERTY 01	PREVENTIVE WORK	MECH	30/06/2014	PM			1		
163	TRUCK 02	PREVENTIVE WORK	MECH	30/06/2014	PM			1		
162	PROPERTY 02	PREVENTIVE WORK	MECH	30/06/2014	PM			1		
161	CUST02-COMP01	PREVENTIVE WORK	DH	30/06/2014	PM					
160	TRUCK 01	PREVENTIVE WORK	MECH	30/06/2014	PM			1		
159	PROPERTY 01	PROJECT	MECH	24/10/2014	SC			1		
158	MACHINE 01	BROKEN BELT ON LEFT SIDE	MECH	20/06/2014	BK			1	3	
75	BUILDING 02 RM 305	LIGHT SWITCH BROKEN	EL	11/07/2014	SC				0	
4	EQUIPMENT 02	PM WORK ORDERS * GO TO WORK MENU, GENERATE P	WR	/ /	SC				0	

Figure 28

Where is possible to indentify many information:

- work orders;
- equipment codex;
- work order description;
- worker assignment;
- schelule of work;
- type of action.

If is possible to have this type of information about the maintenance of the production system then is possible to define many considerations about the best strategies of maintenance. moreover the data input of the simulation model are defined in the same way, so if is available a CMMS software, the simulation model can be used for determinate the total cost of the function.

Determinate a Maintenance Plan

If the company uses a CMMS software for organize the maintenance function, and evaluates what are the best strategies of maintenance with the use of mathematical or simulation equipment, is possible to define the maintenance plan .

The key steps in preparing a typical maintenance plan are:

- (1) **Prepare an asset inventory** - identifying the physical features (e.g., area, material,etc.) of all assets (e.g., schools, roads, etc.) which require maintenance;
- (2) **Identify maintenance activity and tasks** - defining the type of maintenance task (activity) to be performed on each asset and what work should be done under each activity, e.g.
- (3) **Identify the frequency of the task** - determining how often the activities should be performed (frequency of service); this is important particularly in preventive type of maintenance. Emergency or reactive type of repairs are unpredictable, but with good preventive maintenance, the frequency of emergency situations occurring may be reduced;
- (4) **Estimate the time required to complete the task** - indicating how long each task should take to complete;
- (5) **Develop an annual work schedule** - planning what time the maintenance work for the entire year should take place;
- (6) **Prepare and issue a work order** - identifying what, when, where and by whom maintenance work is to be done;
- (7) **Determine a Budget**- determining the costs for all maintenance activities by calculating labour hours, material, equipment, and contracting costs.

For the first three steps a CMMS software is needed, while for the last step, namely determine a budget, a simulation model with Arena can be the best equipment to use.

APPENDIX 1

Application example of calculation Hazard Failure

This appendix shows the application of three algorithms used for the definition of the parameter λ (Hazard Failure Rate).

We used three different algorithms because we want to determinate the difference between the values of λ that the three methods give back.

CALCULATION BEST λ EXP					
	INPUT				
	DM: direct method			n=	4
i	ttfi[hours]	F(ti)= i/n	R(ti)=1-F(ti)	f(ti)=1/[n*(ti+1-ti)]	λ(ti)=1/[(n-i)*(ti+1-ti)]
1	153	0.25	0.75	0.0015	0.0020
2	320	0.5	0.5	0.0022	0.0045
3	432	0.75	0.25	0.0013	0.0053
4	619	1	0	0.0000	0.0000
				λ=	**0.001243113**
	IDM:improved direct method			n=	4
i	ttfi[hours]	F(ti)= i/(n+1)	R(ti)=1-F(ti)	f(ti)=1/[(n+1)*(ti+1-ti)]	λ(ti)=1/[(n+1-i)*(ti+1-ti)]
1	153	0.2	0.8	0.0012	0.0015
2	320	0.4	0.6	0.0018	0.0030
3	432	0.6	0.4	0.0011	0.0027
4	619	0.8	0.2	0.0000	0.0000
				λ=	**0.003025143**
	RM:rank method			n=	4
i	ttfi[hours]	F(ti)= (i-0,3)/(n+1)	R(ti)=1-F(ti)	f(ti)=1/[(n+0,4)*(ti+1-ti)]	λ(ti)=1/[(n+0,7-i)*(ti+1-ti)]
1	153	0.16	0.84	0.0014	0.0016
2	320	0.39	0.61	0.0020	0.0033
3	432	0.61	0.39	0.0012	0.0031
4	619	0.84	0.16	0.0000	0.0000
				λ=	**0.003625186**

In this case we supposed to have track only of the last four ttf. This because we do not have a real application, but we want to evaluate the difference between these three method.

We used to calculate λ:

- Direct Method;
- Improved Direct Method;
- Rank Method.

Then we used these three method to calculate the parameters α and β if the trend of failures of component follows a Weibull distribution.

CALCULATION BEST β and α WEIBULL					
	INPUT				
	DM: direct method			n=	4
i	ttfi[hours]	F(ti)= i/n	R(ti)=1-F(ti)	f(ti)=1/[n*(ti+1-ti)]	λ(ti)=1/[(n-i)*(ti+1-ti)]
1	153	0.25	0.75	0.0015	0.0020
2	320	0.5	0.5	0.0022	0.0045
3	432	0.75	0.25	0.0013	0.0053
4	619	1	0	0.0000	0.0000
				β=	1.0294
				α=	461.93
	IDM:improved direct method			n=	4
i	ttfi[hours]	F(ti)= i/(n+1)	R(ti)=1-F(ti)	f(ti)=1/[(n+1)*(ti+1-ti)]	λ(ti)=1/[(n+1-i)*(ti+1-ti)]
1	153	0.2	0.8	0.0012	0.0015
2	320	0.4	0.6	0.0018	0.0030
3	432	0.6	0.4	0.0011	0.0027
4	619	0.8	0.2	0.0000	0.0000
				β=	1.4122
				α=	463.52
	RM:rank method			n=	4
i	ttfi[hours]	F(ti)= (i-0,3)/(n+1)	R(ti)=1-F(ti)	f(ti)=1/[(n+0,4)*(ti+1-ti)]	λ(ti)=1/[(n+0,7-i)*(ti+1-ti)]
1	153	0.16	0.84	0.0014	0.0016
2	320	0.39	0.61	0.0020	0.0033
3	432	0.61	0.39	0.0012	0.0031
4	619	0.84	0.16	0.0000	0.0000
				β=	1.6889
				α=	448.57

Finally we have estimated how changes the reliability of the component at one hundred hours.

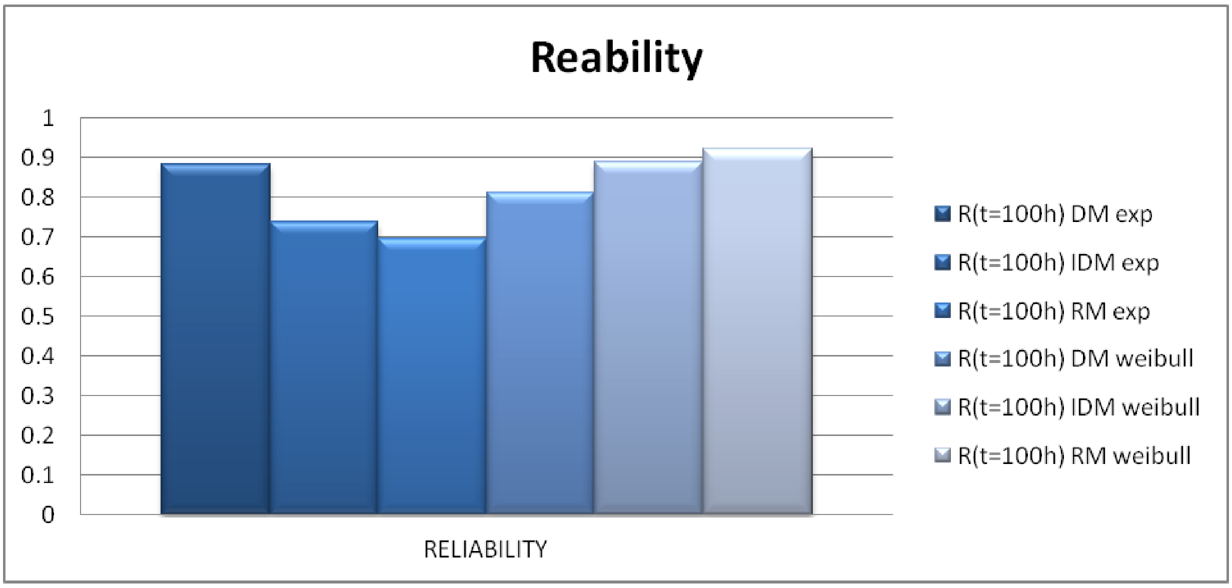


Figure 29

The application of the three different methods generates values of λ very different. This is another example of how all algorithms can give a estimate of the parameter but the more important value of the component is always the lumpyness of the failures.

We can use the best CMMS software, the more appropriate simulation model to estimate the cost, but the most important thing to forecast when a component can have a failure is the lumpyness. For this the most important data inputs for each mathematical or simulation model are the information of the worker, particularly of the maintainer that know the production system more than all software CMMS.

APPENDIX 2
Application example of the mathematical model

With the use of the software Excel, it has been possible to apply the mathematical model previously described to a theoretical degradation stochastic process.

We supposed that data inputs related at the costs (table 4) and related at the degradation process(table 5) are the following:

INPUT	
Cpm [€]	100
Ccm [€]	200
Cp [€]	500
S[€]	50
α=	1.5
β=	1
Hi=	15.62
ϕ1=	0
ϕ2=	0.5
n=	11
τ [€]=	1

Table 6

Where :

- i : index of components in the overall system;
- n : index of maintenance intervals over the planning horizon;
- Xi(t) : degradation of component i on a physical condition;
- τ : maintenance interval at the system level (decision variable);
- Ci : control limit on the degradation level of component i (decision variable);
- Hi : soft failure threshold on the degradation level of component i;
- Zsyst : average cost rate of the overall system;
- Cpm;i : cost per PM action taken on component i;
- Ccm;i : cost per CM action taken on component i;
- Cp;i : soft failure cost rate on component i;
- S : cost per set-up action taken at the system level;

The assumptions at the base of the model are:

1) The components in the overall system are independent of each other.

2) The time horizon is infinite.

3) Maintenance actions are set up at fixed maintenance points nτ; n ∈ N.

4) The system continues its operation with a lower performance when the degradation of components exceeds the failure thresholds (also known as "soft failure").

To define a stochastic degradation process, we have supposed to determine this trend (figure 28) of a parameter that in identify the degradation of the component.

Andamento X(t)		
t[days]	θ	X(t)
1	0.1	0.1
2	0.4	0.67
3	0.6	1.70
4	0.9	3.50
5	0.5	4.62
6	0.8	6.58
7	0.2	7.11
8	0.1	7.39
9	0.9	10.09
10	0.7	12.31
t*		**X(soglia)**
11	**1**	**15.62**

Table 7

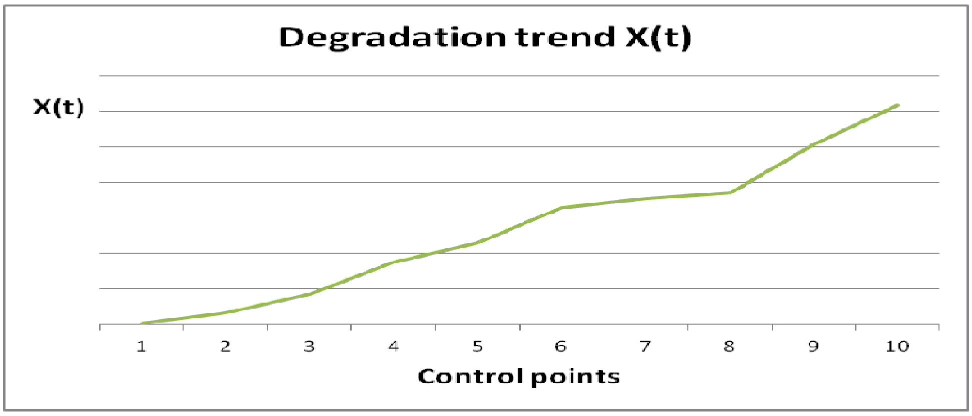


Figure 30

With this data inputs we have applied the mathematical model in Excel and we have evaluated if there is a minimum of the total cost of maintenance. The objective of the analysis is to prove that the model is functioning and determine how changes the total cost in function of two variables:

- τ: maintenance interval at the system level;
- Ci : control limit on the degradation level of component i.

Then changing these variables we define the total costs trend.

In the following table (6) it has been showed the application of the model with τ=1 (namely when the inspection on the components is made each day) and with C_i that varies in a range between the last value of the parameter that it has been read (C_i=12,31) and the value of the threshold of failure (C_i=15,61).

In this way we have estimated the total cost of the maintenance function that carries out preventive and corrective actions on the production system. Finally we have determined the cost trend in function the relation between Cpm (Cost of preventive action) and Ccm (Cost of corrective action).

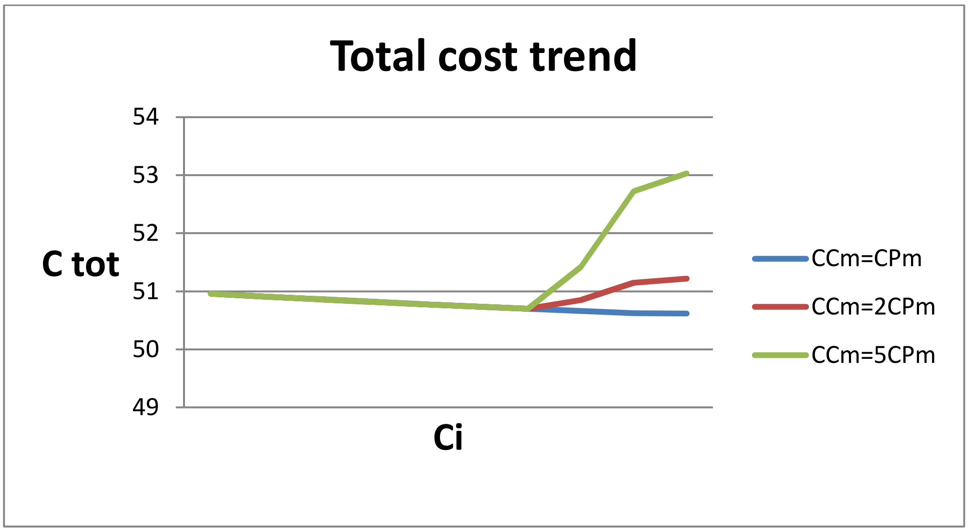
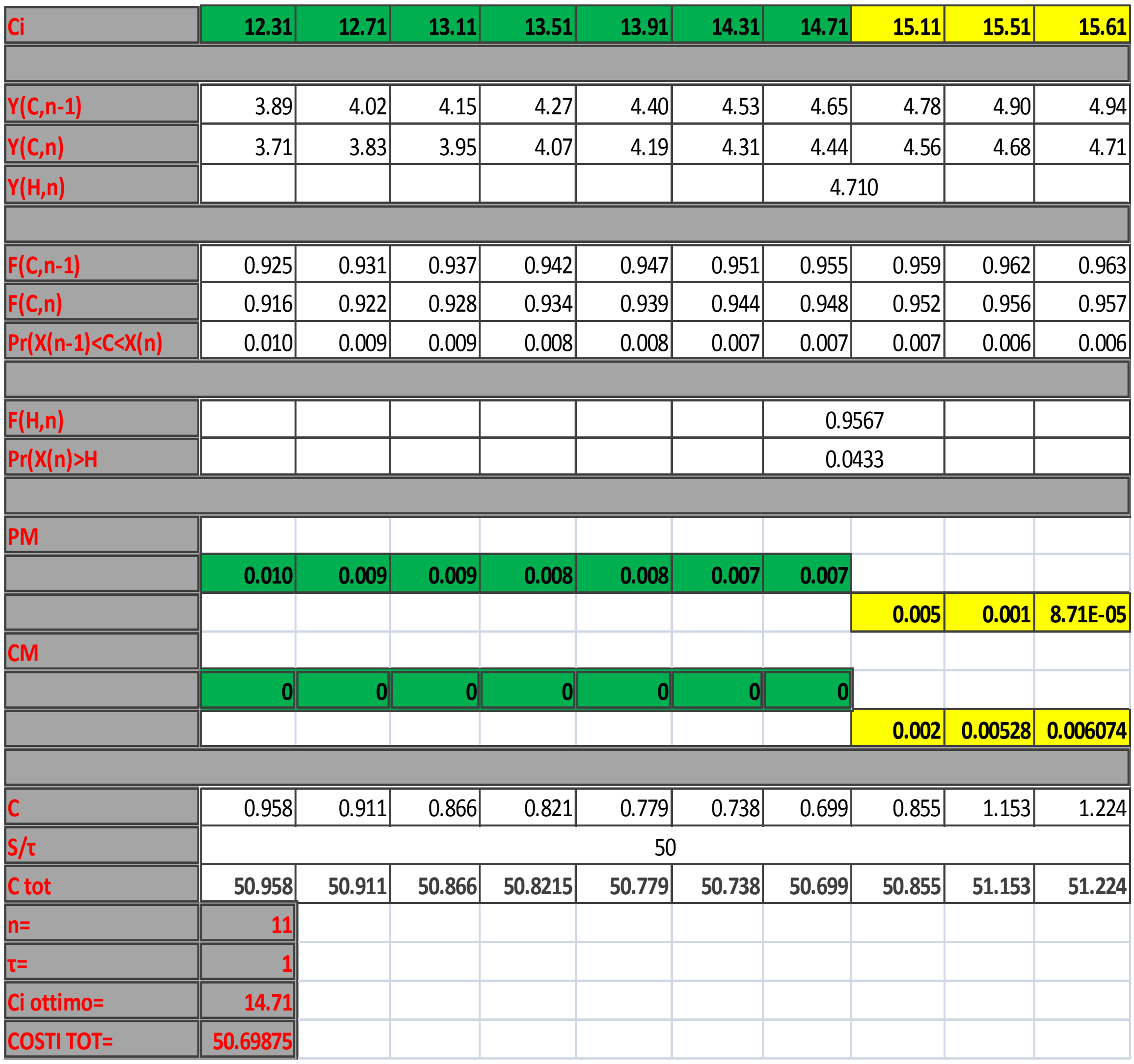


Figure 31

How shows the figure (29), the total cost does not change until to a determinate value of Ci, then when reach the minimum, the total cost varies in function of the relation between Cpm and Ccm. Also in this case, the economical advantages that is possible to get, increase when the cost of a corrective action is more elevated respect to the cost of the preventive action.

In the following table (6) is shown an application on Excel of the mathematical model.



Ci	12.31	12.71	13.11	13.51	13.91	14.31	14.71	15.11	15.51	15.61
Y(C,n-1)	3.89	4.02	4.15	4.27	4.40	4.53	4.65	4.78	4.90	4.94
Y(C,n)	3.71	3.83	3.95	4.07	4.19	4.31	4.44	4.56	4.68	4.71
Y(H,n)							4.710			
F(C,n-1)	0.925	0.931	0.937	0.942	0.947	0.951	0.955	0.959	0.962	0.963
F(C,n)	0.916	0.922	0.928	0.934	0.939	0.944	0.948	0.952	0.956	0.957
Pr(X(n-1)<C<X(n)	0.010	0.009	0.009	0.008	0.008	0.007	0.007	0.007	0.006	0.006
F(H,n)							0.9567			
Pr(X(n)>H							0.0433			
PM										
	0.010	0.009	0.009	0.008	0.008	0.007	0.007			
								0.005	0.001	8.71E-05
CM										
	0	0	0	0	0	0	0			
								0.002	0.00528	0.006074
C	0.958	0.911	0.866	0.821	0.779	0.738	0.699	0.855	1.153	1.224
S/τ	50									
C tot	50.958	50.911	50.866	50.8215	50.779	50.738	50.699	50.855	51.153	51.224
n=	11									
τ=	1									
Ci ottimo=	14.71									
COSTI TOT=	50.69875									

Table 8

Finally we have changed the variable τ and we have determined that is possible with this model identify a minimum in the total cost of the maintenance.

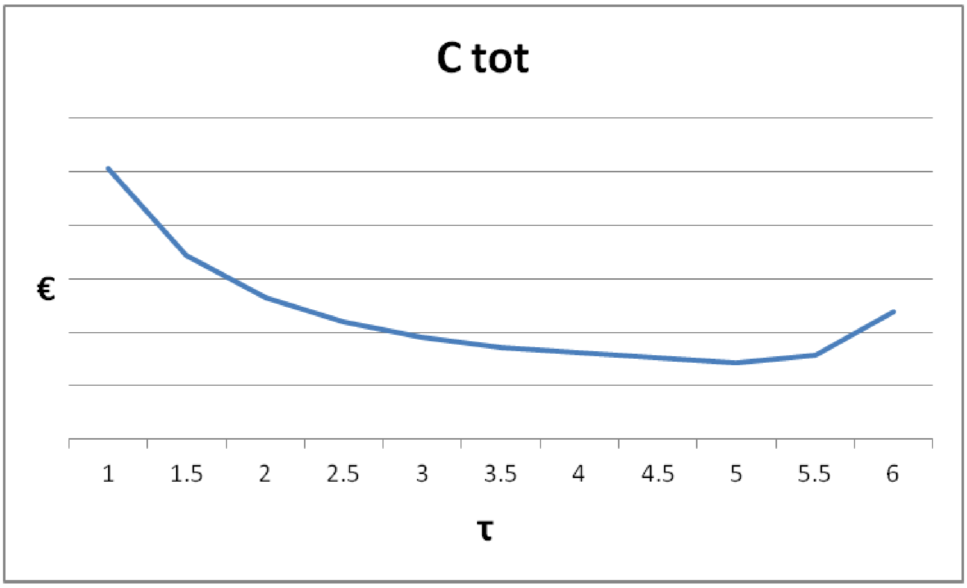


Figure 32

The optimal maintenance interval τ increases when the PM cost Cpmi or setup cost S increases, which implies that it is economically beneficial to have longer maintenance interval and less frequent maintenance setups when the preventive maintenance and the set-up are more expensive.
The optimal control limits increase when Cpmi increases, which means at the individual component level the control policy becomes less strict to avoid high Cpmi. However, when τ becomes larger due to a higher S, the optimal control limits decrease in order to avoid the high CM cost Ccmi and soft failure costs at the individual component level.
In other words, the optimal maintenance interval and control limits decrease when Cpi or Ccmi increases, which suggests that it is economically beneficial to have more frequent maintenance setups and tighter control over the degradations of components.

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