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Simulation Tool Development to Support Customer-Supplier Relationship for CBM Services

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Abstract

Nowadays companies, whose mission is to provide maintenance services to support production equipment built by different product vendors, progressively tend to focus on services based on Condition Based Maintenance (CBM). This can be considered a consequence of the availability of ICT components as new remote hardware devices (i.e. smart sensors) and software tools (i.e. for diagnostics and prognostics): these components may play a fundamental role for the development of CBM in the set of services provided by maintenance service providers. In this context, it is interesting to evaluate new technical solutions, such as CBM based solutions, their technical advantages and subsequent benefits, identifying CBM as a relevant leverage to improve a maintenance service contract. This thesis focuses on the supporting modelling tools that can be of help in order to assess the technical and economic benefits that a CBM service can provide. Thanks to such supporting tools, it is possible to model the CBM adoption in a maintenance service contract, to optimize it and to estimate the resulting benefits, besides the costs. In a few words, it is possible to set up a CBM service and evaluate its impact for the client company that decides to use it. The thesis presents the literature background, in order to demonstrate the usefulness of CBM in the scope of maintenance service provision. Afterwards, modelling tools that can assist in evaluating the benefits of maintenance services, are discussed: a major focus is on simulation tools, having specific concern to the system dynamics as modelling technique. In this thesis a tool is proposed; this tool provides empirical evidence of the use of systems dynamics as a technique promising for supporting the evaluation of technical and economic benefits of CBM in a service contract.

Abstract

Oggigiorno le imprese, la cui mission è di fornire servizi di manutenzione a supporto della produzione di componenti di diversi venditori, tendono progressivamente a focalizzarsi sui servizi di manutenzione su condizione (CBM). Questa può essere considerata una conseguenza della disponibilità di dispositivi ICT come quelli hardware remote (per esempio smart sensors) e strumenti software (per diagnostica e prognostica). Questi componenti possono giocare un ruolo fondamentale per lo sviluppo della CBM come parte di un set di servizi messi a disposizione dai fornitori di servizi di manutenzione. In questo contesto è interessante valutare le nuove soluzioni tecniche, come la manutenzione su condizione, descrivendone i vantaggi tecnici e i relativi benefici, identificando la CBM come un'importante leva per migliorare i contratti dei servizi di manutenzione. Questa tesi si concentra sull'analisi di strumenti di modellazione e di supporto che possono essere di aiuto nella valutazione dei benefici tecnici ed economici, ottenibili grazie all'implementazione di un servizio di CBM. Grazie a questi strumenti di supporto è possibile modellare l'uso di questa politica nei contratti dei servizi di manutenzione, ottimizzandoli e stimandone gli effetti (costi e benefici). In poche parole è possibile predisporre un servizio di CBM e valutarne l'impatto per la compagnia cliente, che quindi può decidere di adottarli. La tesi presenta un background di letteratura che dimostra l'utilità della CBM nella fornitura di un servizio di manutenzione. Sono discussi principalmente gli strumenti di simulazione che assistono la valutazione dei benefici del servizio di manutenzione, dando un maggior focus agli strumenti di simulazione di cui in particolare il linguaggio system dynamics. La tesi propone un tool che fornisce un'evidenza empirica riguardo all'uso di system dynamics come tecnica di supporto alla valutazione dei benefici tecnici ed economici della manutenzione su condizione in un contratto di servizio.

Executive Summary

Today the industry clearly focuses on increasing profitability. Companies wish to improve quality, to supply good service and guaranteed safety, reducing the costs as much as possible. Companies are changing very fast, there is a clear increase of the complexity of operations: mechanization increase, plants are automatized as flexible manufacturing systems or flexible assembly systems. Automation changes industries to be lead with more maintenance workers than production workers. Considering this kind of trends, cost growth is more and more challenging and maintenance area is strongly involved in this process. Trends highlight how focusing on maintenance has become important and it is now the basic area to be improved, in order to reach enterprise targets. Besides, companies have recently moved to service based business models following a process called tertiarisation or servicizing. Maintenance, especially with the growth of technology development, can be considered one of first areas to follow this trend offering service contracts or proactive maintenance based on condition monitoring.

Services Issues:

After sales service offers several benefits to companies, i.e. to compete on differentiation instead of price, to get loyalty and develop a long-term relationship with the customers, increasing revenues and guaranteeing them also during crisis periods. Recently the high market pressure, global competition and decreasing of profits, after sales services have increased their importance also providing to: the product added value, the increasing of firms market share and the strategic driver for customer retention.

It is important to highlight that services have also great importance in financial area. Services contributed improving company revenues and profits of several manufacturing companies. It is explained by customer repair willingness to pay that is more than half of brand new price, generating profits around 50% up to 70% in case of service contracts. Service affects in competition strategy; indeed it is not enough to compete only with the product in the new context. It has also been demonstrated that the availability and quality of service are more important for the customer, than a low price. So, as described above, services allow switching from cost competition to quality competition, creating a long-term customer relationship and guaranteeing customer satisfaction and loyalty.

The main problems of after sales services are concentrated on complexity of systems that need to be handled. It requires the use of strategic planning on services network and it requires uncertainties handling, indeed every system suffers from variability that affects decision maker choices. Moreover there is a big potential for improvements in that field: the developing of frameworks or tools to assist the decision making process is considered the first step to do. It is highlighted how it is difficult to develop an accurate service planning process; first problem in a company is the lack of capability to handle complexity. Surely performance monitoring is fundamental in order to understand problems and opportunities, but it cannot be the only solution. Most parts of complex systems require to be handled having a whole systemic view. As previously described, supporting tools can play a big role in that sense, indeed management must be helped in decision making following efficiency and effectiveness goals. Maintenance service belongs to such areas that need to be supported.

Literature is full of model examples to solve those problems; models typologies can be categorized as mathematical, based on queuing theory and simulation ones. Anyway mathematical models seem inefficient because they have not the capability to model in dynamic way. Instead queuing models can incorporate multiple uncertainties, that significantly impact on parameters i.e. costs, time response and failure rates. However even if they can be used to investigate more complex problems they cannot be detailed enough for realistic studies. So it seems that simulation may be the most appropriate technique to cope with maintenance issues.

Maintenance Issues:

Maintenance has normally been considered as a support to production area, interventions have been seen as annoying events because of stops of production. Anyway something is changing; maintenance has taken a life cycle management approach. The role of maintenance has become strategic, it is linked to enterprise performance, it is shifting/has shifted to use “predict and prevent” method instead of “failure and fix”, indeed preventing problems can reduce costs and at the same time reduce downtime in production. The objective is to maintain production systems in a working condition as long as possible or restore them as quickly as possible in case of failure. Those trends can be supported by information and communication technologies (ICT), e-maintenance and condition monitoring solutions. A good mix of policies helps the changing to be more forceful.

Although there are several condition monitoring techniques available, especially in rotating machinery, the most useful technique is vibration analysis. It seems that vibration analysis is the most reliable investigation technique, resulting in both efficient and effective processes.

CBM policy, supported by condition monitoring, tries to solve common maintenance problems, such as: how to plan maintenance actions on sophisticated components, how to reduce stock costs related to spare parts handling; how to avoid health risks and how to reduce not-planned maintenance actions in the system.

Strong relationship between problems and costs obliges to make a plan and to detect problems before there will be catastrophic failures that involve other problems on the whole system. CBM can guarantee a reduction about spare parts need, a reduction of unnecessary maintenance actions using entities almost their complete life cycle ensuring a good level of health.

Considering the complexity of relationships in that field, several tools were developed to help the decision maker. In that sense it was considered an analysis of literature simulation applications in maintenance systems that describe some modeling categories, which should be considered to develop a complete model.

In most of cases models refer to a specific area, in that sense the simulation of single or few categories cannot guarantee improvements, because in those cases models cannot describe the real interaction between the various areas. The use of simulation is important when models are built considering right relationships; moreover simulation is often used to analyse maintenance systems combined with optimization. Convinced by the above, it was proposed a maintenance service simulation tool.

Objectives and Work Presentation:

This work is done collaborating with VTT Technical Research Centre of Finland (www.vtt.fi) due to the closeness of Politecnico di Milano research targets.

The Objective of the work is to develop a tool that:

- supports an instrument that supports users to face service complexity and uncertainties
- facilitates maintenance system comprehension and handling, supporting decision maker
- facilitates customer-supplier communication, guaranteeing various scenarios comparison.

- reduces customer supplier distance involving customers in simulation game.

In other words, the objective of the research is to present a tool that supports the relationship between service provider and customers who are the decision makers on maintenance service requirements. The tool would allow the customer to understand the whole system and variables that affect the performances of the system. It would guarantee an engineering approach to decision making, allowing the improvement of efficiency and the effectiveness of the system. Due to the complexity of systems and the inability to think with a long-term view, CBM policy and related choices can appear less convenient than the run to fail approach; instead the simulation tool can clearly highlight real costs of a CBM approach and support the decision making process.

Tool development required to define four macro steps to accomplish the work. First period was spent in Finland in order to understand project needs and requirements, indeed considering that VTT is a CBM service provider, their experience helped to correctly set the problem. The second period was spent in Politecnico di Milano making literature analysis and defining the conceptual model on the basis of all information collected. Third period was still spent in Finland to develop the tool, it required to make an additional literature analysis on specific modelling issues. During this period also a case of study was carried out. Last step, in Politecnico di Milano, was to finalize the work better analysing a case of study and to make a sensitivity analysis.

Model Presentation:

The model was developed using Vensim simulation software considering needs of all actors involved in the process: customer, provider (customer manager) and technical provider staff, which makes measurements. Service provider uses the tool to achieve the goal previously described, customer would have benefits and technical area describes needs to make measurements.

The model has been built to support service provider to present his service and its impact on customer’s process equipment performance. The provided services are based on machinery inspections in order to understand maintenance problems to set solutions avoiding failures and preventing them from taking place. So considering machines criticality, customer can choose different approaches (maintenance policies). Customer needs to understand the added value of provided measurements and the real effect on the whole system. He needs to handle the trade-off between costs and benefits.

Model presented below is the result of those evaluations; four modules are used to build it.

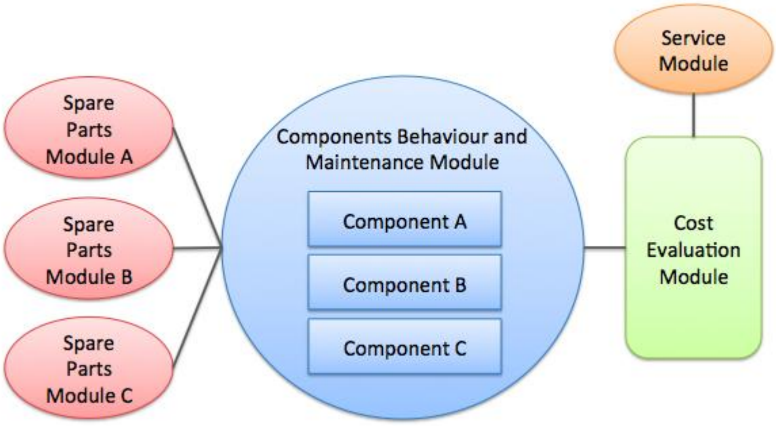


Figure E.1. - Simulation Tool Framework

Components Behaviour and Maintenance Module:

The components behaviour and maintenance module includes degradation simulation category issues, maintenance policies (run to fail or CBM) and some evaluation of maintenance operation performances described with MDT, MTBF and the availability of the system. Components behaviour and maintenance module is the most focused area of the model and it is built to be at the same time accurate and flexible. It allows the evaluation of components in series with different life cycle, failure correlations, policies and alarm conditions. It allows the possibility to choose between to repair or to substitute components for a fixed number of times.

The deterioration of components is described by reduction of remaining life as a function of time, based on a constant degradation speed. Indeed policies are simulated allocating failures on corrective or preventive interventions on the basis of a detection percentage called PoD (probability of detection). That parameter is supported by literature and it is chosen in accordance with component lifecycle and the interval between inspections. A large number of papers describe the statistical construction of this variable, main used are log odds or log normal method, necessary data are not always available Correlation between failures gives to the module a great sense of reality. By defining the correlation matrix it is possible to describe the effects of bad interaction between components as reduction of their remaining life. When component is not substituted after its alarm condition, it starts to work in degraded state, so it affects those that are correlated during time spent in degraded state. Correlation is supported in literature by several studies that underline its power in simulation. Anyway, sometimes correlation cannot be estimated because of historical data lack, so it could be useful to compare the system with a similar one, even if it would be difficult to evaluate which could be an equivalent system in an unambiguous way. However, if there is not the possibility to make a statistical assessment of both correlation and PoD, it is possible to use expert estimation to define them, guaranteeing the whole system comprehension.

The module has been built with three connected components to guarantee system flexibility without building a too complex structure. Surely it could be possible to extend it replicating the framework with more components, but in the most of cases, most critical problems can be fully analyzed describing the relationship between the three connected components. Anyway if it would be necessary to evaluate a more complex situation, it is possible to set a model with two critical components and an average cluster of data of the remaining components, or with three clusters defined using for example an ABC Pareto classification. The same structure can be used to evaluate a series of machines in a chain, but it becomes essential to keep in mind the trade-off between accuracy of simulation and the general view required.

Spare Parts Module:

The module is able to handle different policies and different conditions component by component. It is possible to choose between fixed point and fixed period reorder policies for each component of the model. In the first case, there is a fixed quantity of reorder batch, calculated minimizing costs of stock handling and costs of handling orders. The reorder time is a variable that changes considering the usage of components that means it changes following their behaviour simulated in the main module. The reorder level is evaluated considering purchasing lead-time in order to guarantee the stock level above the security stock level. Indeed in the fixed period policy, customer chooses a fixed reordering interval and quantity batch is calculated like difference between the available stock level and the target stock level.

.Output of the module is the amount of stock management costs for each component. Costs considered in the model are: purchasing costs of components, costs to handle the order (i.e. assurance, transportation, billing and packing charge costs), costs of stock handling (i.e. costs related to handle components in storage, assurance and obsolescence risk) and costs due to the lack of spare parts (i.e. stop of production).

Service Module:

Service module is used to set information related to the inspection of components by technicians, variable included in it coming from a database built by the technical area of the service provider. Database represents an added value of the model because it includes technical information about needs and requirements of each monitoring technique on the specific inspection kind. It allows the use of the tool without to need to have technical background knowledge. Anyway technical support could be appreciable.

Cost Evaluation Module:

This module summarizes a lot of information from other modules elaborating costs. Maintenance costs are divided on the basis of policy, but they depend also on repairing or substitution cases. Down Time is estimated counting all wasted time on repairing or replacing components or inspections, but also waiting for stock refill in the case of spare parts lack. So down time costs are calculated on the basis of time and lack of production costs set by the customer. So the total costs of maintenance include corrective and preventive costs, down time cost, inspection costs and spare parts costs.

Case of Study and Sensitivity Analysis:

Quite a number of meetings were organized between the planning phase and the accomplishment of the work with VTT customer managers, who are the end users of the tool. Customer managers supported directly the development describing their needs related to their daily work. Several meeting were also organized with the technicians of the ICT department specialized on the use of system dynamics software to check the state of the work and improve it. This process supported the validation of the conceptual model by experts. They evaluated the model checking its correctness and completeness.

Instead the system dynamics tool was evaluated by a case of study. The tool was initialized with data related to a public transportation case; it allowed testing it in different scenarios evaluating results. Moreover some sensible parameter of the tool were chosen to lead a sensitivity analysis evaluating stability of case results and making a description of their effects.

Conclusions:

After inputting customer data, that is useful for describing the plant situation and after importing data from the database of the services chosen, the model can be run.

Every module of the model shows different information to the decision maker, even if cost evaluation certainly is the most important. In the components behaviour and maintenance module state of component graph shows their degradation, the effect of correlation, the failures happened in accordance to the policy and the stops of machines due to inspection or maintenance for one of components included in the module. It is possible to understand how meaningful is the degradation, how the correlation affects the other components and how much time is spent in the production stops caused by maintenance. Each parameter is also described with a specific graph in the case that the decision maker needs a detailed view. Anyway components behaviour and maintenance module does not permit to make a decision by itself. The spare parts module too can show to the decision maker the effects of stock policies resumed in the stock inventory level that can be crossed with the state of component information.

However scenarios evaluations are based on costs, so the tool provides a set of outputs to investigate on each cost center. Moreover simpler indicator are included among cost outputs just to understand how cost reduction or increasing affects performances. Outputs are showed below:

- Corrective Maintenance Costs
- Preventive Maintenance Costs
- Down Time Cost
- Total Cost of Service
- Total Cost of Stock Management
- Total Costs
- Availability
- Down Time
- Number of Interventions

Finally, the decision maker has all the instruments to understand the right interval between inspections and the right mix of policies to choose in order to well manage the trade-off between benefits and costs.

The research focused on the supporting modeling tools that can be an aid in order to assess the technical and economic benefits that a CBM service can provide. Once such supporting tools are available, it should be possible to model the CBM adoption in a maintenance service contract. The paper presented a literature background to introduce the research work carried out in the research stream about maintenance services. In this scope, a tool, based on System Dynamics approach has been

proposed; this model provides empirical evidence of systems dynamics as a technique that is promising for supporting the evaluation of technical and economic benefits of CBM in a service contract.

Chapter 1 – Research Outline

This research is an answer to problems underlined by literature in maintenance services, specifically on problems related to the development of a customer-supplier relationship, in order to guarantee a monitoring service to support a condition based maintenance policy. In this chapter it is presented an introduction to the work highlighting goals and opportunities of the field of investigation. Finally, the structure of the work is presented, specifying experiences and collaborations that allowed developing the simulation tool. The work is carried out thanks to collaboration between Politecnico di Milano and VTT – Technical Research Centre of Finland.

1.1 – Goals of the work

Targets of the work can be classified in two categories:

Goals to meet literature requirements:

1. Services intrinsic features surely make difficult their management. Complexity of systems and uncertainties are underlined in literature as the main obstacle to achieve results (see chapter 2), so they need to be strongly faced in order to guarantee results and benefits which companies expect to get when they move towards service maintenance direction. In that sense this work wants to provide a solution that is able to handle those problems.
2. Maintenance choices correctness (i.e. maintenance policies, inspections frequency, spare parts policy) depends on the comprehension of the whole systemic behaviour, (see chapter 3). This work wants to provide an instrument that helps to understand own system behaviour in maintenance field. The solution provided wants to assure a complete maintenance view, building a tool that is able to investigate in most of maintenance requirements to support decision maker choices in a more effective way.

Additional goals to meet VTT project requirements:

1. Considering that customer and maintenance service provider have different targets, sometimes it is difficult to meet needs of each parts, to understand the added value of the service and to communicate them. In that sense this work wants to develop an instrument that is able to consider needs of each parts and that can help to show effects of choices, supporting the comparison with specific data of own case.
2. Another purpose of the work is to build a tool that is able to reduce the distance between customer and supplier, indeed it must be done to be also tuned by customers himself during the comparison between the two parts. It has to be enough user friendly, without to require not available data, but also being enough accurate to be effective. The goal is to actively involve and to interest customer to test own situation instead of listening a fruitless presentation of services.

1.2 – Opportunities of the work

Nowadays industry is affected by several changings, they depend surely on specific area trends like technologic improvements and new customer needs, but also they depend on the contest situation. Economic crisis presses company financial state and so it is required to handle resources more and more effectively to reduce costs and to be able to maintain share market at the same time in a challenging situation. Anyway all changings provide new opportunities for companies that are able to understand which are best choices to face them.

Maintenance is changing following the increasing of plants automation and the availability of ICT technologies, which can provide more data with a lower cost than in the past. In that sense technology allows to keep monitored equipment and to implement preventive policies. Condition based maintenance policy is based on the possibility to monitor the state of components. It allows replacing or repairing the components effectively on the basis of their reliability evaluation done by inspection instruments, avoiding failures but also changing components earlier, wasting money.

Customers require improving safety on equipment, also in order to reduce costs related to down time and to optimize spare part handling, but it is possible only if unplanned failures can be avoided or reduced. So CBM implementation helps to meet customer needs reaching these goals. Competition increasing, economy recession and profits decreasing are pushing companies to choose after sales solutions to provide condition based maintenance services. Indeed after sales service allows improving financial benefits, increasing revenues and also margins. It is demonstrated that services are a more stable market, capable to face also economy recessions. Moreover the after sales service can give the opportunity to compete on the basis of the differentiation instead of cost competition. Furthermore after sales services can be used to reduce the distance between customer’s needs and research and development area. In case after sales service supports the production, it is possible to use information collected to improve the development of products in the direction of customer needs.

So opportunities can be summarized as:

- Technology availability: ICT technologies can be used more that in the past due to costs reduction; now devices and techniques are more accessible.
- Policies Improvement: ICT technologies allow getting data and better investigate on systems, in order to implement more effective maintenance policy.

- Services added value: Context factors reduce market availability stressing on cost competition, services allow switching the competition to the differentiation, obtaining better results.
- Customer knowledge: Services allow directly meet customers, in that sense companies can improve their customer knowledge.

1.3 – Structure of the Work:

This research was done with the collaboration of VTT Technical Research Centre of Finland (www.vtt.fi). Indeed both Politecnico di Milano and VTT were interested to investigate on the same research field. Politecnico di Milano had already worked on System Dynamics simulation language; Farrukku and Gasparetti (2010) is focused on the representation of maintenance services describing a general level view of all systemic features, so the purpose of this research is to continue their work describing a model that is able to be more detailed, in order to investigate on the technical level of maintenance services. This research work is focused specifically on the description of maintenance monitoring services to prevent failures and to implement a condition based maintenance policy, to demonstrate benefits and criticalities of inspection services provided to the customer. In that sense, it is focused on the modeling of components degradation and on failures correlation to support technically costs generation in each case, considering maintenance interventions, down time, inspection service and spare parts costs.

VTT needed to develop a tool that is able to support his monitoring services, communicating the added value of condition monitoring to his customers. Monitoring service process that needs to be supported is described in the following figure:

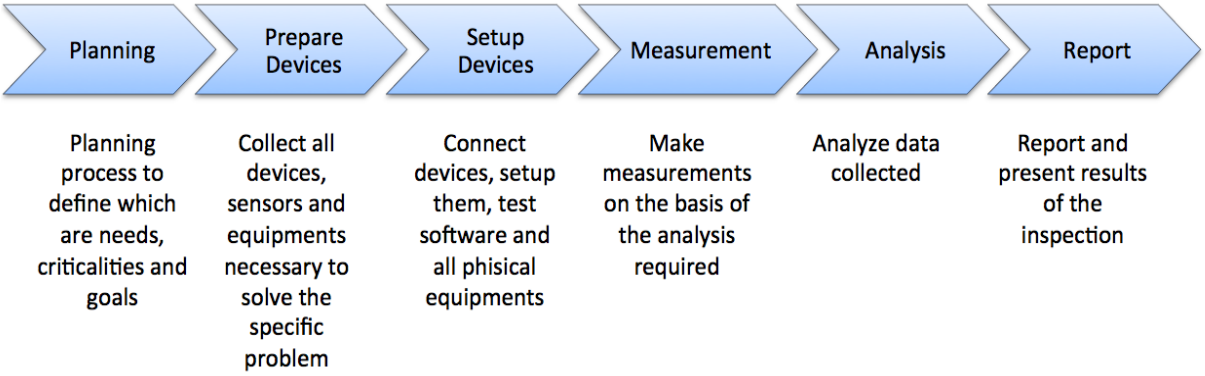


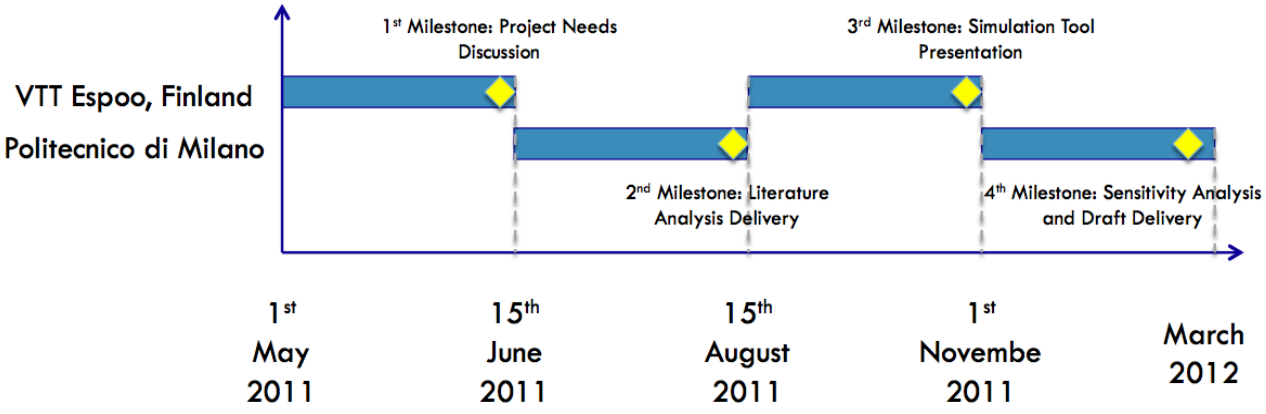
Figure 1.1 – Inspection Process

Considering the closeness of purposes it was profitable to join efforts to develop a simulation tool based on literature researches but also strictly supported by real problems of customers and service providers.

Method used to develop the tool follows these steps:

- Problem description
- Literature research
- Conceptual model definition
- Model building
- Validation of the model

Work process required four macro steps to implement the methodology defined, spending two periods in Finland and two periods in Milan. The following Gantt describes these periods:



Graph 1.1 – Tool Project Development Gantt

1st May 2011 – 14th June 2011: In the first period it was spent time in VTT working with maintenance research team to understand services provided. Several meetings were organized to talk directly with technical staff who described his needs and with customers managers who described customer problems, needs and expectations. Therefore it was developed a database structure to support the model development in order to include in it all technical information, but also to use it as a more understandable interface for customers. At the end of this period, before leaving VTT, it was organized a general meeting to clarify and set needs of the simulation tool development project.

15th June 2011 – 14th August 2011: Second period was spent in Milano, in this time it was done a complete literature research on problems underlined in Finland. Information collected was also analyzed in order to be ready to present a conceptual model to answer the requirements previously collected.

15th August 2011 – 31st October 2011: Third period was spent again in Finland. In this time it was presented the conceptual model to stakeholders of the project. Maintenance team, technical staff and customer managers discussed and improved it and finally they approved it with a qualitative validation. Then the idea was discussed with IT research staff that works specifically on system dynamics simulation, which carefully and proactively supported the tool building on the basis of conceptual model previously done. Anyway simulation tool development required making an additional literature research about specific modeling information to support the work. Furthermore the tool was tested step by step by customer managers and technical staff to check its consistency with the target. Finally the tool was presented in a conclusive meeting with stakeholders.

1st November 2011 – March 2012: Last period was spent in Milano making a review of the model developed at VTT, making a sensitivity analysis of it supported with data collected in an Italian case of study and writing the thesis.

Reference:

CONTENTS	REFERENCES	PUBLICATION YEAR	WORK CONTRIBUTION
A supporting tool for the evaluation of CBM impact in After Sales Services.	Farrukku K., Gasparetti M., DIG, Politecnico di Milano.	2010	Politecnico di Milano background reference on maintenance simulation field

Chapter 2 – After Sales Services

Nowadays services are more and more important in business creation because of context factors Alexander et al. (2002), indeed several researches investigate on the after sales services The purpose of that chapter is to present a literature review on services features, focusing on the added value that lead to the implementation of those solutions, but also describing motivations which justify the need of a simulation tool to support decision maker.

2.1 – After Sales Services Added Value:

Manufacturing sector is moving to after sales business, Lay et al. (2009), Meier et al. (2010) and Rothenberg (2007) document the increasing trend to base business on service models. Authors called that process tertiarisation or servicizing of industry sector. Meier et al. (2010) describe in details the paradigm shift of engineering industry that stopped to focus on the product and started to link services to it, creating a mix of products and services called product service system (PSS). In that sense many companies are focusing on supporting customer about all his needs with a customer centric view, instead to simply provide him the best goods. Hertz and Finke (2011) underline that maintenance business follows this trend providing service contracts or proactive maintenance based on condition monitoring of products during their whole lifecycle.

Cohen Agrawal and Agrawal (2006) underline that this is the golden age of service business, companies are moving to after sales services, but most of them do not understand really which are the opportunities in that field and they waste their potential. Most of companies still consider services as a duty (i.e. warranty or assistance service) and they focus on the optimization process and cost reduction to compete with competitors. They show results of studies, that explain how companies, which stress on the cost competition, are not favorite. A reason of service power is also explained in Alexander et al. (2002), consumers have a willingness to pay around half of the original price for a repair of a product and they said that margins on replacement are 50%, indeed in service contract this value increase up to 70%.

Recently, due to a context of high market pressure, global competition and decreasing of profits from sold products, after sales services increased their importance thanks to:

- Product added value
- Source of differentiation from the competitors
- Increase market share for the firms
- Strategic driver for customer retention
- Customer satisfaction connected to the value-in-use

In accordance with Cohen Agrawal and Agrawal (2006), it is strictly important to underline that, services can provide lots of benefits, but only if they are correctly handled and with the right after sales service culture. Customer satisfaction strongly depends on quality of services; so the service, which does not reach customer expectations, it cannot provide expected value.

Financial Benefits of After Sales Services:

Literature review demonstrates that after sales service models can significantly improve financially companies, in that sense Hertz and Finke (2011) highlights that IBM, which was transformed in a service company, has recently overtaken Microsoft in stock market value, from 41 % of service revenues in 2003 to 55.3% service revenues in 2007. Godlevskaja et al. (2011) says that a combination of products and services create a higher financial value. Also in Dennis and Kambil (2003), authors underline that after sales services had contributed to 25 % of all revenues and 30 – 40 % of all profits in many of manufacturing world companies. Some examples are available on this topic to demonstrate the relationship between earnings and the after sales field: Wharton Stanford Service Supply Chain Thought Leaders Forum says that in 2004 companies generated between 29% and 50% of revenues from services. AMR Research Report 1999 makes an estimation of 45% of gross profit from the aftermarket, generating 24% of revenues. In that paper authors also describe an Accenture study about GM that gains 9 billion of dollars in after sales services in 2001, and a Wall Street study which demonstrates a direct correlation between after sales service quality and company stock price.

Another important point was underlined by Hertz and Finke (2011): services can assure more or less stable revenue contributions that can be a benefit especially in recession time, helping companies to handle economic crisis.

Despite that the choice of these models can guarantee big gains, it seems that much more could be done in this direction. Services are not developed as best as possible, probably because of handling complexity. It is surely possible to improve them, additional revenues could come from services if they would be increased, they could even be 400% of sales price, Wagner et al. (2007).

Strategic Benefits of After Sales Services:

Some authors stress on the strategic effects that after sales services can provide. In accordance with Legnani et al. (2009) and Kurata and Nam (2010) the higher advantage is the possibility to compete on the differentiation instead of costs, indeed availability and quality of services result more important for the customer, than a low price, also because services can be personalized much more than products. The customization allows building long term relationship with customers increasing revenues and margins, moreover free and basic services can be used to capture the attention of customers. In that sense Tang et al. (2008) underlines that good services improve the customer satisfaction and the loyalty; this is possible when services are able to reach customer expectations: understanding their wills and communicating correctly company purposes. Exactly in that sense Goffin and New (2001) say that after sales service area can interface close to customers to better understand needs and criticality of the product, so that information can be used in the development department, improving solutions in a more customer centered view.

Several authors wrote about these points, also Cunningham and Roberts (1974) and Lele and Karmarkar (1983) highlight the importance to switch from cost to quality competition. Indeed Boyt and Hrvey (1997)and Desiraju and Shungan (1999) confirm that, in the sector of manufacturing goods, this strategy leads to a long term relationship with customers and it guarantees customer satisfaction and loyalty. In that sense, Cohen Agrawal and Agrawal (2006) say that ABB, Caterpillar, GE and Saturn companies obtained a strong loyalty at the same way.

Customer Satisfaction Importance:

Cohen Agrawal and Agrawal (2006) underline how in automotive field, it is possible to highlight correlation between after sales service quality and purchasing tendency. They explain that customers do not expect to receive a perfect product without any failure, they know that problems can happen but they expect to be supported in problems solution having a quick answer. They are often disappointed because of the low quality of reparation service, instead of failures. Authors conducted a survey in 1997 to establish the relationship between after sales services and customer satisfaction and they discovered that satisfaction level was about 10% - 15 % lower than customer expectations. It was assessed that in those years customers were disposed to wait for 2 days to get a solution, nowadays this time is reduced to 15 minutes.

Considering these factors, a good after sales service can directly influence customer's actions. Therefore, surely services can be a great perspective for the future, but it is always more important to be able to manage their complexity as well as possible, in order to actually reach customer expectations and to be able to really get benefits showed by literature.

2.2 – Why After Sales Services Require to Be Supported by a Modeling Tool

2.2.1 – After Sales Services Complexity:

The main problems of after sales services are concentrated on the complexity of systems that need to be handled. It is required the use of service network strategic planning, so considering every system suffers from variability that affects decision maker choices, uncertainties must be handled. In that sense Alexander et al. (2002) highlights that there is a big potential for improvements in after sales services: the developing of frameworks or tools to assist decision makers is considered the first step to do.

Finke and Hertz (2011) make a study on the uncertainties in after sales service and they also underline that service network planning process is still in an infancy state, because of complexity and uncertainty of parameters which affect performance and operations, referring to the use of integrated and structural approaches. In that sense an excellent planning requires to consider all important factors, clarifying which aspects really affect these problems.

Chase & Erikson (1988), Ellram et al. (2004), Erkoyuncu et al. (2011), Nie and Kellogg (1999) and Vargo & Lusch (2004) describe services intrinsic features, which are directly connected to their complexity:

- Intangibility: it represents the feature in which services cannot be purchased, seen or touched from customer.
- Inseparability of production and consumption: it represents the impossibility to separate the production from the consumption time.
- Customer influence: it is a consequence of previous feature that affects in production process customer involvement, influencing results.
- Heterogeneity: it represents a consequence of customer involvement that makes heterogeneous services provided.
- Perishability: it represents the feature in which services cannot be stored for sale in future.
- Labour intensive: it means that service process usually requires more human involvement and efforts instead of automated solutions.

2.2.2 – After Sales Services Uncertainty:

Uncertainty was analyzed by Finke and Hertz (2011) that made a literature overview in order to identify categorizations of the problem. They divide uncertainty in external and internal and they integrated this view with Meier (2010) one who divides it in customer demand related uncertainties and supply related uncertainties. Authors also consider other categorization levels identified in literature: internal processes problems, people, systems and external event. Finke and Hertz (2011) consider these categorizations just making some adjustments, indeed they changed 'internal process problems' to 'organization' because process failures depend on organization choice and they also prefer to change 'external event' as 'macroeconomic'. In that sense they built a classification of uncertainties categories in in after sales field service network, as showed in the following figure:

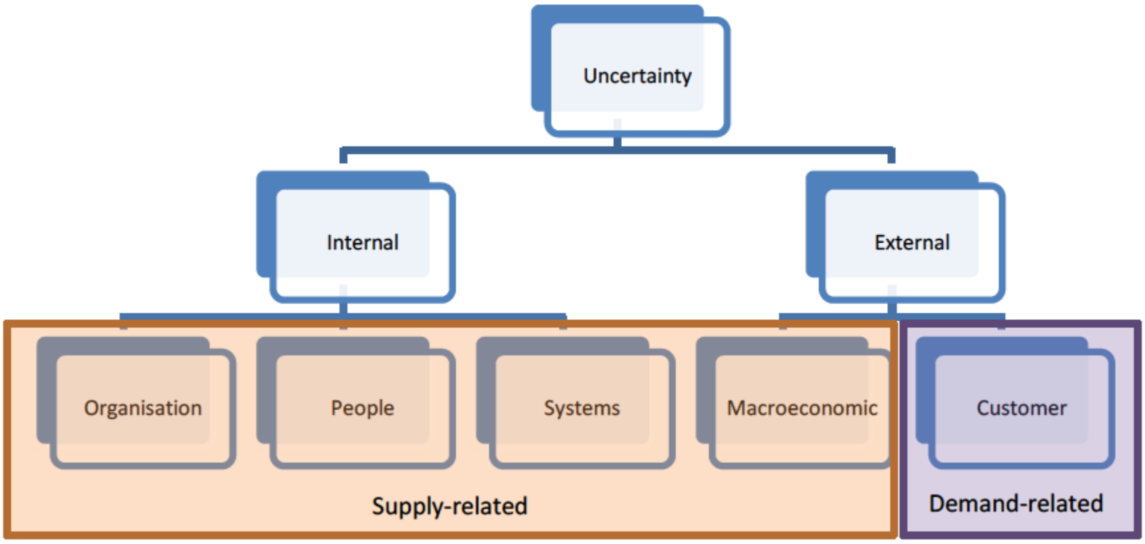
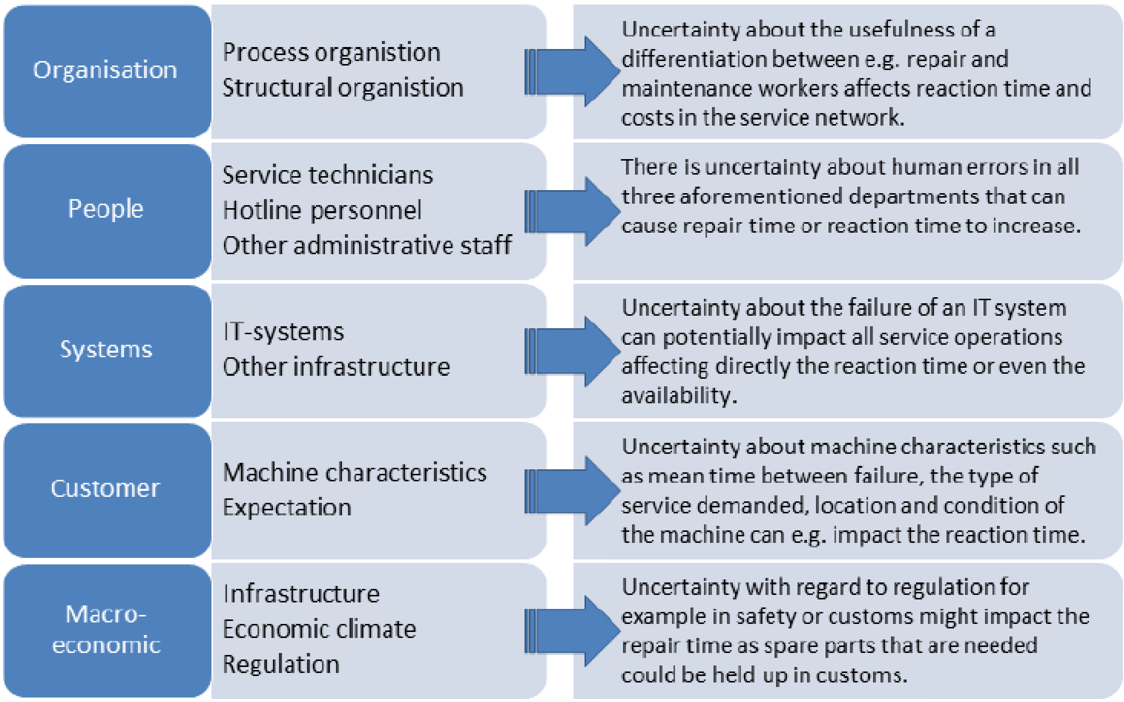


Figure 2.1 - Uncertainties categories in in after sales field service network (Finke and Hertz 2011)

- <u>Organization</u>: Uncertainty related to organization is represented by the lack of organizational structures knowledge to handle processes. In accordance with Saccani et al. (2007), organizational configuration of services depends on vertical integration, centralization levels and the decoupling of activities. Organization uncertainties, in maintenance field, are related for example to spare parts handling or maintenance policies in order to reduce costs and be reactive in response time. Wrong choices on the organization level, depends on wrong interpretation of the system, directly affecting on performances and customer satisfaction.

- People: Uncertainty in that case is defined as the inability to avoid human errors. Anyway human errors cannot be completely avoided, but people need to be supported by instruments to get knowledge required and reduce this possibility. Tool development helps to solve those problems. For more details Dhillon and Liu (2006) study human errors specifically in maintenance cases.
- System: Uncertainty in that field is generated by the possible ineffectiveness about internal company systems used to support services.
- Macroeconomic: This category is an external uncertainty source, it is not verifiable by companies and it is composed by three elements: general available Infrastructure to support services, general economic climate and regulations presence.
- Customer: This category is the most important source to be considered, in order to evaluate the introduction of uncertainties, indeed customers are obviously external. One of most relevant element, which affects service performances, is the demand estimation.

In the following figure it is presented an overview of uncertainties on after sales services making some examples:



Organisation	Process organistion Structural organistion	Uncertainty about the usefulness of a differentiation between e.g. repair and maintenance workers affects reaction time and costs in the service network.
People	Service technicians Hotline personnel Other administrative staff	There is uncertainty about human errors in all three aforementioned departments that can cause repair time or reaction time to increase.
Systems	IT-systems Other infrastructure	Uncertainty about the failure of an IT system can potentially impact all service operations affecting directly the reaction time or even the availability.
Customer	Machine characteristics Expectation	Uncertainty about machine characteristics such as mean time between failure, the type of service demanded, location and condition of the machine can e.g. impact the reaction time.
Macro-economic	Infrastructure Economic climate Regulation	Uncertainty with regard to regulation for example in safety or customs might impact the repair time as spare parts that are needed could be held up in customs.

Figure 2.2 - Categories of uncertainty and examples (Finke and Hertz 2011)

On the basis of features of services, considering how important they are in the current situation, authors underline that it is fundamental to improve and support as much as possible planning process in service network field, in order to handle complexity and uncertainties presented and to guarantee the achievement of customer performance expectations. Lin et al (2002) underlines that the use of CBM strategy tries to reduce those uncertainties.

2.3 – Decision Making Supporting on After Sales Field Service:

Considering all criticalities found in after sales service, companies try to answer to the problems, monitoring what is happening. Their purpose is to understand the service, to improve its quality level and to guarantee the customer satisfaction. Anyway customer satisfaction is not the only performance that needs to be monitored in order to guarantee quality of after sales services. Gaiardelli et al. (2007) propose a framework to measure performances on different levels:

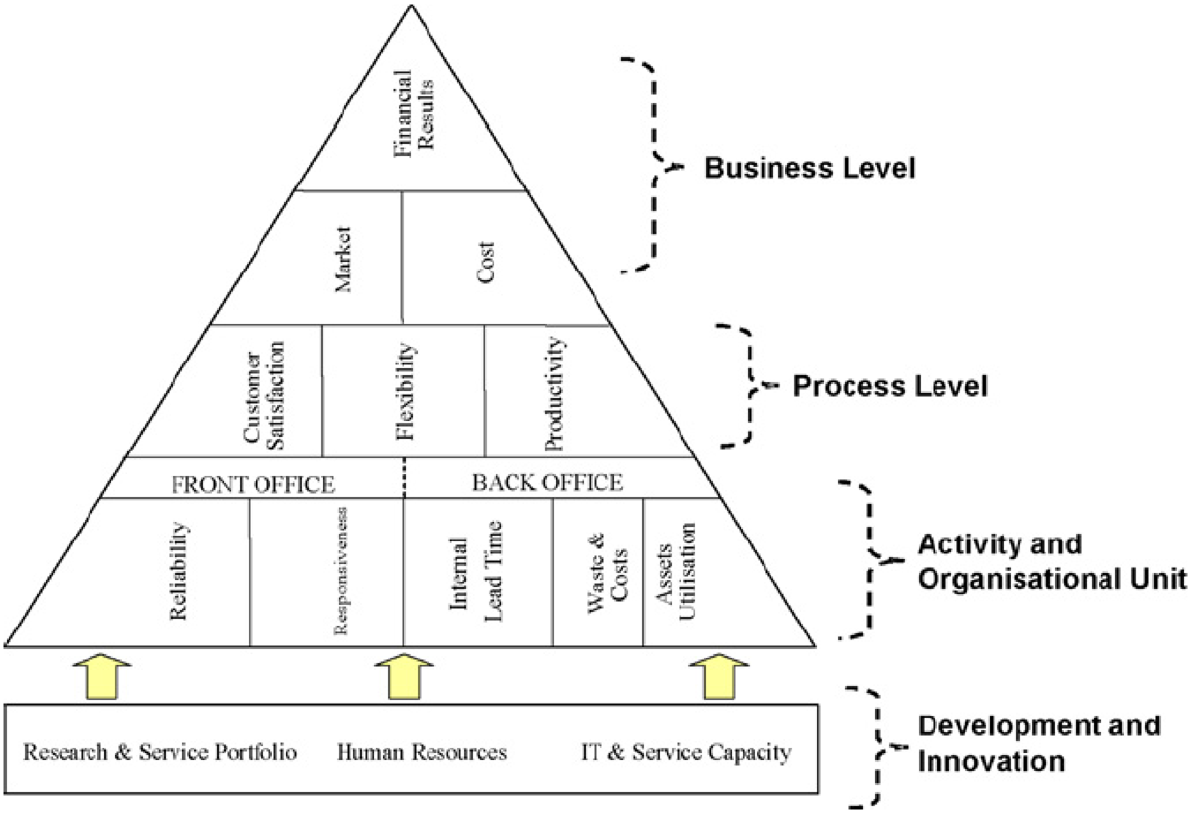


Figure 2.3 - A performance measurement system for after-sales services (Gaiardelli et al. 2007)

The framework proposed links strategies of each actor involved in the after-sales service with their related performance attributes, which include a short-term and a long-term perspective. Anyway in most of cases it is difficult to define KPI and to monitor performances correctly, it is often difficult to understand which are problems so before define right KPI it is fundamental to know the system.

Literature highlights how it is difficult to develop an accurate service planning process. Cohen Agrawal & Agrawal (2006) underline that the first problem in a company is the lack of capability to understand and to handle complexity; every year 23% of spare parts became obsolete because of that. Legnani et al. (2009) analyzed process performances to develop ASFS network and divided them in accordance to service lifecycle and criticality (i.e. strategic level, tactical level, operational level). Surely performance monitoring is fundamental to understand problems and opportunities, but it is often difficult to define the right KPI. Most choices require to be supported having a whole systemic view. Supporting tools can play a big role in that sense clarifying system relationships, indeed management must be helped in decision making following efficiency and effectiveness goals. Maintenance service belongs to such areas that need to be supported.

In order to tackle those problems, literature studies support the idea that after sales services requires models, which help decision maker to handle complex systems. Strategic network planning requires the use of modeling to be understood, Meier et al. (2010). In accordance with Hertz and Finke (2011) it is possible to identify 3 models categories used to support after sales services:

- Mathematical models
- Queuing models
- Simulation models

<u>Mathematical models</u>: they are used from some authors in literature, for example Klimberg's and Van Bennekom's (1997) talk about an optimization mathematical approach to support facility location decisions for after sales field service network, instead Farhani (2010) and Araz (2007) propose a multi-objective maximal covering location model for emergency services. Tamir and Halman (2005) develop a model to solve an extended p-center problem (p-center problem is a facility location-allocation problem that is based on the minimization of maximum distance between client and the facility to which it is allocated). The main problem related to mathematical models is that they seem inefficient in too complex cases because they have not the capability to model the system in a dynamic way.

<u>Queuing models</u>: they have the advantage to incorporate multiple uncertainties, that significantly impact on parameters i.e. costs, time response and failure rates, but even if they can be used to investigate more complex problems they cannot be detailed enough for realistic studies. Examples of the use of these kinds of model are available in Tang et al. (2008) who developed a model to investigate the relationship between staffing levels, travel distance and time window service levels, but also in Waller (1994)

that present an approach that includes manpower allocation, availability of spare parts and emergency delivery options.

Simulation models: Ford (1995), Struben (2006), Bosshardt (2006) and Zang (2007) are all examples of studies to evaluate system dynamic simulation method as the best supporting choice in automotive PSS (Product Service System), but a lot of others examples are available in literature. Simulation models seem the best choice in maintenance services handling, indeed Mjema (2002) underlines how maintenance problems are too complex to be handled by analytical models and said that simulation may be the most appropriate technique to cope with maintenance issues. In literature some authors (i.e. Dear and Sherif (2000), Mjema (2002), Visser and Howes (2007)) present simulation models supporting services and others present simulation frameworks. In particular Lin et al. (2002) presents a simulation framework specifically focused on CBM to analyze the impact of the policy, describing the main features of a real scenario in a detailed way.

Bianchi et al. (2009) underline that PSS systems require a support, which is able both to promote PSS and to identify critical factors of the system. They state that simulation is the best solution because it can dynamically analyze strategies required to manage complex non-linear factors with positive and negative reinforcement loops. In particular, They choose System Dynamics as the best methodology to face simulation of an after sales service in accordance with literature studies.

It is now clear how much strategic are after sales services, but also how much it is difficult to handle them and to make decisions considering all information which really affect the system. Models proposed become ever and ever important in order to be able to achieve successful results in this field.

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Chapter 3 – Maintenance Service Model

System modeling involves investigating contents of several fields, indeed the right tool development requires to analyze their trends and features underlining needs and criticalities. In that sense the purpose of this chapter is to explain why maintenance is important in companies and why the use of a simulation tool is fundamental to support the decision maker when facing issues related to maintenance services.

A section is reserved specifically on condition-based maintenance (CBM), highlighting benefits, in order to introduce the reader to this kind of preventive policy. Another section is reserved to description of the added value of CBM, describing tests and techniques used to investigate on components that represent features of the service implemented in the model. On the other hand, in this chapter, literature about spare parts management is not specifically discussed, because it was enough discussed in previous works that are the background of this thesis. For more details to this concern, it is possible to refer to Farrukku and Gasparetti (2010).

Finally, the last part of the chapter is dedicated to a literature review (21 paper) of the use of simulation in maintenance field, discussing motivations, which lead the need of simulation support, and describing how it is possible to develop an effective conceptual model.

3.1 – Maintenance Introduction

In accordance with Noemi M. Paz and William Leigh (1994), the direction of industries efforts focusing on profitability increasing. Companies want to improve quality, supply a good service and guarantee safety, reducing costs as much as possible.

Companies are changing very fast, there is a strong growth about complexity of operations: mechanization increase, plants are always more automatized (i.e. flexible manufacturing systems or flexible assembly systems). Mann (1983) says that automation increase forces industries to be lead with more maintenance workers then production workers.

Considering this kind of trends, cost growth is more and more challenging and maintenance area is involved too. We have to consider that a failure is both a lack of production but also a worsening of safety and quality. Wireman (1990) conducts a study on industrial firms of USA and discovered that maintenance costs increase by 10-15% every year since 1979. In accordance to Noemi M. Paz and William Leigh (1994) the percentage of productivity in maintenance workers is low, about 30-50%, these data are linked with inefficient of maintenance department and a bad organization. All these information highlights how is becoming important to focus on maintenance and to consider it a basic area to improve in order to reach enterprise targets.

The terminology standard SS-EN 13306 (2001) defines maintenance as:

"Combination of all technical, administrative, and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function."

Anyway it was normally considered as a support to production area, interventions were seen as annoying events because of stops of production. But something is changing; considering more recent references, Takata et al. (2004) explain maintenance has taken a life cycle management approach. In accordance with DeSimone and Popoff (1997) and Cunha and Caldeira Duarte (2004) there are two important trends in maintenance activities:

- To participate in design of product to define how should be made to be easy to maintain "eco-efficiency".
- To introduce more intelligence in product "active product".

The role of maintenance is becoming strategic, it is linked to enterprise performance, it is getting “predict and prevent” method instead “failure and fix”, indeed to prevent problem can reduce costs and at the same time reduce Down Time in production. In accordance with Francois Pérès, Daniel Noyes (2003) the target is to maintain system of production in a working condition as long as possible or restore it as quickly as possible in case of failure. Life Cycle Maintenance concept is emerging, and also one related to maintenance value chain Takata (2004).

All the changes are supported by Information and Communication Technologies (ICT): eMaintenance, CBM solutions and a good mix of policies help the changing to be more forceful, in fact all data need to be collected and integrated, starting from object data, worker data until system data, Adolfo Crespo-Marquez and Benoît Iung (2008).

3.2 – Why Condition Based Maintenance

As described in the previous section the maintenance approach has changed in the direction of preventive approaches. Several authors gave a definition of CBM in literature: “Maintenance actions based on actual condition (objective evidence of need) obtained from in-situ, non-invasive tests, operating and condition measurement” Mitchell (1998), instead Butcher (2000) says: “CBM is a set of maintenance actions based on real-time or near real-time assessment of equipment condition, which is obtained from embedded sensors and/or external tests & measurements taken by portable equipment.”

Further British Standards Institution (1993) says that Condition Based Maintenance approach is used to reduce uncertainty on maintenance, and it depends by conditions monitoring devices that show which one is the need.

In accordance with a study of Tse and Atherton (1999) Condition Based Maintenance policy tries to solve common maintenance problems, as: how to pre-plan maintenance actions on sophisticated components with high complexity and difficulty to predict their behavior; how to reduce stock costs related to spare parts handling; how to avoid health risks on failures and how to reduce not planned maintenance actions in the system. Moya and Vera (2003) defines the purpose of CBM policy saying: “…improve system reliability and availability, product quality, security, best programming of maintenance actions, reduction of direct maintenance costs, reduction of energy consumption, facilitates certification, and ensures the verification of the requisites of the standard ISO 9000”. The strong relationship between failures and costs obliges to plan and to detect problems before they are catastrophic failures that create other problems to the whole system. CBM can guarantee a reduction of spare parts, a reduction of unnecessary maintenance actions, using entities almost for their whole life ensuring a good level of health.

Grall et al. (2002) said that, if deterioration of the system or a control parameter is strongly correlated with the state of the system, the use of condition monitoring allows the implementation of condition based maintenance policy, obtaining the possibility to base each decision on the actual monitored state of system, instead of the use of a time based policy. Therefore it surely improves the effectiveness of maintenance decisions; clearly it is possible only if failures are not completely random.

CBM policy assumes there is the possibility to understand what will happen to an entity, using different tools and analyzing weak signals. They can be detected with diagnostic methods to qualify the equipment state. It is fundamental to understand actual behavior of components to prevent what will occur. Information has to show changings in performances in case there will not be maintenance actions, for example detecting the deterioration of a material or changes in specific parameters of the system.

Rao B. (1996) underlines that CBM demonstrated to be able to minimize maintenance costs, to improve the safety level and to reduce the quantity and severity of system failures. Also Lin et al. (2002) said that the use of condition based maintenance, supported by equipment condition guide, has the capability to reduce down time as well as the reduction of maintenance costs, but the paper underlines that it is also important to consider specific costs related to the implementation of the policy. It means there are costs to install and use monitoring equipment (i.e. sensors, computers) and all costs that involve in monitoring actions. Therefore it is necessary to make an evaluation of both CBM policy benefits (failures avoided, the reduction of down time, different maintenance costs) and the additional costs for the policy implementation. In that sense, a component requires CBM policy only if the whole evaluation of costs is beneficial. Considering the high level of complexity of systems, which generally requires CBM, simulation tools are often used to support this evaluation. For a more accurate CBM trade-off assessment, it is possible to refer to Al-Najjar and Alsyouf (2003) and Starr (1997).

CBM policy structure is well described by Chinnam and Baruah (2004) through the use of an architecture for condition based maintenance:

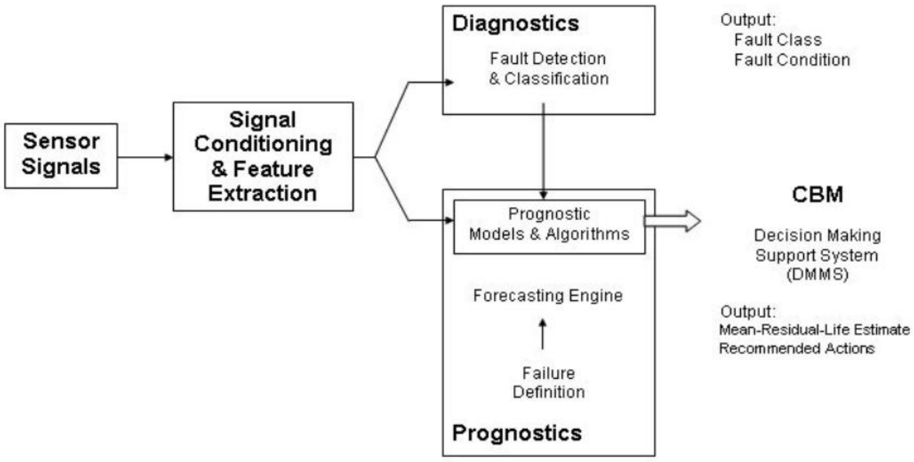

Figure 3.1 – Basic CBM structure (Chinnam and Baruah (2004))

Diagnostic activities are operations that investigate on the current object state using historical and monitoring data, indeed prognostic activities are operations that investigate on what will be object conditions. Sensors are mounted on the monitored components in order to capture degradation signals that can lead to a development of the maintenance policy. Advances in sensor technology, data acquisition hardware and signal processing algorithms, reductions in cost for computing and networking, and the increased easiness for information technology products, makes diagnostics and prognostics more effective as well as cheaper, that allow to support decision maker evaluations.

The use of condition monitoring involves the representation of components reliability estimating the reliability step by step.

It is hard to predict the date when they will occur, but it is possible to use the changed condition of the equipment to understand when a failure is coming, indeed condition state usually changes progressively through condition levels before to not work. The base level describes normal functioning, the increasing levels signal the state of the equipment until the emergency state which involves there will be imminent failure. Condition alarms are represented in the figure below:

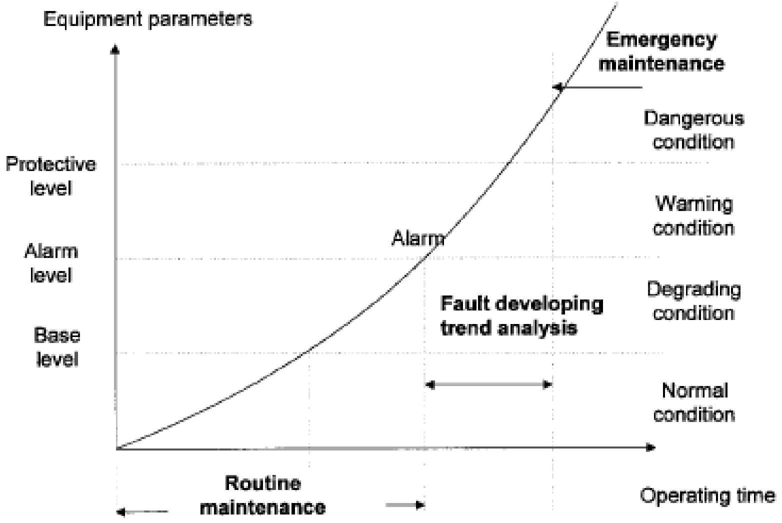

Figure 3.2 – Condition Alarms (Yam et al. (2001))

Failure conditions, on the variation of reliability, are set in accordance with criticality of components: costs are the main reference, but safety plays a big role too, indeed more dangerous can be a failure and more the condition emergency levels are pressing.

3.3 - Monitoring techniques

In this section condition monitoring techniques are presented, describing their features.

Monitoring is defined by SS-EN 13306, 2001 as:

“Activity, performed either manually or automatically, intended to observe the actual state of an item.”

Instead Beebe (1998) said that condition monitoring is the process of systematically collecting data for the evaluation of asset performance, reliability, and/or maintenance needs for the planning of maintenance actions.

Anyway quite a lot authors wrote about monitoring and about the architecture of condition monitoring systems, for example one of main reference on the topic is Rao B. (1996) who describes in detail benefits, approaches and techniques of it.

Wilfried et al. (2003) say that the use of condition monitoring is increased because of these factors:

- increased quality expectations reflected on product liability legislation
- increased automation to improve profitability and maintain competitiveness
- increased safety and reliability expectations reinforced by legislation
- increased cost of maintenance and production due to labor and material cost
- increased market pressure due to globalization of markets

Surely technology speed calculation improvement and telecommunication allowed developing modern monitoring systems, indeed the supply of more cost-effective monitoring tools has been made possible by technical advance such as:

- reduced costs of instrumentation,
- increased capability of instrumentation such as data pre-acquisition, data storage, radio transmission direct by
- the sensors with integrated electronic circuits,
- improved data storage media in combination with low cost computation, and
- faster and more effective data analysis using specialist software tools.

The analysis of maintenance problems requires having engineering knowledge on failures, but also the possibility to collect enough data to favor their detection. Companies need to be specialized in monitoring process techniques to be able to collect data and manipulate them in the right way, in most of cases due this knowledge management complexity, measurement service provider are becoming always more specialized in specific techniques. Rao B. (1996).

The major measurement technologies used within condition monitoring are:

- Vibration
- Lubricant Analysis
- Thermography
- Acoustic Emission

Vibration analysis is the most used technology and the most tangible, Higgs et al. (2004). Almost all machines generate vibrations and it is simple to monitor the link between vibrations and component conditions. Attaching accelerometer sensors to the machine it is easy to collect data, because mechanical processes and fault types all produce energy at different frequencies. Separating frequencies through spectrum analysis, it is possible to investigate with a higher level of detail on what kind of failure will occur. Rao B. (1996).

Lubricant analysis is the second most common technique and it is used especially to detect the root cause of a problem. Indeed it is possible to detect very small dust particles and remove them even before they cause any abrasive damage to the component or detect ferrous materials carried out by lubricant. In this category it is included contaminants detection but also viscosity checks and moisture evaluation, but the problem is that samples need to be taken away to laboratory to analyze them. Rao B. (1996).

Thermography is commonly used to evaluate temperature distribution in electrical panels, to detect loose of connection or hot spots in the system. It is also used referring to pipework, vessels, bearings and couplings even if users of that technique need a little training for the interpretation of data. Rao B. (1996).

Acoustic Emission is used combined with vibration analysis for the detection of friction or the presence of energy bursts in rotating components attaching sensors in the same position or with the same transducer to create economies in time and manpower in collecting data process. Rao B. (1996).

Many factors involves to choose the more appropriated technique to use, each case is different and requirements lead the choice, but after a literature review that compares monitoring techniques, it is possible to maintain that, especially on rotating machinery, the most useful CM technique is vibration analysis. In accordance with studies of Want and McFadden (1996), Maxwell and Johnson (1997) and Luo et al. (2000) vibration analysis is the greater and more reliable investigation technique, resulting both efficient and effective. The powerful of this technique is that mechanical failures, caused by physics phenomena, produce an increasing quantity of vibrations that are analyzed with spectra frequencies. Each failure on a component kind produces a different signal with a recognizable shape because this technique allows distinguishing natural frequencies from the noise. Each specific problem is classified following spectra results component by component (i.e. bearing, shaft or gear problems can be affected by different problems as unbalance, misalignment, cavitation etc.) identifying the incoming failures; Barron (1996) and Eisenmann (1998).

Through an experimental study, Ahmadi and Mollazade (2009) investigate on the correlation between vibration analysis and fault diagnosis, in order to evaluate the effectiveness of the condition monitoring technique in case of bearing fault diagnosis of a mine stone crasher. *"The results from vibration analysis of this practical study indicated some defaults in our bearings. From the vibration analysis of stone crasher left and right side bearings, it was determined that bearings were in an unhealthy condition. The correlation between vibration analysis and fault diagnosis was able to present a boarder pictures for machine condition. Vibration analysis technique was capable in covering a wider range of machine diagnostic and faults within the bearings"*

The conclusion of the study was that collecting natural frequencies of ball bearings and both sides of it, using a Fourier transformation to calculate spectrum of frequencies, it is possible to detect problems just comparing current vibration with expected one. In this way, the approach does not require to stop machine to make measurements.

Citing Wilfried et al. (2003) "*The experiences obtained by monitoring several machine arrangements in power plants as well as in production industries prove the successful use of aimed vibration monitoring for fast failure source localization and process optimization at machines in operation. Most installed vibration monitoring systems serve for threshold comparison and alarm monitoring. To get the alarm is state of art, to quantify and classify the obtained information is the second step implemented in modern process control systems. To fix the excitation source and to develop reaction strategies with short time delay proving the success of actions still requires certain expert knowledge. As proved by several industrial projects the interlink between vibration analysis and the process parameters represent a fast and reliable tool for condition-based description of Machines in operation*". In accordance with the authors vibration analysis results an optimum method to monitor health status of components in case of manually or automatic inspections. In most of cases it is considered a profitable strategy also from an economical point of view if compared with others monitoring techniques, indeed investment costs can be amortized easily.

Considering his importance it is better to deepen the knowledge on that technique. Vibrations are ubiquitous, they are defined as a periodic motion about an equilibrium position and they can be generated by rubbing of materials or others mechanical phenomena that have all different frequencies. Rao B. (1996) presents in detail the handling data and their manipulation to obtain information on equipment condition.

More details about vibration analysis are provided in Annex 1.

3.4 – Why developing a simulation tool in maintenance field

3.4.1 – The purpose of simulation models

Maintenance needs and trends were discussed at the beginning of this chapter. They underline the importance to guarantee safety, reliability, availability of machines, but also low costs. Moreover they highlight the importance to provide quality and challenging services and to communicate benefits to the customer. Anyway correct choices needed to reach expected results depend on the possibility to understand systemic behaviour. Several authors wrote about this topic underling how models, especially simulation, are the right choice to face complexity and uncertainties of services and to support decision maker in maintenance field. Indeed simulation models are fundamental to supports complex systems comprehension to optimize parameters, make an assessment of strategies.

Simulation goals are:

- Describe systemic behaviour
- Simplify complex problems
- Show uncertainties
- Supports maintenance decision maker in his work
    - Evaluate safety
    - Evaluate costs reduction
    - Evaluate strategic choices (i.e. Policies)
    - Evaluate planning choices

In accordance with Mont (2002), services were modeled in order to better support needs evaluation and implementation of approaches. For example Jahangirian et al. (2010) used simulation as experimentation of healthcare, defense and public services systems. Simulation allowed him testing those services and evaluating performances to better understand their behaviour. Mont (2002) says also that several models were developed to support maintenance services from simple spreadsheet to sophisticated simulation tools to support decision makers, in order to improve performances: component reliability and availability, safety of the system, quality and cost reduction. Robinson (2004) underlines that in maintenance simulation it is better to use dynamic system simulation to guarantee the capability to effectively describe the relationships between variables. In that sense, Szczerbicki and White (1998) described how to use simulation to model condition monitoring.

In the following sections there is a presentation of maintenance simulation models proposed by literature and it is analyzed a maintenance simulation framework that is considered close to the scope of this work.

3.4.2 – Literature review on simulation maintenance models

Simulation is widely diffused in operations management, but it is becoming more and more used also in maintenance field. Anyway, most of maintenance simulation tools are focused on a specific area without providing a view of the whole maintenance system.

Alabdulkarim et al. (2011) analyzed maintenance tools state-of-art and they pick out the categories of maintenance models presented in literature. They underline that maintenance requires the use of modeling solutions to support the decision maker, highlighting their added value, but also underlining in which directions should be focused efforts to improve their quality.

The following picture resumes the results of such analysis:

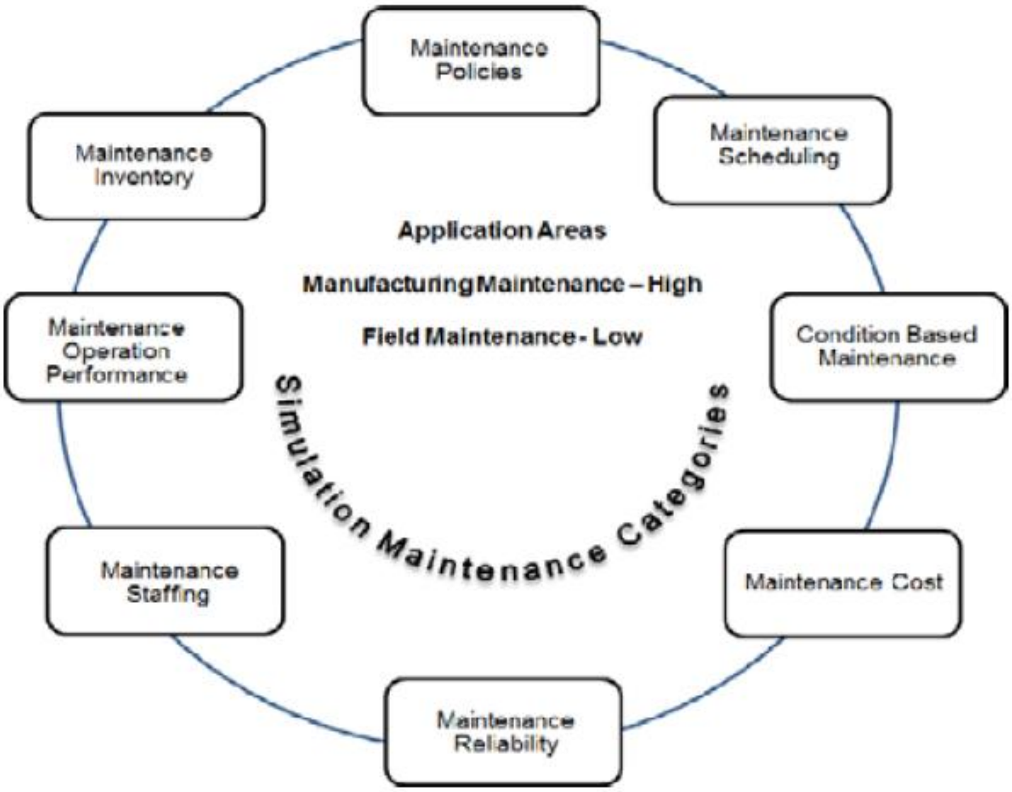

Figure 3.3 – Simulation Maintenance Categories (Alabdulkarim et al. (2011))

- Maintenance Policy:

  Some authors developed models to validate policies and to evaluate their effectiveness; their purpose is to check strategies in each specific business. To cite some of them, Hennequin et al. (2009) proposed a fuzzy logic simulation model to optimize preventive maintenance on a single component. Indeed Burton et al. (1989) and Boschian et al (2009) developed models, which include optimization. However maintenance policy modeling is pretty popular and it is generally mixed with other categories (i.e. maintenance costs, inventory) to handle their interactions.

- Maintenance Scheduling:

  Simulation in this field is used to establish maintenance events and to validate or to compare different plans, like models proposed by Celik et al. (2010) and Aissani et al. (2009). A maintenance optimization model was proposed in Cavory et al. (2001), indeed they built an optimization tool for a production process with machines dedicated to a single product. He used the model to plan maintenance during machines stops. Maintenance scheduling simulation helps to save money and time, but Cavory et al. (2001) is one of few models that include optimization to guarantee high effectiveness in that direction.

- Condition Based Maintenance:

  Grall et al. (2002) considers models of this category like tools that try to evaluate effectiveness of condition based maintenance systems case by case. One of most important literature paper is Vardar et al. (2007) who used a queuing model to evaluate how much condition based maintenance policy is appropriate to provide after sales maintenance services. Another good example is Caesarendra et al. (2010), because in this case it was developed a prognosis algorithm in a real dynamic system, so considering the dynamic importance. Anyway even if literature is full of papers of CBM policy validation, there are not so much models that make a detailed failure forecast; even if it would become more and more important in case of product service system evaluation.

- Maintenance Costs:

  Maintenance costs module is a popular category used to understand cost centers, reducing them or improving machinery reliability in order to avoid them. In some cases are developed optimization models with linear and non-linear programming, even if the use of dynamic simulation models provides more interesting results. Boussabaine et al. (2004) developed a simulation tool to evaluate maintenance sport center costs.

- Maintenance Reliability:

  Reliability affects directly on availability of machines, so it is fundamental to support this category with models in order to understand which are their features, how to guarantee reliability and how optimize parameters. A lot of papers were written about this topic, for example Ciarallo et al. (2005) and Basile et al. (2007). Anyway most of researches are focused on the evaluation of a specific component/machine in order to improve performances, but few models mix reliability modeling with other categories. One of these is Boulet et al. (2009) model that describes reliability but comparing preventive and corrective policies to understand how to reduce maintenance costs.

- Maintenance Staffing:

  Models, which are included in this category, try to establish how much workers are required and which activities need to be planned. Agbulos et al. (2006), Dinesh and Bhadury (1993) proposed models based on the staff assessment. Nothing was done in order to optimize.

- Maintenance Operations Performances:

  Performances generally monitored are directly linked to up time and down time evaluation. Luit and Knights (2001) developed a model for mine maintenance, instead Duffaa and Andijani (1999) developed one of most complete maintenance model in the whole literature about Saudi Arabian Airlines, indeed they built a model made by several modules, obtaining a systemic view and the capability to have a high effectiveness in behaviour understanding. Their model includes: planning, scheduling, organization, supply, quality control and performance measurement. Instead Ball et al. (2010) propose a model using discrete event software to evaluate performances of sensing technology on complex products. It is important to evaluate performances considering that customer could have different parameters to evaluate the service instead of provider.

- Inventory:

  Some model were proposed also in inventory area, indeed to handle spare parts correctly can save money. Chua et al. (1993) developed a spare parts module instead Petrovic et al. (1982) built an optimization inventory model, even if it is one of few people who did it.

3.4.3 – How should be an effective simulation model:

After a deep review in maintenance modeling, it is possible to underlines that:

- Most of models built can simulate the behaviour, but few of them can also optimize the system. It would be great to include optimization.
- Areas most commonly modeled are areas more related to productivity. Models require to be oriented to cost evaluation.
- Simulation is not usually oriented to customer needs and satisfaction.
- In most of cases models are not done mixing different modules; it is fundamental to model the relationship between categories to represent the whole systemic behaviour.
- Some categories could be added to complete the maintenance system description, like sensing technology module, part replacement and multiple personnel visits.

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Chapter 4 – System Dynamics Simulation

4.1 – Simulation Modeling Added Value

Every decision maker wish to use an evaluation process to elaborate information to choose the best solution. In most of cases problems to face are too much difficult to be described analytically, especially when it is required to consider soft variables, which has not an expressed metric. Anyway when complexity increases, it became fundamental to switch to simulation tools avoiding to assume a dangerous set of limitative hypothesis. Literature supports this view and explains why it should be used system dynamics.

The use of mental models is described in literature by several authors, the concept is rather ambiguous, basically they are described by J.W. Forrester (1961) and Peter M. Senge (1990) as mental images of how everything works and as beliefs about the causes and effects of what happens Sterman (2000). Making a decision involves the use of mental models to simulate and test different decisions and their consequence. People use to apply mental models to interpret reality and interact making choices, verifying the accuracy of the system knowledge and making corrections to reduce errors.

Building a model means to represent a real situation collecting information, it is necessary to pick out main elements and to isolate them to the others, determining which relationships there are among them. Usually mental models have a linear relationship between causes and effect, so, in accordance with Sterman (2000), it means that they have some limitations:

- Every factor is considered as independent
- Causality has only one direction, from cause to effect
- Every factor seems important at the same way

Therefore, more complex is the system, more difficult is to handle information without dangerous misunderstandings.

Another problem of this approach is the lack of a formal structure, indeed mental models developed by someone are difficult to understand by others as described in Sterman (1991). Despite all the defects, mental models determine how we think, conditioning what kind of decisions we make Peter M. Senge (1990). When system is very complex it becomes difficult to make decisions because people are not able to build a rational think due too much variable to consider together and because of too much variable implications. Peter M. Senge (1990) said that people tend to be distracted by the complexity, which is caused by numerous variables and details in the system.

In systems there are two kinds of complexity, Sterman (2000):

- Combinatorial complexity (also known as detail complexity)
- Dynamic complexity

Combinatorial complexity depends on the number of components or the number of combinations that must be considered in decisions, instead the dynamic complexity depends on interactions between the components.

Moreover, Sterman (2000) writes that there is dynamic complexity if the system is dynamic, that means it constantly changes, it depends on history, it is governed by feedback, it is self-organized, adaptive, counterintuitive, nonlinear and tightly coupled. In that sense it is simple to understand, that the difficulties to understand dynamically complex behavior have not a strong relationship with combinatorial complexity. In fact, a system could have dynamic complexity even with low combinatorial complexity, Sterman (2000). This highlights that information about all the details of subsystems does not explain all the complexity in the whole system. That is why system analysis methods, developed to deal with the detail complexity but not the dynamic complexity, can fail.

When decisions concern systems with high complexity, mental models are usually oversimplified Sterman (1994) and inadequate to simulate the behavior of the system J.W. Forrester (1961). Therefore, our interventions have a tendency to trigger unexpected or even unwanted outcome. Forrester calls this kind of phenomena "counterintuitive behavior". Social systems affected by complexity, which are full of soft variables that are difficult to understand and often to present unfortunate surprises J.W. Forrester (1971).

Such obscure dynamics lead often to policy resistance, which means systems tendency for interventions to be delayed, diluted or defeated Sterman (2000). Policy resistance is the system response to the interventions. Nevertheless, when these problems occur, people tend to blame external reasons for them. If this is the case, the problems may never get solved.

One of the most significant reasons to policy resistance are flawed mental models as people tend to perceive systems as series of events without recognizing feedbacks Sterman (2000). When decisions are based on such an "event-oriented thinking", a major part of the system's structure and behavior is ignored. Even if the existence of feedbacks is understood, informing dynamic complexity makes it difficult to understand the behavior. In practice, this means that system's essential causal relations, feedbacks, and their influence on the dynamics should be understood before making any decisions. Otherwise, our interventions can, and probably will, cause unexpected behavior.

Mental models are updated in the course of time as people get feedback and learn from their environment. Learning from experience is considered to be one of the most powerful ways to learn, Peter M. Senge (1990). It can be, however, slow and difficult if the system at issue involves dynamic complexity. Peter M. Senge (1990) names certain characteristics to the behavior of such systems that hinder people from learning from experience:

- actions have significantly different effects in the short and the long run,
- actions have significantly different effects locally and in other parts of the system.

In other words, learning from experience is difficult if the connection between actions and consequences cannot be seen. This inability stems from too narrow perspective to the system and too myopic thinking. As it has been discussed, people have very limited understanding of complex systems. Moreover, learning from experience can be difficult. It is important to understand these limitations of mental models and human rationality when it comes to solving problems that seem to be persistent and without solutions.

4.2 – System Thinking and System Dynamics

Considering problems related to subjectivity and complexity of systems and the difficulties to face them with not formalized framework of metal models, system thinking is the answer to those problems. The approach presented by Sterman (2000) is based on these principles:

- Each system needs to be described considering a whole view
- Every problem can be generated by multiple causes
- Behaviour of the system is caused by his structure
- A problem cannot be really solved without to understand the system structure that caused it
- Time is essential to describe a system, delays can affect relationship between cause and effect, today problems can be caused from past solutions
- Relationship must be supported by loops
- Short term view cannot be the only point of view, Long term must be considered
- Some variables can be more important of others
- Soft variables should be considered too

Sterman (2000) supported the building of models in accordance with system thinking approach with system dynamic; it is a discipline that collects theoretic and technical tools to model and simulate systems. System dynamic language allows to represent real cases building connections between variables, but it allows to simulate the behaviour and to fix errors helping the user to understand step by step the structure of the model, improving his knowledge. This approach supports decision maker describing complex features of a system that are not possible to handle without a tool and giving him/her the possibility to understand by experience, without wasting costs and time to make experiments. “*Models can be a basis for experimental investigation at lower cost and less time than trying changes in actual systems”* J.W. Forrester (1961).

System dynamics support can be classified in two categories Mollona et al. (2006):

- Ex ante (model building)
- Ex post (model use)

Ex ante means that system dynamics is able to support decision maker to understand the system, giving to the user elements to represent relationship, indeed stock, flaw, auxiliary variables and loop connections are available to describe the whole system. Instead ex post support is represented by the possibility to make decisions following results obtained with the simulation. Simulation tool can provide both.

For more details on System Dynamics, see Annex 2.

4.3 – Summary of System Dynamics

System dynamics is targeted to solve problems caused by complex feedback systems. It is an approach to study dynamically complex, nonlinear, and large systems. People are limited in understanding these kinds of systems. Moreover, for such systems, there are no known analytic approaches. System dynamics opens up a possibility to:

- Enrich mental models as it reveals the causal map concerning the problem.
- To facilitate group working among the different parties, experts of different disciplines and finding a shared view and strategy for the process.
- To simulate and test policies before put into use
- To find levers for process improvement

Reference:

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Learning in and about complex systems.	John D. Sterman, System Dynamics Review, 10(2 – 3):291 – 330.	1994	Technical knowledge about System dynamics
Modellazione, Simulazione e Apprendimento: L'Approccio System Dynamics al Controllo della Strategia.	Mollona, E., In *Le Nuove Frontiere del Controllo di gestione. Valore, processi e tecnologie*' a cura di F.	2006	Specific knowledge about system dynamics use

	Favotto, McGraw-Hill: Milano.		
The fifth Discipline: The Art & Practice of the Learning Organization.	Peter M. Senge, Century Business.	1990	Specific knowledge about system dynamics use

Chapter 5 – Conceptual Model

Literature research done allowed collecting information to understand problems and to support customer and supplier requirements underlined during the first period in Finland from stakeholders of the project that represent the scope where this thesis has been developed. To this concern, the purpose of this chapter is to present needs and criticalities underlined in the first VTT experience, but also to describe the conceptual model developed to meet requirements and to present how it is supported by literature.

5.1 – Project Requirements:

Project needs detected with the VTT staff collaboration can be classified on the basis of customer and supplier expectations:

Customer needs:

- Understand the added value of the service proposed
- See the whole systemic service impact in a long term view
- Understand benefits and criticalities specifically on the own plant case
- Provide to supplier few and simple own data to discuss about service effects
- Understand the solution proposed without a specific technical knowledge of problems, but also without a simulation software knowledge
- Translate information in the “cost language”

Provider needs:

- Demonstrate the added value of the service proposed
- Develop a supporting tool for customer manager’s work
- Develop a tool enough user friendly to be used without technical and simulation knowledge from customer manager, but describing in a satisfying way problems
- Include also technical staff needs in the service presentation
- Reduce the distance between customer and supplier cut in actively the customer
- Flexibility of the model

The development of the conceptual model was done trying to meet all these requirements and checking their correctness with the literature analyzed.

5.2 – Conceptual Model Description:

Considering project requirements the model has been built to support the service provider to present his service and the impact of this service on customer's process equipment performance. The provided services are based on machinery inspections in order to understand the problems or the monitoring of components to avoid failures and prevent them from taking place. Considering the criticality of machines, the customer can choose different policy approaches that influence the time between inspections. The customer needs to understand the added value of services supplied and the real effect on the whole system, because he needs to handle the trade-off between costs and benefits, between interval of inspections and reliability and safety of assets. Considering that customer does not often understand how much important could be condition monitoring, because the whole system is complex and benefits are clear only in a long term view, and considering he uses to evaluate costs in short term, it becomes important to define a conceptual structure of a model that is able to simulate and to handle all relationships.

The structure proposed divides the model in four modules (Figure 5.1), which represent areas that include all features to describes the activities (expressed by modules of the model) and the actors involved in the customer supplier relationship:

Actors:

- Service Supplier Sellers: they use to talk directly with customer and they try to sell them benefits of service
- Service Technical Staff: they deal in measurement and analysis
- Customer Managers: they evaluate service costs and benefits

Modules:

- Components Behaviour and Maintenance Module
- Spare Parts Module (three modules for three different components)
- Service Module
- Costs Evaluation Module

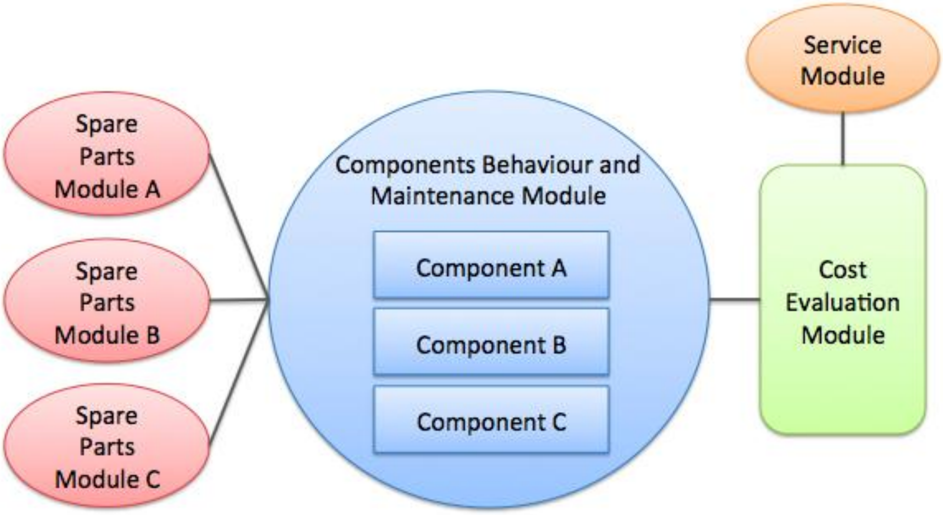

Figure 5.1 – Model Framework

<u>The Description of the Model and How it meets requirements</u>:

Customer's view is described by 'components behaviour and maintenance module' and with 'spare parts module', indeed in those sections there are all variables related to customer plant (i.e. constraints or targets). 'Components behaviour and maintenance module' supports behaviour simulation of components/machines through different maintenance policies (Corrective/Preventive) considering service supplied. It is an important area of the model, because all evaluations depend on the structure of degradation simulation. It allows evaluating 3 components in series with different lifecycle, failure correlations, policies and alarm conditions. It also allows handling the possibility to choose between repairing instead of substituting components for a fixed number of times.

Service module is defined in order to represent inspection service. Considering that customer manager is the direct person who looks at the results provided by the tool to demonstrate service effects, and considering he does not know technical information of the service, module is supported by external database that provides all specific information required to technically initialize it. That database is firstly filled from technical service staff including needs, costs and requirements of monitoring techniques, avoiding the involvement of a technical expert during model use.

The class diagram of that database is presented below:

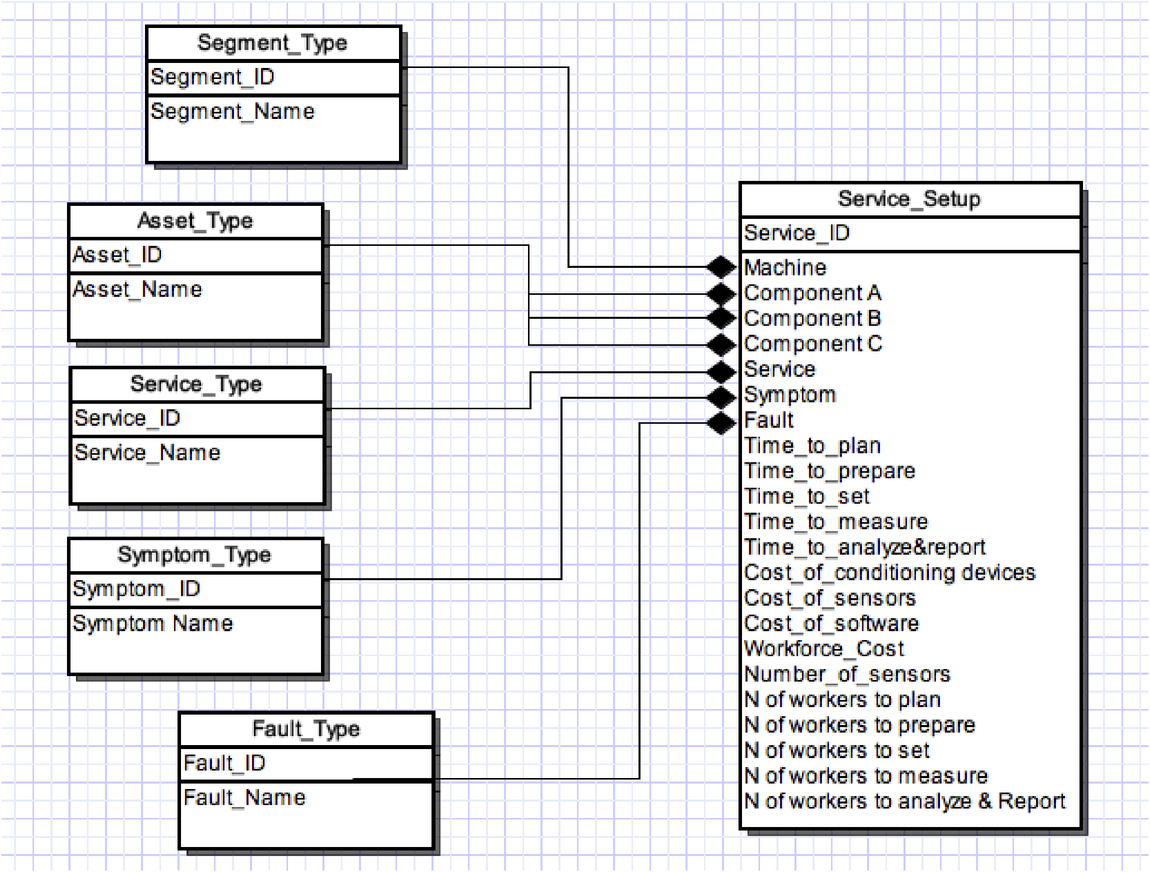

Figure 5.2 – Technical Data Base Class Diagram

Finally 'Cost evaluation module' is the module that combine all technical information of the chosen service with customer data evaluating the specific case.

The framework, above quickly presented, allows to clarify relationships between different choices in maintenance field demonstrating connections among the kind of monitoring service, the maintenance policies chosen, the degradation of components and the spare parts handling. It highlights service complexity and uncertainties as described and required by studies showed in chapter 2.2. Moreover it answers to maintenance simulation needs required by literature showed in section 3.4. Indeed the structure meets the requirements of simulation modeling literature. It is built combining modules like it is done in Lin et al. 2002 framework, basing all choices on the effects simulated on the components behaviour and maintenance module. Anyway it is oriented to the cost evaluation also keeping on mind the importance of customer point of view.

The importance of a simulation tool was underlined in order to support decision maker, which is able to connect different areas on maintenance fields instead of the simulation of a focalized area.

The possibility to describe specific plant situation (i.e. kind of component, spare parts handling policy adopted or targets on specific variables) helps the evaluation to be more interesting for the customer, anyway flexibility introduced in the model giving the possibility to choose how much in detail describe the case allows avoiding to require sensible or unknown data to the customer. The database introduction makes the model technically detailed avoiding to be too complex for customer managers or to require a specific knowledge of operations or specific needs for each case. Moreover the conceptual model presumes the use of the database interface to fill data and to get results, helping customer to understand the model even if he is not familiar with simulation software. The possibility to quickly and simply fill data give to customers the possibility to tune parameters evaluating different scenarios, in that sense it involves actively customers in a sort of “maintenance evaluation game”. It is worth mentioning that the tutoring of an expert in the use of the simulation software is always advisable.

5.3 – Simulation Software Choice:

The choice of simulation software to build the tool was done considering two possibility: VENSIM and Open Modellica on Simantic platform. The first one is a commercial software, the second one is a system dynamics simulation software developed by VTT. Features of both software are described below:

VENSIM:

- Commonly used
- Tested and supported by a complete set of functions
- Not modular software

Open Modellica:

- Modular software
- Developed internally
- Only Beta version available

Although Open Modellica is developed internally and it could guarantee a modular construction of the tool, that means it could be built with independent modules, it was chosen to built it with VENSIM, because the beta version could not provide a detailed set of functions, considering it was under construction. Anyway, Open Modellica can import VENSIM models thanks to a specific command, so it would be possible to open the model with the VTT software and to organize the tool in a modular way.

Chapter 6 – Additional Literature Analysis for Model Implementation

After the development of the conceptual model, its implementation requires to investigate specific features of maintenance simulation modeling. In that sense it was done an additional literature analysis focusing on modeling mechanisms and parameters estimation. This chapter analyzes three topics:

- Maintenance modeling (review of a guideline framework and its mechanisms)
- Failure correlation importance in maintenance modeling
- Literature research on probability of incipient failure detection parameter and its estimation.

6.1 – Maintenance Simulation Framework:

Lin et al. 2002 deals with the development of a simulation model for maintenance service field with condition based maintenance approach. they presents a complete framework that meets most of literature requirements; it could be used to base some modeling approach for tool building. Considering his closeness to the purpose of this work, and considering it is one of few examples of complete simulation framework in literature, it is presented below.

The conceptual model proposed describes three maintenance types of services: regular preventive maintenance (time-based or based on inspection frequency), condition based maintenance and unplanned maintenance. The model is developed using five modules:

1. An Equipment Model
2. A Maintenance Planner
3. A CBM Planner
4. A Scheduler
5. A Field Service Module

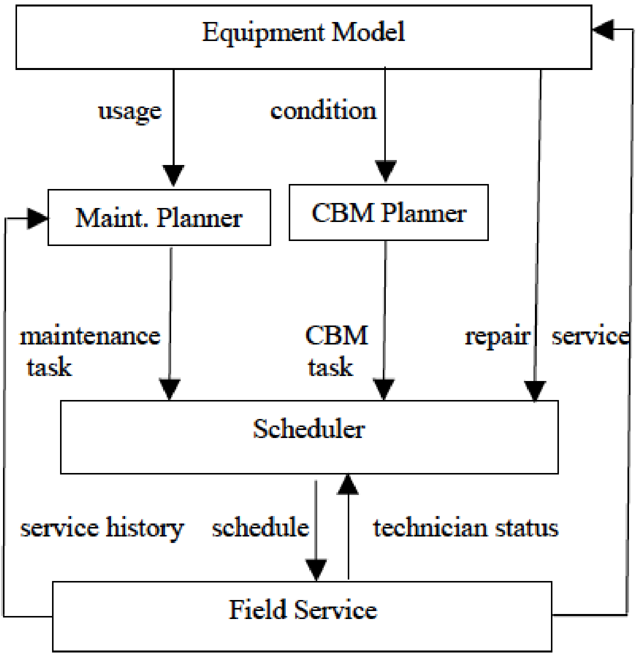

Figure 6.1 – A Generic Field Service Model (Lin et al. (2002))

The equipment module is done combining simulation of the equipment usage and simulation of components condition, including failures. When failure happens, maintenance request is simulated to be sent to the maintenance planner and it constantly communicates with CBM planner, in order to update it on the state of components. In this module it is simulated the reliability of components, using a failure rate based on a Weibull function, and there is an evaluation of remaining life, considering the reliability level, indeed when it reaches a certain level, it defines that a maintenance task is requested.

Maintenance planner elaborates maintenance tasks following a time based policy or considering frequency of tasks in accordance with features of equipment handled. This module is able to update itself following historical failures data received from equipment module. Instead CBM planner defines condition-based tasks following monitored parameters on equipment or components. If one of them reaches the alarm condition, this kind of task is activated by this module. The scheduling module receives all information from others and his job is to allocate maintenance tasks to each worker in order to guarantee the maximum level of availability of the system, it means that if it is possible this module tries to collocate each maintenance operation during a machine stop, also considering costs, needs and emergency of it. Finally, field service module describes in detail technical needs and involvement of a maintenance intervention, and there are also included performance maintenance tasks for each case. This module also updates the condition of components after their repair, communicating with the equipment module.

Lin et al. 2002 highlights that it is not necessary to build a model using each of module proposed in their case, but they underline how it is important to choose the more related ones to the specific case which is requested to represent. They notice that the equipment model is the driver of the whole system, because its behaviour affects directly on the other modules, but it is also true that the other modules affect the equipment model too in a looped way. Indeed firstly the model can be used to assess the value of CBM policy, but after its evaluation can establish the value of other policies and their mix and the value of other business process, for example the effects of scheduling on the productivity and on the equipment condition.

It is important to underline that Lin et al. 2002 framework can be a good guideline on the development of the real simulation tool, because it is oriented on literature needs. Anyway authors did not build a simulation tool on the basis of their framework, so its development could be a great improvement, completing a lack.

6.2 - Failure Correlation Assessment

Failure correlation is a parameter that can help to describe combined degrade of components, which affect each other. Components Behaviour and maintenance module, presented in the conceptual model, requires to be built in order to handle also this feature, so this section wants to underline importance of correlation in component behaviour simulation. Failure correlation helps to describe what really happens between components, helping the model to simulate variables relationships dynamically. In that sense, avoiding the hypothesis of independence between failure, it is possible to significantly affect correctness of degradation assessment, so it becomes fundamental to include it in model building. Wei Le and Mary Lou Soffa, (2010) that completely supports this point of view and they built an interprocedural, path-sensitive, and scalable algorithm to automatically compute correlated faults in software, underlining how correlation needs to be modeled in a dynamic way to describe all the potential dynamic effects of a fault. Lots of static software are not able to do it, but system dynamics makes this feature achievable.

Correlation estimation requires to analyze case by case system data to statistically understand fault relations and at the end to model them.

Hsu et. al (1991) investigates on correlation estimation specifically on maintenance modeling cases. In that paper authors includes correlation features in their degradation model, improving it in a more realistic way. They tested the model during components life cycle and they made several sensitive analysis as proof of their work.

Their work is interesting because it demonstrates how the time spent in degraded state, affects component increasing the failure rate. Moreover, the work could be extended with the same structure underlining, in case of correlation, the relationship between time spent in degraded state by component x to failure rate of component y. Indeed if two components are correlated, a malfunction due the degraded state of one of them can affect the reliability of the other, even if it is working in the right way. Decision maker who does not consider those kind of implications can choose in an ineffectiveness way.

In accordance with results of Hsu et. al (1991), correlation estimation provides these benefits:

- Accuracy of model increase: failure rate, reliability and risk estimation would be more realistic, giving a good prediction of results

- Model could be set in a CBM view considering degraded stats as critical conditions.
- A more accurate relationship based on correlation would improve maintenance policies becoming more effective.

Results underlines that the best solution is to build a model that includes fault correlation on the basis of strong statistical evaluation of historical data.

Linear correlation coefficient r_{ij}, Vercellis Carlo (2006):

$$r_{ij} = corr\ \ a_j; a_k\ \ = \frac{v_{ij}}{(\sigma_j \sigma_k)} \qquad (6.1)$$

where:

- a_j is the first value to compare
- a_k is the second value to compare with the first
- σ_j and σ_k are the standard deviation of two values
- v_{ij} is the covariation between values

r_{ij} can assume values in that range: [-1;1], because the maximum value of v_{ij} is the result of multiplication of both standard deviations, indeed if $r_{ij} = 1$, then there is perfect correlation and values will be disposed in a graph following the straight with a positive slope, else in case of $r_{ij} = -1$, values will be disposed on a straight with a negative slope. As much as r_{ij} tend to 0, as much lack of correlation there will be between values, or maybe correlation could be not linear disposed.

Anyway sometime it is not possible, and the lack of any correlation value can strongly reduce the accuracy of the model and compromise his usefulness. Independent failures hypothesis is in most of cases absolutely far from reality and it can affect significantly on the reliability assessment. Therefore if it is necessary it can be also possible to determine correlation values using an empirical and experience-based evaluation from experts instead to introduce the hypothesis of independent failures.

In accordance to Myron Hecht et. al (1997), correlation values can be estimated also on the basis of data to empirically determine the probability of a correlated failure, in other cases it could be useful to compare the system with similar one, even if it would be difficult to evaluate which could be an equivalent system in a unambiguous way.

6.3 - (PoD) Probability of Detection

Probability of Detection (PoD) is an important parameter in maintenance assessment, it represents the probability to detect a flaw using NDT (Non Destructive Test), it involves that this parameter is strictly important to evaluate and to model CBM policy, because of his relationship with inspections. In that sense it is also fundamental in reliability trend, indeed it is possible to define the relationship between PoD of flaws and a characteristic size of the flaws, using experimental data. However the estimation of this value is important, because his representation involves in whole maintenance results. This section wants to present a review of main studies on PoD assessment, showing its importance and supporting it with some statistical models.

In accordance to Forsyth and Fahr (1998) there are three different methods to collect data to build PoD parameter, therefore:

- Demonstration at one flaw size, based on sampling theory considering a 90% confidence.
- Estimation of PoD using single inspections based on a specific experiment to investigate the PoD, results of inspections are recorded until flaw happened, this story about reliability of component is used to rebuild PoD. In case of several estimation referred to some flaws, the PoD is a mean of whole evaluation
- Estimation of PoD using multiple inspections, based on the same structure of single inspection, but it is done with more than one NDI to be rebuild PoD in a more accurate way.

Data collected can be used to build PoD curve using two statistics methods:

1. Log Odds model
2. Log-Normal model

Log Odds model is result of the study of Berens and Hovey (1982), they determined there were several methods to build probability of detection, but they concluded that log odd distribution is the most consistent distribution to determine PoD. The functional form of distribution is:

$$P_i = \frac{\exp(\alpha + \beta \ln\ a_i\ )}{1 + \exp(\alpha + \beta ln\ a_i\ )} \qquad (6.2)$$

where:

- P_i is the probability of detection for a crack i
- a_i is the length of crack i
- α and β are the parameters which define the curve

Anyway to build the complete function it is necessary to estimate parameters α and β, so in their work they discussed two methods:

- Range Interval Method (RIM), as known as regression analysis, assumes that variability of PoD within a small crack size range or interval is small and the detection within the range follows a binomial distribution. Data are divided in into t intervals of equal length. The PoD is calculated for each interval as the ratio between detected cracks and total number of cracks in that interval. Data pairs of PoD and crack length were transformed into linear domain and using a linear regression it was determined the parameters α and β of the straight. Using also the transformation described below it was possible to convert a linear relationship in a log odds distribution function:

  $$Y_i = \ln \frac{P_i}{1-P_i} \quad ; \; X_i = \ln \; a_i \qquad 6.3$$

  Results of transformation on the previous equations are a set of points resumed with the line:

  $$\mathrm{Y} = \alpha + \beta\mathrm{X} \qquad (6.4)$$

  The resulted parameters can be used in (6.2) to find the probability of detection curve for a range of crack length, anyway if PoD estimated is 0 or 1 that transformation is undefined, so in case of 0 it is used the value of $1 \;\; (t+1)$, in case of 1 it is used the value $t \;\; (t+1)$.

  The obtained log odds curve describes that probability to detect a flaw with a NDI increases as much as flaw size increases.

- Maximum Likelihood Estimators (MLE) is a method to define α and β parameters maximizing the probability to obtain the observed data. The likelihood for a single data is:

  $$\mathrm{L} \;\; P_i; a_i, x_i \;\; = P_i{}^{x_i}(1-P_i)^{1-x_i} \qquad (6.5)$$

  Where:

- P_i is the probability of detection for a crack i

- a_i is the length of crack i
- x_i is the inspection outcome, 0 for a miss and 1 for a hit

The likelihood of a series of independent inspections is product of the individual observation:

$$\mathrm{L}\ \ \mathrm{P}; a, x \ = \ \overset{h}{\underset{i=1}{}}\ P_i \ \ \overset{n-h}{\underset{j=1}{}}\ (1-P_i) \qquad 6.6$$

Taking the logarithm of equation (6.6) it is obtained equation (6.7), therefore a series of sums. Considering logarithm is a monotonic function, the maximum of the log likelihood for α and β is the same of maximum likelihood.

$$\ln \mathrm{L}\ \ \mathrm{P}; a, x \ = \ \overset{h}{\underset{i=1}{}}\ \ln P_i \ \ \overset{n-h}{\underset{j=1}{}}\ \ln P_j \qquad 6.7$$

The estimation of α and β in case of maximum likelihood is possible solving the derivative equations respect to α and β and set to zero.

Also that method explains the relationship between PoD and size of flaw, the graph below describes and compares obtained curves.

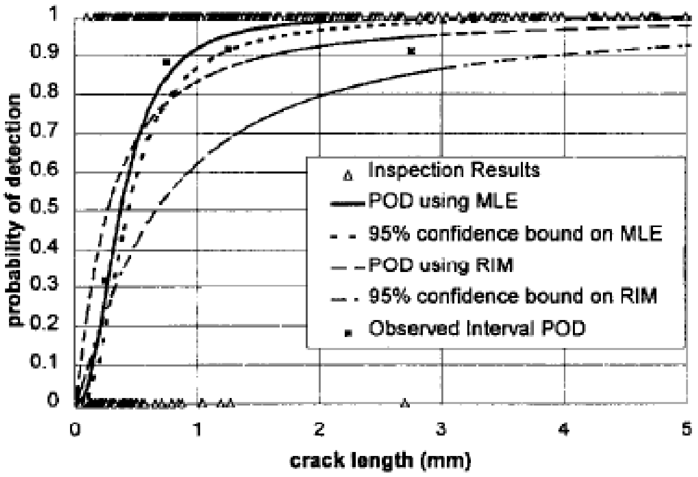

Figure 6.2 – A comparison of RIM and MLE methods of fitting log odds curves to inspection data (Forsyth and Fahr (1998))

Log-Normal model is suggested by the study Petrin et Al. (1993) describes PoD with a cumulative log normal distribution as:

$$P_i = 1 - \mathrm{Q}\ \ z_i \qquad (6.8)$$

$$z_i = \frac{\ln(a_i) - \mu}{\sigma} \qquad (6.9)$$

where:

- $Q\ z$ is the standard normal survivor function
- z_i is the standard normal variate
- μ and σ are the location and the scale parameters of the PoD curve

It is possible to find parameters using maximum likelihood estimators also in case of log normal distribution using the equation (6.7) solving the derivative equations respect to μ and σ and set to zero.

It is showed below the log normal curve referred to an ultrasonic inspection:

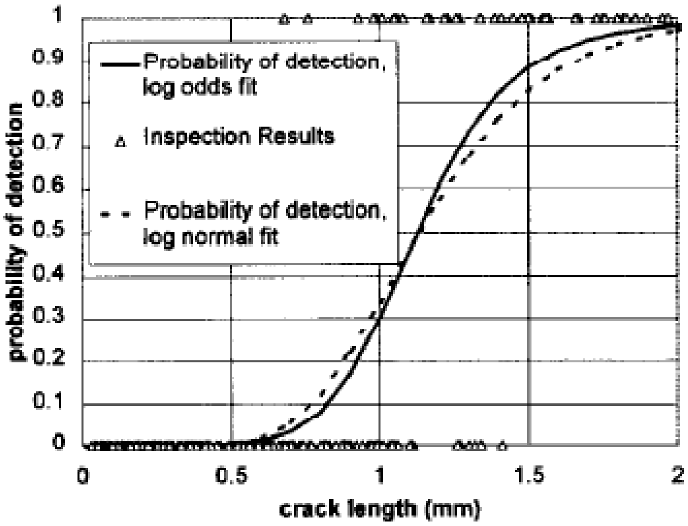

Figure 6.3 – Log odds and log normal curve fits to results of an ultrasonic inspection of compressor disk bolt holes (Forsyth and Fahr (1998))

Results of Forsyth and Fahr (1998) are that methods are similar, but in most of cases log normal distribution is more conservative and accurate, anyway referring to methods to collect data, multiple inspections usually improve PoD accuracy, even if in case of automation in NDI these benefits are reduced too.

These are not the only studies done on this topic, several analysis were done from both aerospace research and nuclear research but also in every field which requires to pay attention on health and safety.

Christina Müller et al. (2006) made a reliability assessment using PoD referred to the problem of failures linked with nuclear waste encapsulation. They said that the discontinuity size establishes what will be detected with a sufficient reliability and compared to the demand of integrity, using PoD curve and its lower confidence bound. Later results need to be compared with destructive test data or with several NDT data. The idea is that a discontinuity of size a is causing a signal a of heighta', so a certain PoD curve, described below, is generated by the statistical distribution of the signals in dependence of the discontinuity size.

The relation expressed between a and a' is:

$$a' = \mu(a) + \delta \qquad 6.10$$

where:

- $\mu(a)$ is the mean value of the probability density $g_a(a')$
- δ is the random error whose distribution determines the probability density $g_a(a')$, therefor it is assumed that δ is distribuited normally with 0 mean and constant variance.

In that sense $g_a(a')$ is the normal density function with mean $\mu(a)$ and δ variance. Anyway PoD function is:

$$\mathrm{PoD}(a) = P(a'(a) > a'_{dec}) = \int_{a'_{dec}}^{+\infty} g_a(a')\, da' \qquad (6.11)$$

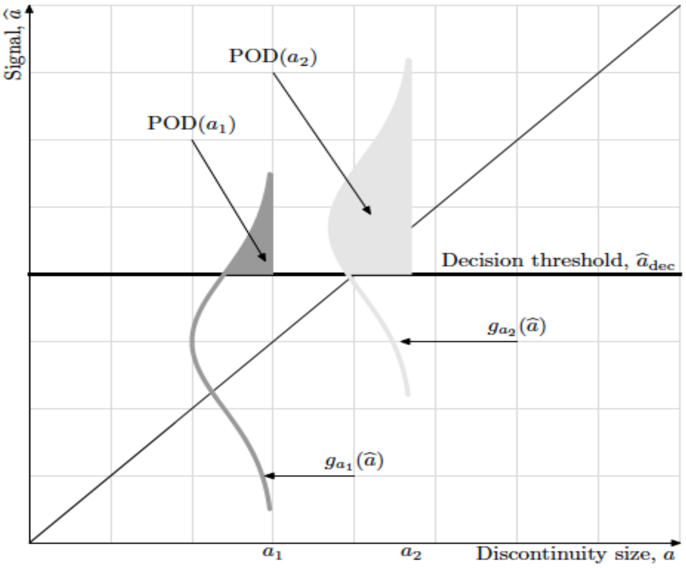

Figure 6.4 – Probability of Detection (Christina Müller et al. (2006))

The following formula is used to model the relationship between a and a':

$$\ln a' = \beta_0 + \beta_1 \ln a + \delta \qquad (6.12)$$

δ is normally distributed with 0 mean and costant variance ${\sigma_\delta}^2$, under assumption of the model PoD has the following form:

$$\text{PoD}\ \text{a}\ \ = P\ \ a' > a'_{dec}\ \ = P\ \ln(a') > \ln(a'_{dec})\ \ = \Phi\ \ \frac{\ln a - \mu}{\sigma} \qquad (6.13)$$

Where Φ is the standard normal distribution function with:

$$\mu = \frac{\ln(a'_{dec}) - \beta_0}{\beta_1} \qquad (6.14)$$

$$\sigma = \frac{\sigma_\delta}{\beta_1} \qquad (6.15)$$

The parameters β_0, β_1 and σ_δ describe the linear dependency of a' on a, β_0 is the intercept, β_1 is the slope and σ_δ is the standard deviation of the residuals; those values are determined with the maximum likelihood method. It is showed below the formula in case of 95% lower confidence bound:

$$\text{PoD}_{95}\ \text{a}\ \ = \Phi\ \ z' - h \qquad (6.16)$$

where $z' = \frac{\ln a - \mu}{\sigma}$ and variable h reflects the sample size and the scatter of the source data.

George A Georgiou (2006) describes in detail each feature referred to PoD curves, also the methods proposed in that paper are concordant to methods showed in other papers (i.e. a versus a' and log odds distribution method). Anyway in that paper: the large discussion on PoD curves, their usefulness in industry and other features, give to its content a lot of importance.

In accordance with authors PoD use is absolutely important for industries, indeed it was commonly used in those cases:

- Establishing design acceptance requirement
- NDT procedure qualification and acceptance
- Qualification of personnel performance
- Comparing performance capabilities of NDT procedures
- Selecting an applicable NDT procedure
- Quantifying improvements in NDT procedures
- Developing repeatable NDT data for fracture mechanics

In that sense the accuracy of PoD used in a simulation model to handle management complexity is fundamental to estimate components behaviour in the right way without describe a false representation of reality.

Although PoD is usually expressed as a function of flaw size (i.e. length or depth), many other physical and operational parameters affect it in real cases, such as, materials, the geometry, the flaw type; anyway enough methods are available to build a realistic parameter in a statistic sense, as seen in this section.

The issues presented by this literature review are used in the following chapter
when it is presented the tool supporting spreadsheet to make PoD assessment based on log odds model.

Reference:

CONTENTS	REFERENCES	PUBLICATION YEAR	WORK CONTRIBUTION
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Probability of Detection (PoD) curves Derivation, applications and limitations.	George A Georgiou, Health & Safety Executive, Research Report 454.	2006	Specific knowledge on probability of detection estimation.

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A Recommended Methodology for Quantifying NDE/NDI Based on Aircraft Engine Experience.	Petrin, C., Annis, C., and Vukelich, S. I., AGARD-LS-190.	1993	It provides a probability of detection estimation model.
Path-Based Fault Correlations.	Wei Le and Mary Lou Soffa, Department of Computer Science –University of Virginia, Charlottesville.	2012	It provides motivation on importance of correlation

Modelli matematici e sistemi per le decisioni.	Vercellis Carlo, Business intelligence. McGraw-Hill.	2006	It provides statistical knowledge on data mining

Chapter 7 – Model Building

The conceptual framework presented in chapter 5 and showed in the figure 7.1, and the specific literature research done, were implemented for the tool development. Figure 7.2 shows an overview of the whole system dynamics tool representation.

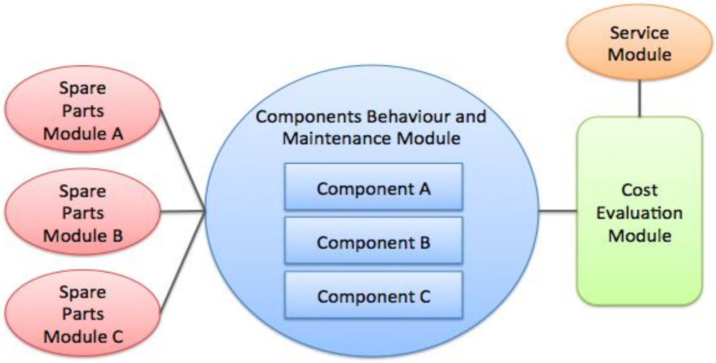


Figure 7.1 – Model Framework

The purpose of this chapter is to present in detail all areas described in the model framework, showing their variables, equations and describing modeling mechanisms. Anyway the description is divided in four sections, which describe:

- Component Behaviour and Maintenance Module
- Spare Parts Module
- Service Module
- Cost Evaluation Module

Each section presented in this chapter follows this structure, in accordance with description needs:

- Short simulation module graph label
- Description of module features (underlining hypothesis introduced to represent it, and possible external supporting tools description (i.e. spreadsheet, DB))
- Summary of module capability
- Input variables and measurement unit description
- Auxiliary variables description
- Flow variables description
- Stock variables description
- Mathematical equations description

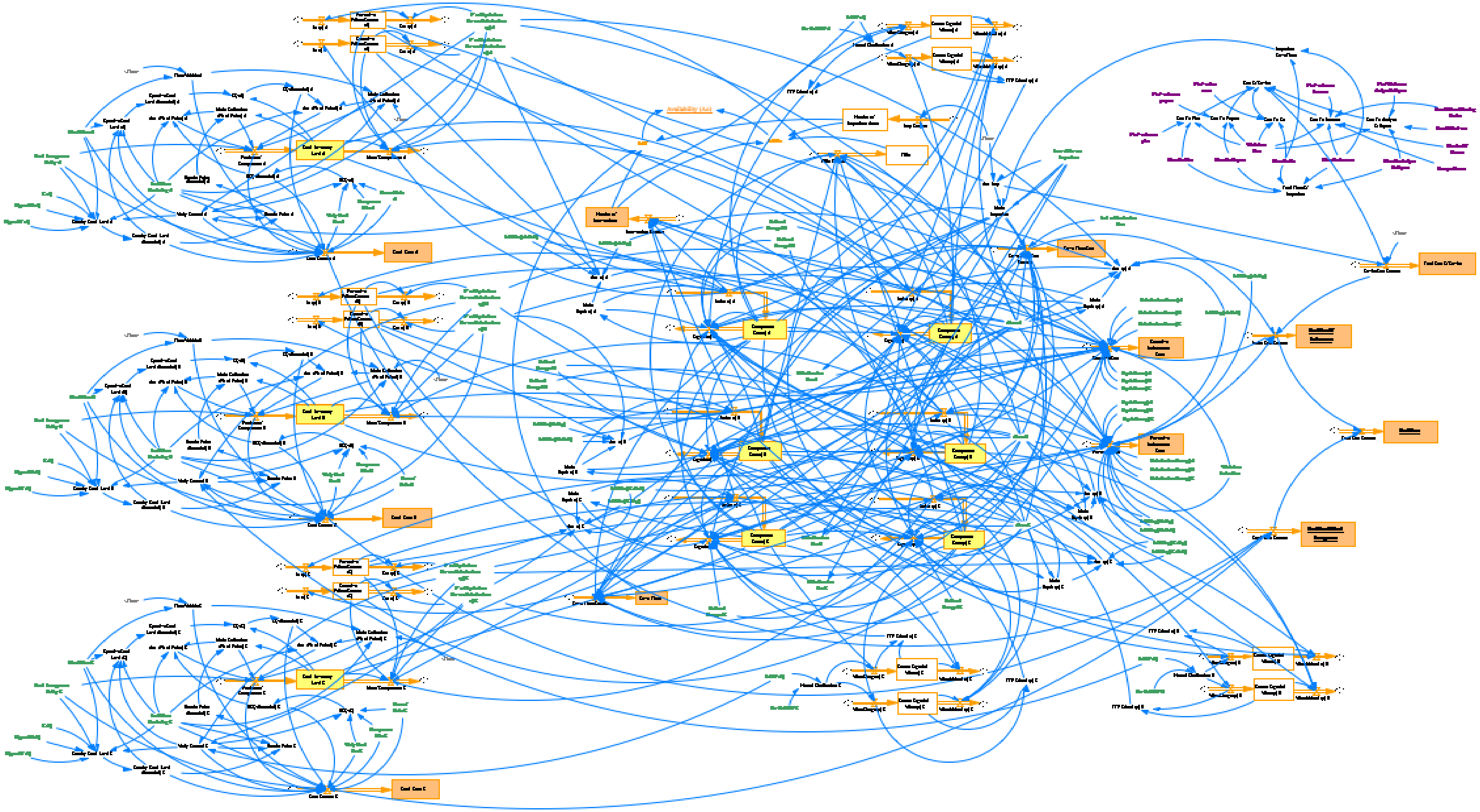


Figure 7.2 – Simulation Tool

7.1 - Components Behaviour and Maintenance Module:

7.1.1 – Short simulation module graph label

This section describes components behaviour and maintenance module. The figure 7.3 was built connecting ‘Components Behaviour and Maintenance Module’ with a basic view of variables of modules directly connected and included in mathematical equations of its variables. In that sense:

- Blue connections belong to this module
- Grey variables underline connections that come from other modules.
- Green auxiliary variables highlight inputs of the module and they should be filled by customer to describe own plant situation and targets in components behaviour and maintenance.
- Orange variables are outputs of the module

The picture 7.3 describes the whole module, but the high complexity does not allow explaining well it, so it is built a second picture 7.4 that highlights only arrows of component A. It includes in light grey variables of other components B and C correlated with the first one and connected with dotted lines. However, understanding the single component framework, it becomes simple to build the whole module, just replicating the same structure for each other.

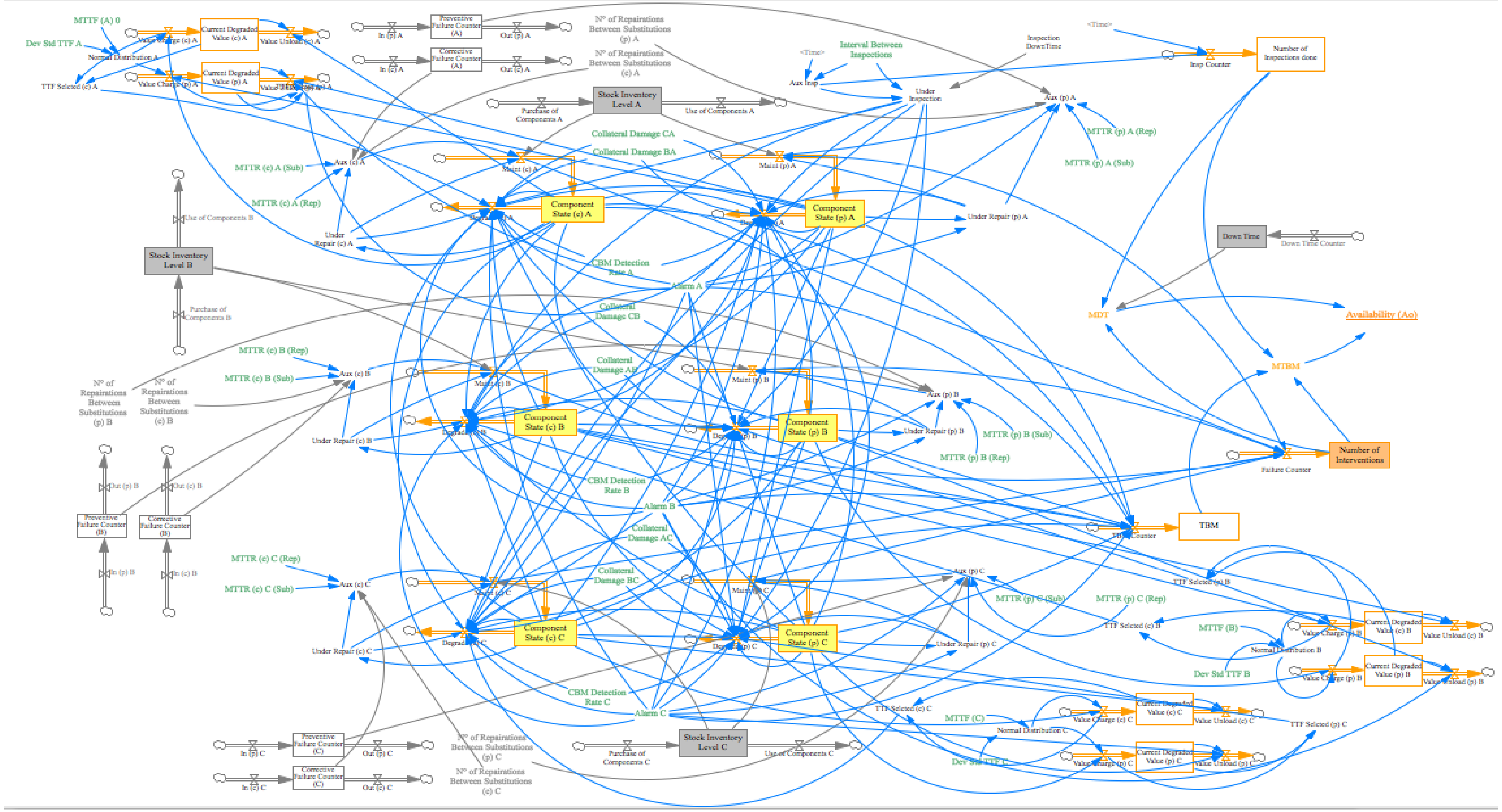


Figure 7.3 - Components Behaviour and Maintenance Module

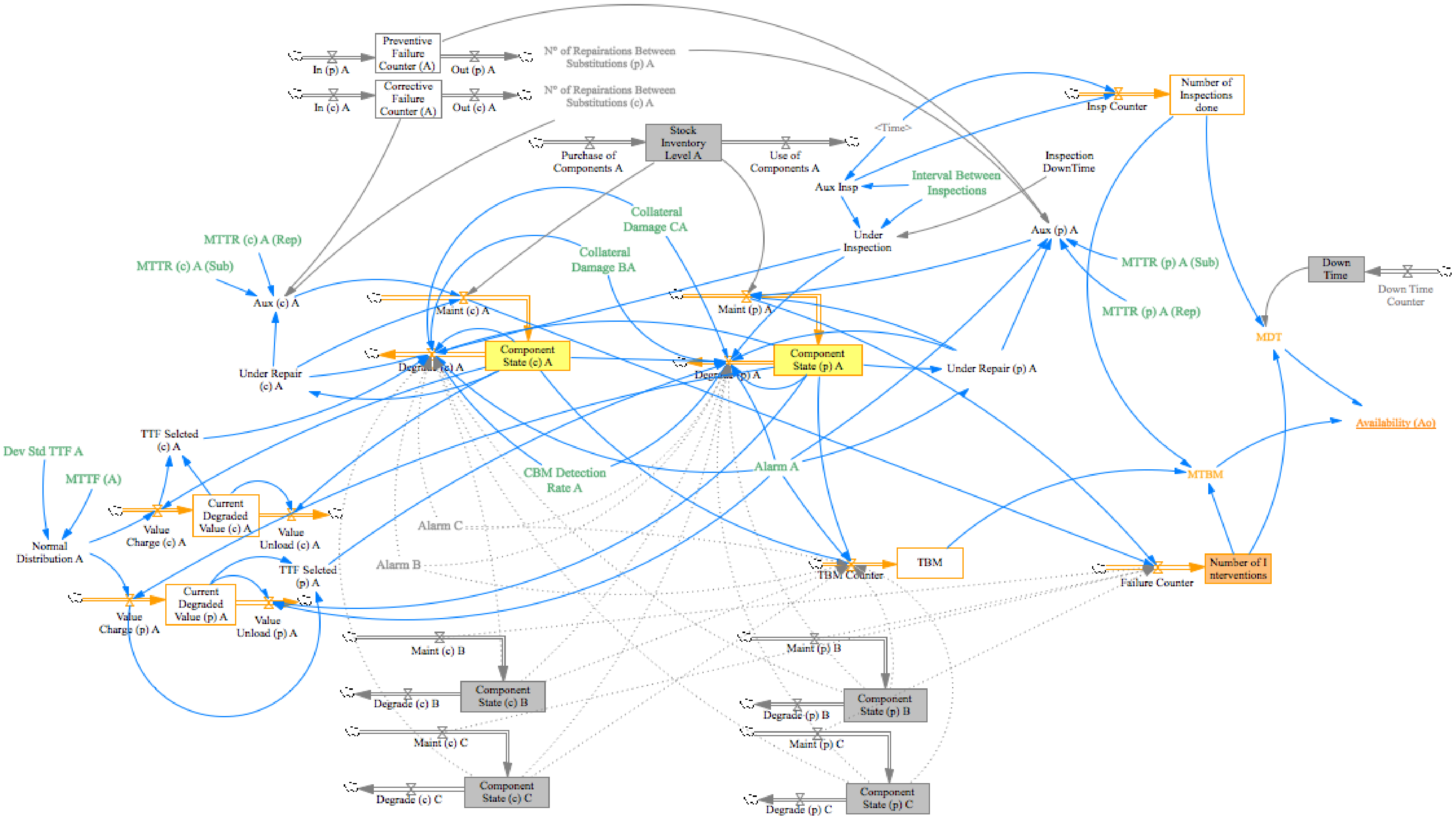


Figure 7.4 – Single Component Behaviour and Maintenance

7.1.2 – Description of module features:

‘Components behaviour and maintenance module’ is the most important section of simulator indeed it describes the state of components during their lifecycle. Consequently this module provides to model maintenance implications that depend on components lifecycle:

- Maintenance policies simulation
- Interventions simulation
- Inspection simulation
- Interventions counting
- Down time counting
- Availability calculation

Besides those functionalities are supported by some modeling elements that make possible the description of components behaviour and functionalities interactions:

- Failure correlation simulation (allows to combine degradation of components)
- Probability of Detection simulation (allows to simulate the possibility to actually implement CBM)

Finally some descriptive variables help to situate the specific case that user wants to evaluate:

- Time to make maintenance interventions (distinguishing between repair and substitute).
- Alarm level (last tolerable component degraded level before to start working in a wrong way. It can implicate consequence to the state of other components).
- Expected component lifetime and standard deviation.
- Interval between inspections established.

So most of tool capabilities depend on this module, indeed other sections make calculations on the basis of trend described in this area.

Summarizing, the purpose of the module is to simulate components lifecycle and their behaviour in relationship with the inspection service choices, indeed as much often there are inspections as much failures could be prevented. Anyway, as touched on above, prevention depends on state of component detection rate.

In order to clarify how this idea is implemented, simple sections of the module are presented below, but before to start the presentation it is fundamental to underline again that the purpose of system dynamics simulation is to represent the general view of the system, stressing on the capability of the model to show complex relationships, to model soft features and to support the whole comprehension instead of playing exactly what happens in real cases; for those others purposes more accurate simulation methods have been developed.

Details Description:

Component State Evaluation Structure:

Firstly it is fundamental to describe the degradation representation. For each component included in the module, it is simulated its state by the use of a stock and flow relationship.

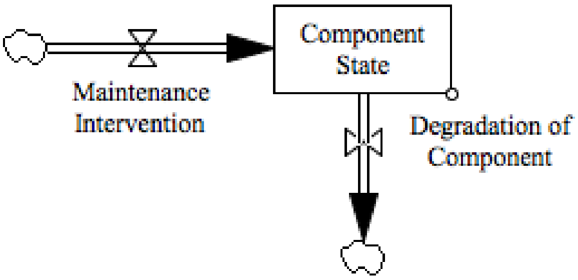


Figure 7.5 – Component lifecycle modeling

The component state is a value initialized at the 100% and it is reduced by degradation flow during his lifecycle, simulating its decline. Instead maintenance flow is activated only when it is time to make a repair or a substitution intervention. The representation of this structure to simulate the remaining life is very close to the remaining life modeling described in Lin et al. (2002) showed in chapter 6, section 6.1.

The following are hypotheses required to the lifecycle representation:

- Constant Degradation: the degrade of component is considered constant and it is represented by the formula: $\text{Degradation Flow} = \frac{1}{TTF}$, but the TTF (time to failure) depends on the expected lifecycle time of the component.
- Normal Distribution of the TTF: To guarantee intrinsic variability of systems, TTF is built on the basis of a normal distribution. It means that component lifecycle depends on MTTF (mean time to failure) value and its standard deviation. A

random function select a TTF from the normal distribution allocating it to a specific component; when this component is repaired or substituted, the random function allocates another TTF value to the new/restored one.

Variability of degradation justifies the use of inspection to know the state of components supporting the implementation of CBM, anyway it is possible only if degradation trend is known and it does not generate completely random failures.

Figures below show this behaviour. First one represents component degradation, so how component state decreases until to reach value 0 getting a failure. The second one represents its derivative showing in detail how degradation speed changes each time components are replaced/restored.

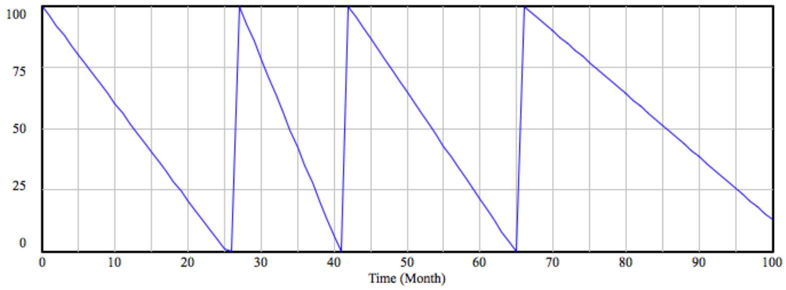


Figure 7.7 - Variability Representation

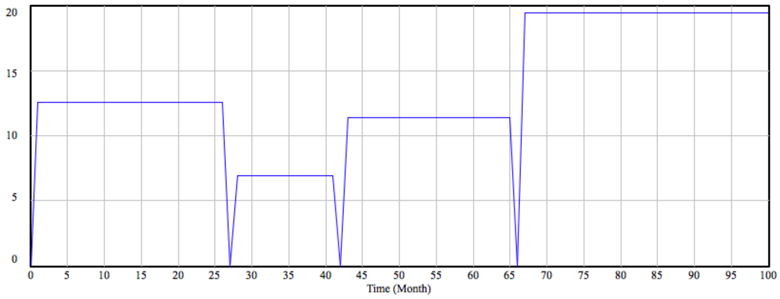


Figure 7.8 – Degrade speed variation in different components

- Maintenance reparation interventions follow the hypothesis that repaired components get the same condition of new components. Anyway considering it is not real, but necessary, the number of possible reparations for each component was limited to a specific one defined from tool user. It simply allows introducing limitations of this hypothesis as much as necessary and on the basis of component kind.
- Modeling structure considers components broken when the state value reach the zero, so the variable describes an indicator of the remaining life.
- Reliability of the single component is described with a step function. This choice wants to consider a single component like something that usually works and

collapses in a generic and unknown t’ time. It means it is supposed to consider the component reliable until it works and suddenly not reliable just an instant before to collapse.

This simplification used on each single case allows simulating components lifecycle and represent a cyclic alternation of component use, in which base all management implications. Anyway it does not means that components have not the possibility to collapse earlier, variability, previously introduced, allows the representation of different lifecycle length based on a normal distribution. It means that the amount of failure data collected during the simulation, at last, allows building the reliability function with its real probabilistic shape. Moreover long-term view of simulation reduces the negative effect of this hypothesis.

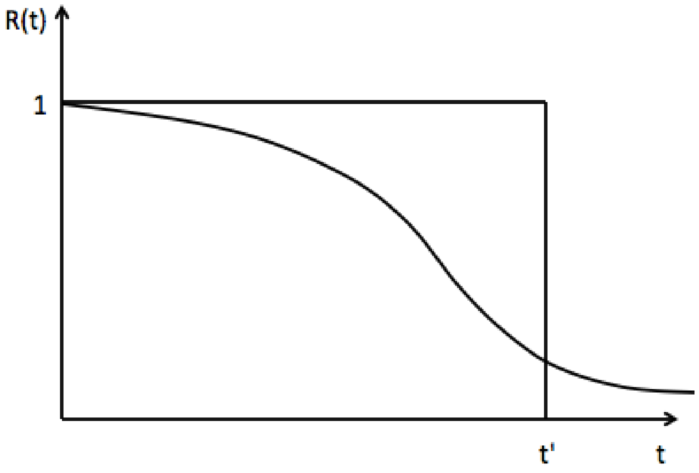


Figure 7.9 – Reliability modeling

In the picture below it is resumed functions trend included in the stock and flows structure above presented:

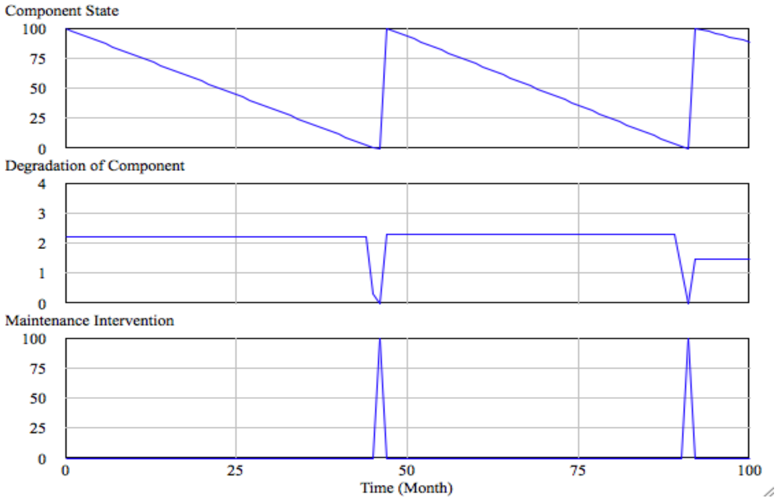


Figure 7.10 – Component Lifecycle Functions Interactions

Policies Modeling:

After the description of the component state simulation, it is possible to describe how maintenance corrective and preventive interventions are modeled.

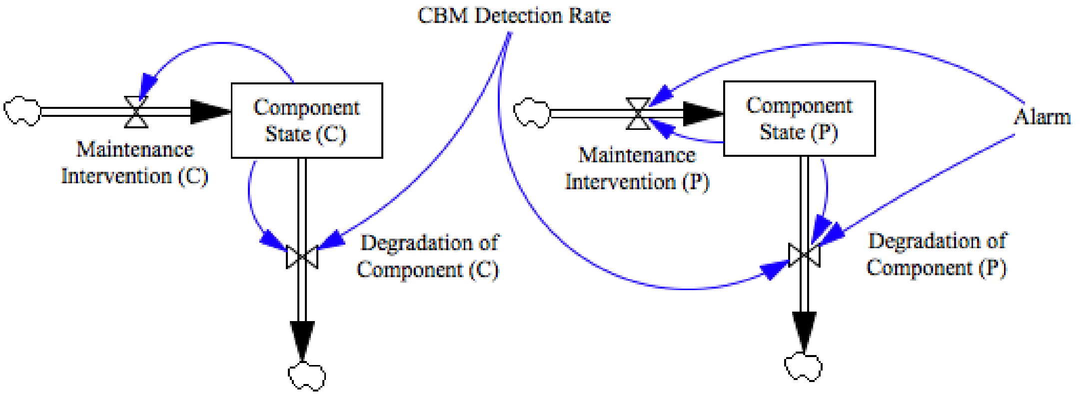


Figure 7.11 – Corrective and Preventive Interventions Simulation

Each component is described by two component state evaluation structures (corrective and preventive) that are able to classify component failures on the basis of intervention kind used to solve the problem. In other words the tool is able to allocate failures in preventive or corrective structure in accordance with inspections efforts. Each inspection evaluates the state of component and calculates when it will be next failure on the basis of information collected. In other words components are not changed exactly after the inspection but after spending the estimated time. If the inspection does not detect anything, there will not be actions. It is important to underline that the lack of the detection can be generated by the lack of problems or due to a low inspections frequency. In that sense CBM Detection Rate variable regulate degradation flows of both structures; it activates or stops their functioning allocating the whole failures number of each component to the two policies involving in different maintenance requirements and costs.

Corrective structure is exactly the same one presented above, instead the preventive one introduces some changings.

Preventive structure simulates component degrade too, but it does not stop when it reaches the zero, but when it reaches the alarm level. Using the same definition presented of the beginning, alarm is the last tolerable component degraded level before to start working in a wrong way involving in possible problems.

For example if alarm level is fixed at 20% of the state (80% degraded), at that condition a maintenance intervention is activated, replacing or repairing the component.

Picture below can better clarify the concept:

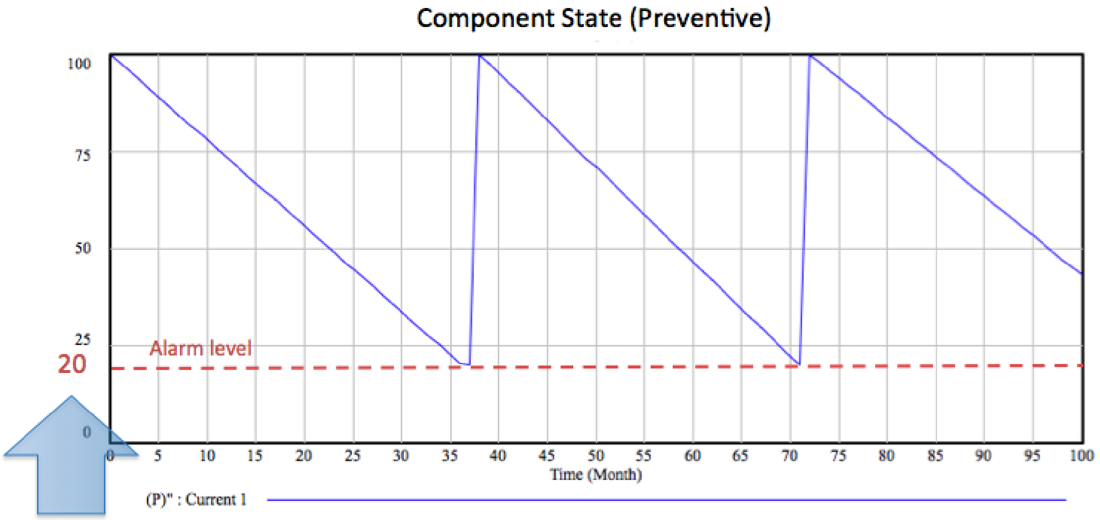


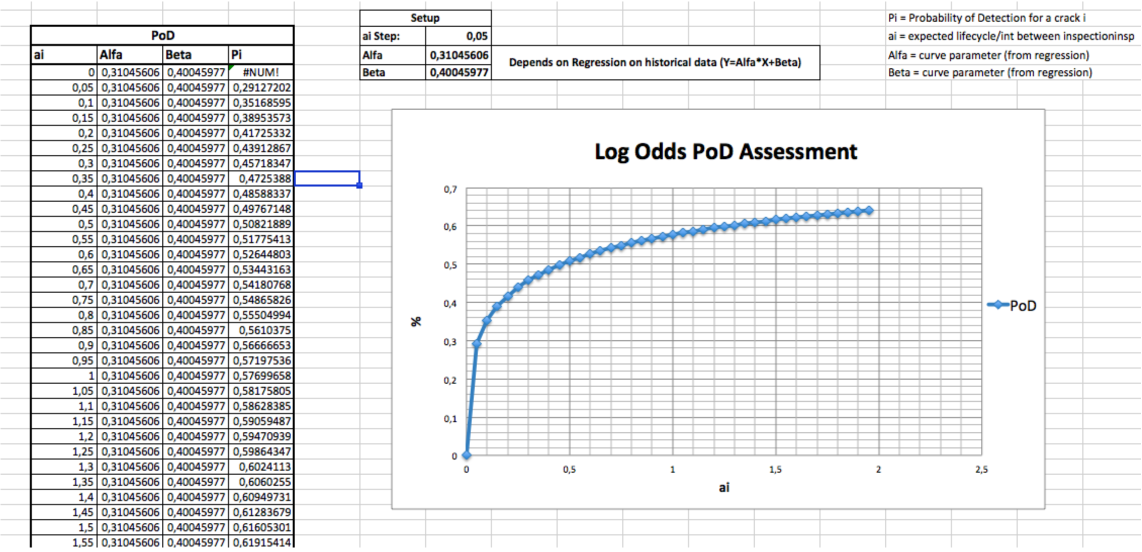
Figure 7.12 – Component State Trend with Preventive Interventions

<u>CBM Detection Rate</u>:

CBM Detection Rate is based on the estimation of how much inspections could prevent failures, in relation with interval between inspections and expected component lifecycle ratio.

Literature research underlines how to statistically estimate this parameter on the basis of historical data. A PoD assessment spreadsheet is attached to the tool in order to investigate data (if they are available), estimating PoD.

It is the log odds model presented in chapter 6.3. Pictures below shows two screenshots of the supporting instrument (data of pictures are not referred to any case, they are initialized like an example):



PoD			
ai	**Alfa**	**Beta**	**Pi**
0	0,31045606	0,40045977	#NUM!
0,05	0,31045606	0,40045977	0,29127202
0,1	0,31045606	0,40045977	0,35168595
0,15	0,31045606	0,40045977	0,38953573
0,2	0,31045606	0,40045977	0,41725332
0,25	0,31045606	0,40045977	0,43912867
0,3	0,31045606	0,40045977	0,45718347
0,35	0,31045606	0,40045977	0,4725388
0,4	0,31045606	0,40045977	0,48588337
0,45	0,31045606	0,40045977	0,49767148
0,5	0,31045606	0,40045977	0,50821889
0,55	0,31045606	0,40045977	0,51775413
0,6	0,31045606	0,40045977	0,52644803
0,65	0,31045606	0,40045977	0,53443163
0,7	0,31045606	0,40045977	0,54180768
0,75	0,31045606	0,40045977	0,54865826
0,8	0,31045606	0,40045977	0,55504994
0,85	0,31045606	0,40045977	0,5610375
0,9	0,31045606	0,40045977	0,56666653
0,95	0,31045606	0,40045977	0,57197536
1	0,31045606	0,40045977	0,57699658
1,05	0,31045606	0,40045977	0,58175805
1,1	0,31045606	0,40045977	0,58628385
1,15	0,31045606	0,40045977	0,59059487
1,2	0,31045606	0,40045977	0,59470939
1,25	0,31045606	0,40045977	0,59864347
1,3	0,31045606	0,40045977	0,6024113
1,35	0,31045606	0,40045977	0,6060255
1,4	0,31045606	0,40045977	0,60949731
1,45	0,31045606	0,40045977	0,61283679
1,5	0,31045606	0,40045977	0,61605301
1,55	0,31045606	0,40045977	0,61915414

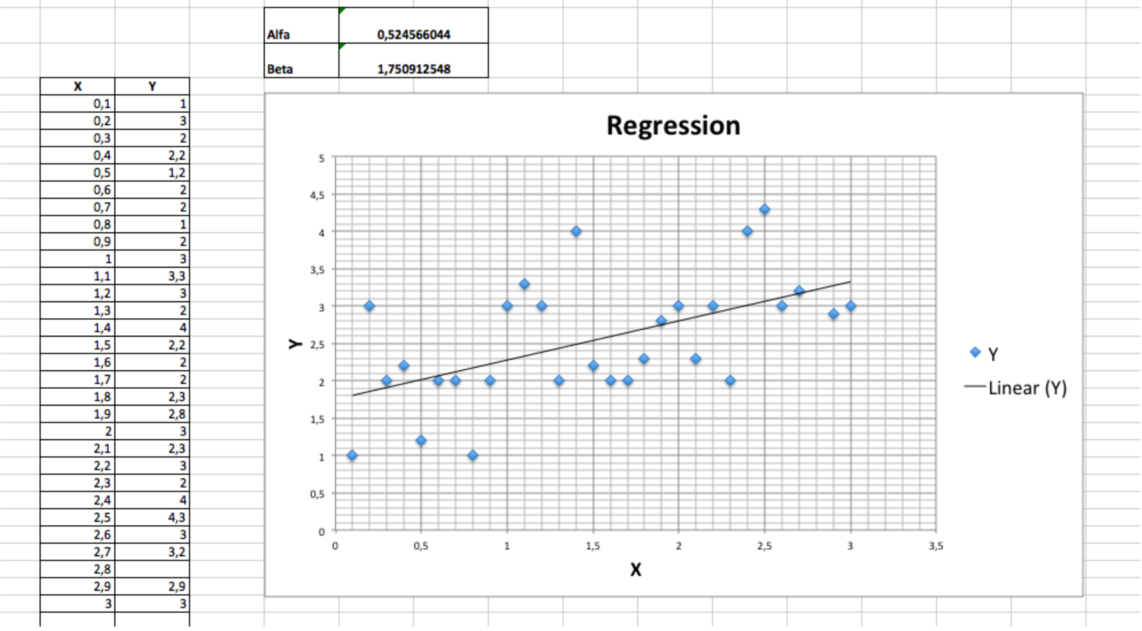
Setup	
ai Step:	0,05
Alfa	0,31045606
Beta	0,40045977

Depends on Regression on historical data (Y=Alfa*X+Beta)

Pi = Probability of Detection for a crack i
ai = expected lifecycle/int between inspectioninsp
Alfa = curve parameter (from regression)
Beta = curve parameter (from regression)

Graph 7.1 – PoD assessment supporting spreadsheet

The evaluation of regression parameters is done in a separate sheet, filling it with own plant data:



Alfa	0,524566044
Beta	1,750912548

X	Y
0,1	1
0,2	3
0,3	2
0,4	2,2
0,5	1,2
0,6	2
0,7	2
0,8	1
0,9	2
1	3
1,1	3,3
1,2	3
1,3	2
1,4	4
1,5	2,2
1,6	2
1,7	2
1,8	2,3
1,9	2,8
2	3
2,1	2,3
2,2	3
2,3	2
2,4	4
2,5	4,3
2,6	3
2,7	3,2
2,8	
2,9	2,9
3	3

Graph 7.2 – Alfa and Beta estimation supporting spreadsheet

Anyway considering that simulator is used in the negotiation phase, PoD value cannot be easily available due to lack of data. In those cases it is defined by expert of monitoring service that could be supported by experience and by standard tables used as references.

Pictures below can clarify the allocation of failure frequency on the basis of CBM Detection Rate. Three scenarios are described:

– CBM Detection Rate = 0,5 (both policies with 50% of detection probability)

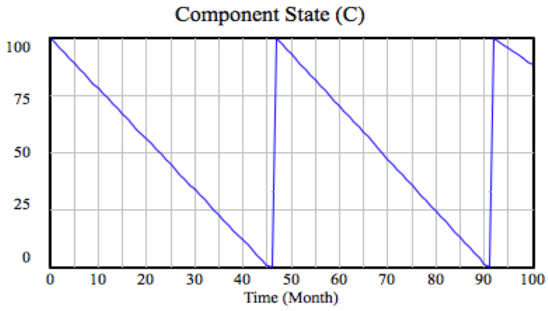


Figure 7.13 – Component State (C) with CBM Detection Rate 0.5

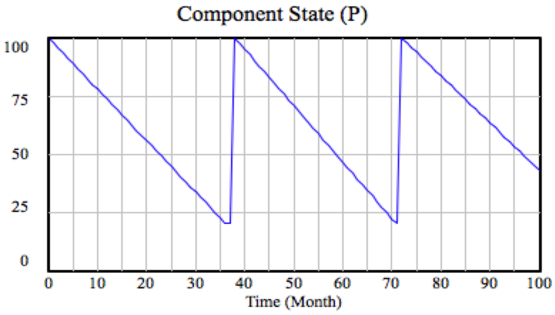


Figure 7.14 – Component State (P) with CBM Detection Rate 0.5

– CBM Detection Rate = 0 (corrective only)

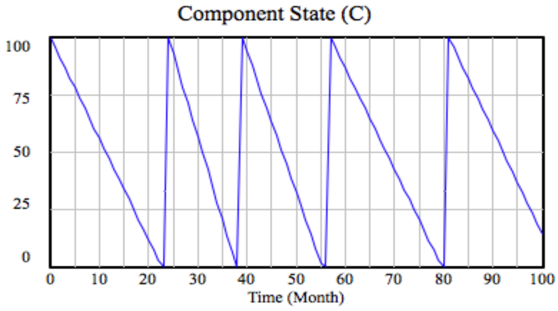


Figure 7.15 – Component State (C) with CBM Detection Rate 0

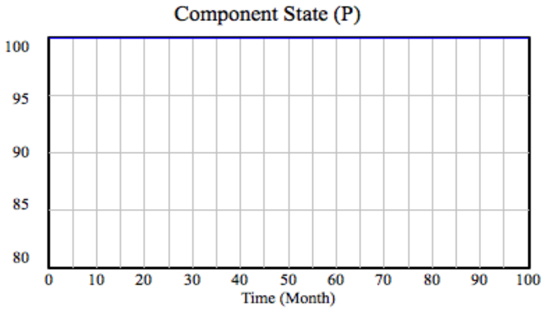


Figure 7.16 – Component State (P) with CBM Detection Rate 0

– CBM Detection Rate = 1 (preventive only)

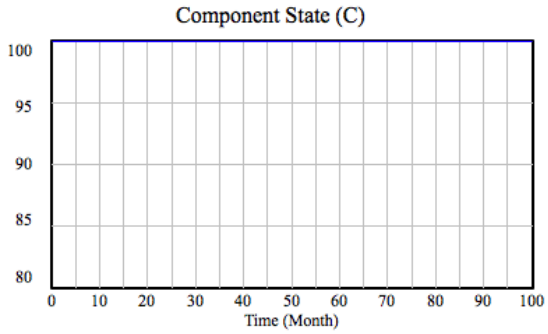


Figure 7.17 – Component State (C) with CBM Detection Rate 1

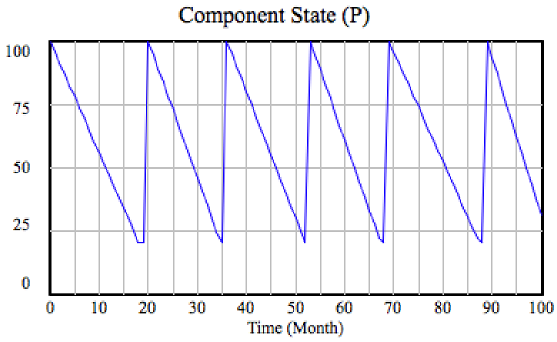


Figure 7.18 – Component State (P) with CBM Detection Rate 1

The development of the preventive simulation introduces other hypothesis to the model:

- The most important hypothesis of the model is that alarm level, interval between inspections and CBM detection rate should be provided by the same expert who is able to provide congruent data. Interval between inspection and CBM detection rate congruency is supported by the log odds model, but alarm level depends on expert capability to provide right data; on the basis of this criticality in the next chapter it is analyzed how model results change in case it is provided a not congruent data. (see section 8.3.1 for alarm level sensitivity)
- ‘Interval Between Inspections’ is an input value that is defined at the same way for all components, because an inspection is referred to the whole machine and it checks all components at the same time. This value is chosen with customer in accordance to his needs and could be tuned in simulation just to demonstrate how much it affects in the specific case.
- The model considers the alarm level as the condition that defines the moment when it is required a preventive maintenance intervention. It is supposed at t-1 time, where t is the beginning of the working time in a degraded state.

- When component reaches alarm level (time t1) and it is not changed, it starts to work in degraded state functioning until to fail (time t2). Picture below underlines the interval of degraded functioning that involves to a possible speed degrade acceleration on correlated components.

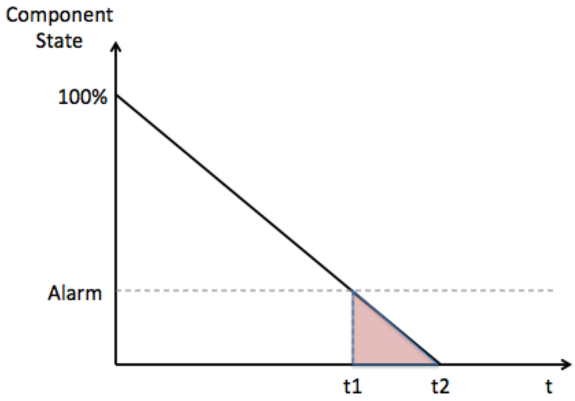


Figure 7.19 – Degraded State

In other words the model assumes that if a component A is correlated with a component B, the degraded functioning of the component B affects directly on the degradation of A increasing his degradation speed. So if B alarm is not detected, A suffers the additional effect during the interval between t1 and t2. However this effect stops when the component B is repaired or changed. Correlation data are defined by statistical evaluation as explained in literature section, but considering that this kind of data are not always available from the customer, setting the correlation matrix it is possible to introduce the hypothesis of independence between failures. Anyway as underlined in literature section expert estimations, even if they are not completely exact, could better represent the system behaviour then the independence hypothesis.

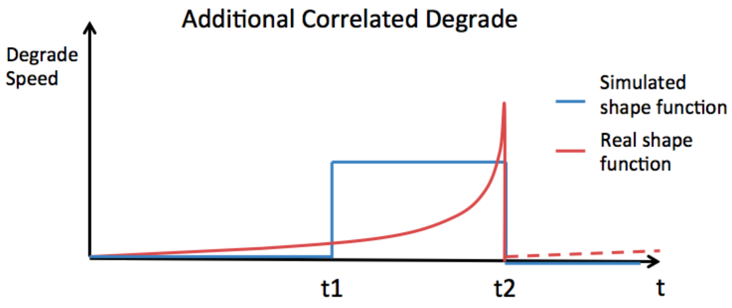


Figure 7.20 – Additional Degrade Speed Function

- Additional degrade speed function is modeled with a step function. It assumes effect does not exist before t1 and it is considered constant between t1 and t2. Even if an exponential function would better describe the phenomenon, increasing slowly from the beginning and quickly at the end, initial effect is considered not significant until the achievement of the alarm condition.

Module structure was done also considering tool flexibility need. In that sense it is chosen to build it with three components connected to guarantee a complete but not too complex structure. Surely it could be possible to extend it replicating the framework with more components, but in the most of cases, the most critical problems can be fully described analyzing a group of three connected components. Anyway if it would be necessary to evaluate a more complex situation, it is possible to set the model with two critical components and the average cluster data of remaining components, or with three clusters defined using an ABC Pareto classification. The same structure can be used to evaluate in series machines of a chain, but it becomes essential to keep in mind the trade-off between accuracy of simulation and the general view required.

7.1.3 – Summary of module capability:

After a complete representation of fundamental simulation mechanisms, it is possible to summarize what the module is able to handle:

- Represent degradation of components
- Handle both preventive and corrective policies
- Handle correlation between failures and effects of degraded state functioning
- Choice between substitute or repair component
- Set different price and time for replace or substitute component in each policy
- Represent a series connection between components (all is stopped for every kind of intervention on each component)
- Stops everything in case of lack of spare parts
- Count Failures
- Calculate the MTBM
- Calculate the availability of the system on the basis of operative formula $Ao = \frac{MTBM}{MTBM+MDT}$

7.1.4 – Input variables and measurement unit description:

In the table below there are all input module variables of components A, B and C. Data used are not referred to any kind of real situation but they are used to justified graphs showed in the section.

Variable Name	Variable Meaning	Variable Value	Unit of measurement
MTTF (A)	It's the mean time to failure of component A and it describes lifecycle expected	200	Days
MTTF (B)	It's the mean time to failure of component B and it describes lifecycle expected	90	Days
MTTF (C)	It's the mean time to failure of component C and it describes lifecycle expected	30	Days
Dev Std TTF A	It is the standard deviation of the time to failure of component A	5	Days
Dev Std TTF B	It is the standard deviation of the time to failure of component B	5	Days
Dev Std TTF C	It is the standard deviation of the time to failure of component C	5	Days
CBM Detection Rate A	It's the percentage of detection of incipient failures A	0.8	%
CBM Detection Rate B	It's the percentage of detection of incipient failures B	0.6	%
CBM Detection Rate C	It's the percentage of detection of incipient failures C	0.35	%
Alarm A	It's the level of reliability under it component A works in	10	%

	deteriorate state		
Alarm B	It's the level of reliability under it component B works in deteriorate state	10	%
Alarm C	It's the level of reliability under it component C works in deteriorate state	30	%
Collateral Damage BA	It's the percentage of deterioration added to component A if component B is working in deteriorated state.	0.4	%
Collateral Damage CA	It's the percentage of deterioration added to component A if component B is working in deteriorated state.	0	%
Collateral Damage AB	It's the percentage of deterioration added to component B if component A is working in deteriorated state.	0.1	%
Collateral Damage CB	It's the percentage of deterioration added to component B if component C is working in deteriorated state.	0.5	%
Collateral Damage AC	It's the percentage of deterioration added to component C if component A is working in deteriorated state.	0	%
Collateral Damage BC	It's the percentage of deterioration added to component C if component B is working in deteriorated state.	0.2	%

MTTR (c) A (Rep)	It's the mean time to repair component A in corrective policy	15	Days
MTTR (p) A (Rep)	It's the mean time to repair component A in preventive policy	7	Days
MTTR (c) B (Rep)	It's the mean time to repair component B in corrective policy	2.5	Days
MTTR (p) B (Rep)	It's the mean time to repair component B in preventive policy	2	Days
MTTR (c) C (Rep)	It's the mean time to repair component C in corrective policy	2	Days
MTTR (p) C (Rep)	It's the mean time to repair component C in preventive policy	2	Days
MTTR (c) A (Sub)	It's the mean time to substitute component A in corrective policy	15	Days
MTTR (p) A (Sub)	It's the mean time to substitute component A in preventive policy	3	Days
MTTR (c) B (Sub)	It's the mean time to substitute component B in corrective policy	1.5	Days
MTTR (p) B (Sub)	It's the mean time to substitute component B in preventive policy	0.5	Days
MTTR (c) C (Sub)	It's the mean time to substitute component C in corrective policy	0.5	Days
MTTR (p) C (Sub)	It's the mean time to substitute component C in preventive policy	0	Days

Interval Between Inspections	It's the interval between two inspection of service supplied	100	Days

Table 7.1 – Auxiliary Input Variables (Components Behaviour and Maintenance Module)

7.1.5 – Auxiliary variables description:

The variables showed in next tables are related only to component A, because they contain equations with the same structure, so it is enough to replicate them.

Variable Name	Variable Meaning
Normal Distribution A	It is the normal distribution of expected time to failure of component A, the variable generates casual numbers from this distribution.
TTF Selected (c) A	It is the time to failure selected from normal distribution, when a component A is substituted in corrective policy, to simulate random life definition.
TTF Selected (p) A	It is the time to failure selected from normal distribution, when a component A is substituted in preventive policy, to simulate random life definition.
Aux (c) A	It's an auxiliary variable used to describe the delay of maintenance flow, due maintenance down time in case of corrective policy
Aux (p) A	It's an auxiliary variable used to describe the delay of maintenance flow, due maintenance down time in case of preventive policy
Under Repair (c) A	It's a support variable used to describe

	time spent by component A in repairing or substitution operations in case of corrective policy
Under Repair (p) A	It's a support variable used to describe time spent by component A in repairing or substitution operations in case of preventive policy
Aux Insp	It's an auxiliary variable used to describe the periodic inspection time.
Under Inspection	It's a support variable used to describe time spent by component A in inspections
MDT	It's the mean down time, the average of down time of simulation
MTBM	It's the mean time between maintenance, it describe the average between 2 maintenance event, both corrective and preventive
Availability (Ao)	It's the operative availability of the system

Table 7.2 – Auxiliary Variables (Components Behaviour and Maintenance Module)

7.1.6 – Flow variables description:

Variable Name	Variable Meaning
Maint (c) A	It's the maintenance flow to fix or substitute components in case of corrective policy
Maint (p) A	It's the maintenance flow to fix or preventive components in case of corrective policy
Degrade (c) A	It's the degradation flow that describes

	reduction of reliability flow in corrective policy
Degrade (p) A	It's the degradation flow that describes reduction of reliability flow in preventive policy
Value charge (c) A	This parameter is used in case of corrective policy to charge the selected time to failure in the stock when the component is brand new.
Value charge (p) A	This parameter is used in case of preventive policy to charge the selected time to failure in the stock when the component is brand new.
Value unload (c) A	This parameter is used in case of corrective policy to unload the selected time to failure from the stock when the component is failed.
Value charge (p) A	This parameter is used in case of preventive policy to unload the selected time to failure from the stock when the component is failed.
TBM Counter	It counts the time between maintenance events
Insp Counter	It counts the number of inspections done
Failure Counter	It's the variable that counts failures

Table 7.3 – Flow Variables (Components Behaviour and Maintenance Module)

7.1.7 – Stock variables description:

Variable Name	**Variable Meaning**

Component State (c) A	It is the component A state stock in corrective policy and it describes his behaviour.
Component State (c) A	It is the component A state stock in preventive policy and it describes his behaviour.
TBM	It is the amount of all time between maintenance events
Current Degraded Value (c) A	It is used to memorize the selected time to failure along component A life, in case of corrective policy.
Current Degraded Value (p) A	It is used to memorize the selected time to failure along component A life, in case of preventive policy.
Number of Inspections done	It is the amount of inspections done
Number of Failures	It is the amount of failures

Table 7.4 – Stock Variables (Components Behaviour and Maintenance Module)

7.1.8 – Mathematical equations description:

- Under Repair (c) A

  This variable is zero when component is working and it is 1 when it is broken, if it is repaired it became zero again.

  ```
  IF THEN ELSE("Component State (c) A">0,0,1)
  ```

- Under Repair (p) A

  It's the same of previous variable

  ```
  IF THEN ELSE("Component State (p) A" >Alarm A,0,1)
  ```

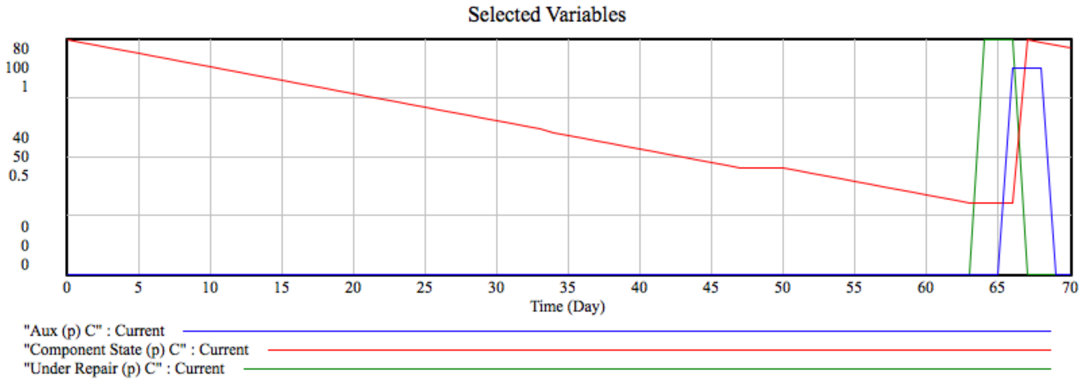
- Aux (c) A

This formula means to add 100 to Component State (c) A in case of corrective intervention, anyway it is possible only when “Under Repair (c) A” is different to zero and it happens only if component is broken. (Component State (c) A = 0). In that case the fixed delay postpones this event as much as MTTR (c) A (Rep) value, in case of reparability, else using replacing mean time to repair.

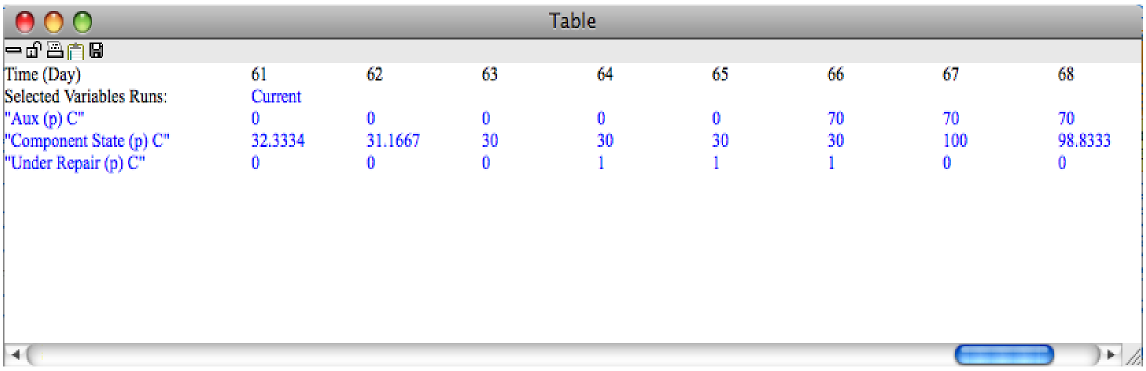
```
DELAY FIXED((100*"Under Repair (c) A"),
IF THEN ELSE("Corrective Failure Counter (A)"<"N° of
Reparations Between Substitutions (c) A","MTTR (c) A
(Rep)","MTTR (c) A (Sub)"),0)
```

Considering this formula and how it works Under Repair variable, it’s important underline that they are complementary. When Component State (c) A becomes zero, under repair becomes 1, Aux (c) A is activated, and it continues to work in recursive way. Anyway, when Aux (c) A completed its function and Component State (c) A becomes 100, Under Repair (c) A come back to zero avoiding further effects of Aux (c) A variable.

It’s simple to see it in the pictures below:



Graph 7.3 – Aux (c) A, Under Repair (p) C and Component State (c) A Trends



Time (Day)	61	62	63	64	65	66	67	68
Selected Variables Runs:	Current							
"Aux (p) C"	0	0	0	0	0	70	70	70
"Component State (p) C"	32.3334	31.1667	30	30	30	30	100	98.8333
"Under Repair (p) C"	0	0	0	1	1	1	0	0

Figure 7.21 - Aux (c) A, Under Repair (p) C and Component State (c) A Values

- Aux (p) A

The following formula is the same of previous but related to preventive case

```
DELAY FIXED(((100-Alarm A)*"Under Repair (p) A"),
IF THEN ELSE("Preventive Failure Counter (A)"<"N° of
Reparations Between Substitutions (p) A","MTTR (p) A
(Rep)","MTTR (p) A (Sub)"),0)
```

- Aux Insp

In that case Aux Insp is only an auxiliary variable to build a cyclic function where cyclic time is interval between inspections. It is combined at the same time with Under Inspection function but without any fixed delay.

```
MODULO(Time,Interval Between Inspections)
```

- Under Inspection

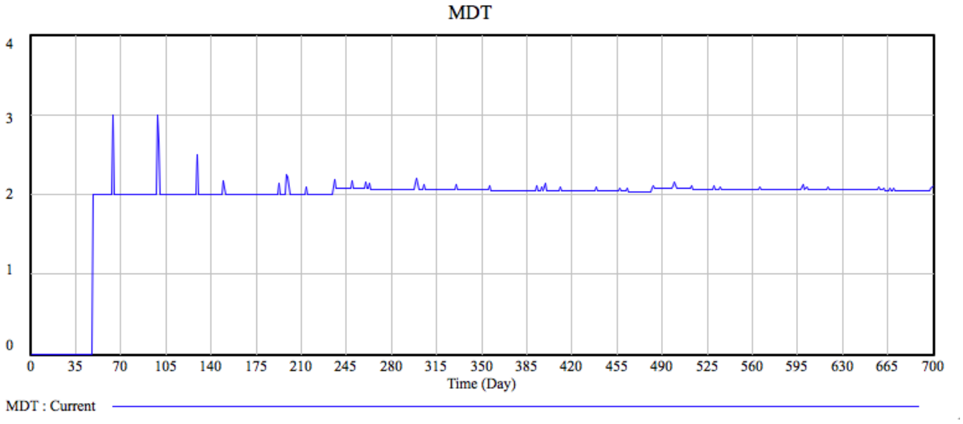
Since it is known values of cyclic Aux Insp function, using the constant interval between inspections set, it is possible to choose which are values that describe when component is Under Inspection. When the variable is 1, it means the inspection is causing down time.

```
IF THEN ELSE(Aux Insp>(Interval Between Inspections-
(Inspection DownTime)),1,0)
```

- MDT

It's calculated as the amount of down time divided by the number of failure and the number of inspections done

```
zidz(Down Time,(Number of Interventions+Under Inspection))
```

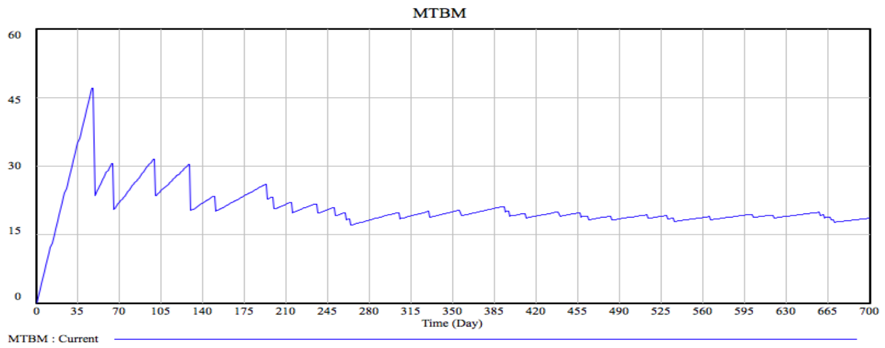


Graph 7.4 – MDT Trend

- <u>MTBM</u>

The variable calculates the mean time between maintenance dividing the amount of normal working time minus the stops done to inspect, with the number of failures.

```
zidz((TBM-Under Inspection),(Number of Interventions+1))
```

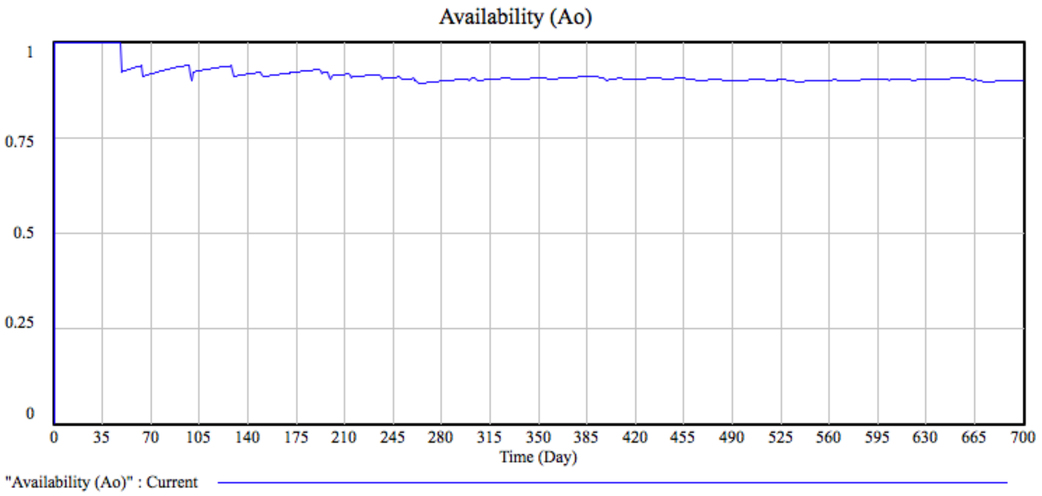


Graph 7.5 – MTBM Trend

- <u>Availability (Ao)</u>

It is calculate with the typical formula of operative availability of literature:

```
zidz(MTBM,(MTBM+MDT))
```



Graph 7.6 – Availability Trend

- <u>Maint (c) A</u>

Maintenance flow formula adds the condition that the stock must have spare parts available. There won't be a maintenance event until stock inventory level isn't refilled.

```
IF THEN ELSE(Stock Inventory Level A>0,"Aux (c) A"*"Under
Repair (c) A",0)
```

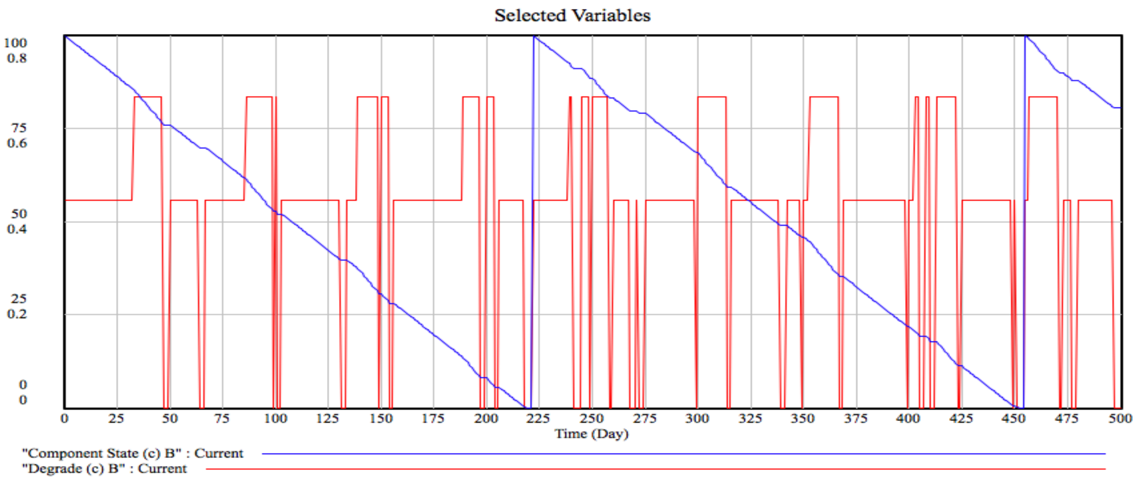
- <u>Maint (p) A</u>

```
IF THEN ELSE(Stock Inventory Level A>0,"Aux (p) A"*"Under
Repair (p) A",0)
```

- <u>Degrade (c) A</u>

```
IF THEN ELSE(
"Component State (c) B" =0:OR:
"Component State (c) C" =0:OR:
"Component State (p) A" =Alarm A:OR:
"Component State (p) B" =Alarm B:OR:
"Component State (p) C" =Alarm C,0,
(MIN("Component State (c) A",((100/TTF Selected (c) A)*(1-
CBM Detection Rate A))
+IF THEN ELSE("Component State (c) B" <Alarm B,((100/TTF
Selected (c) A)*(1-CBM Detection Rate A))*Collateral Damage
BA,0)
+IF THEN ELSE("Component State (c) C" <Alarm C,((100/TTF
Selected (c) A)*(1-CBM Detection Rate A))*Collateral Damage
CA,0)))*(1-"Under Repair (c) A")*(1-Under Inspection))
```

The graph below describes the variation of degradation, it is always a constant, but it stops in case of system stopped. It increases more than normal when component B (in corrective policy) starts to work under alarm B because there is a correlation damage BA > 0



Graph 7.7 – Degrade (c) A and Component State (c) A Trends

- <u>Degrade (p) A</u>

This variable works at the same way of the previous

```
IF THEN ELSE(
"Component State (c) A"=0:OR:
"Component State (c) B"=0:OR:
"Component State (c) C"=0:OR:
"Component State (p) B"=Alarm B:OR:
"Component State (p) C"=Alarm C,0,
(MIN(MAX(0,"Component State (p) A" -Alarm A),((100/TTF
Selected (p) A)*CBM Detection Rate A)
+IF THEN ELSE("Component State (c) B"<Alarm B,((100/TTF
Selected (p) A)*CBM Detection Rate A)*Collateral Damage
BA,0)
+IF THEN ELSE("Component State (c) C"<Alarm C,((100/TTF
Selected (p) A)*CBM Detection Rate A)*Collateral Damage
CA,0)
))*(1-"Under Repair (p) A")*(1-Under Inspection))
```

- <u>TBM Counter</u>

This variable counts the amount of normal working time

```
IF THEN ELSE(
"Component State (c) A">0:AND:
"Component State (c) B">0:AND:
```

```
"Component State (c) C">0:AND:
"Component State (p) A">Alarm A:AND:
"Component State (p) B">Alarm B:AND:
"Component State (p) C">Alarm C,1,0)
```

- Failure Counter

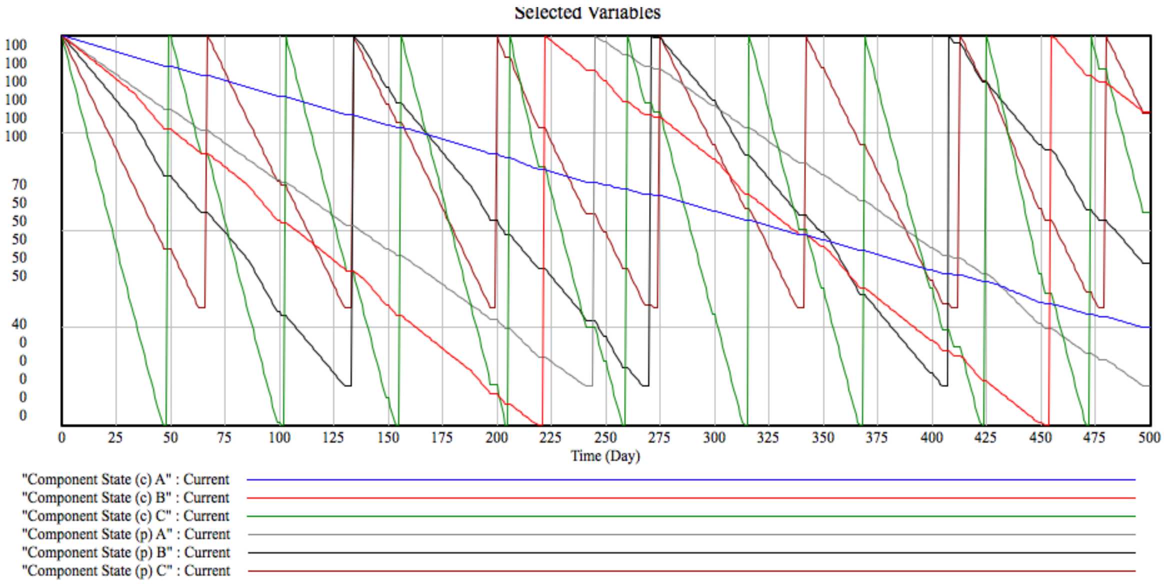
The variable counts failures counting the number of times maintenance variable isn't zero.

```
IF THEN ELSE("Maint (p) A">0,1,0)+
IF THEN ELSE("Maint (c) A">0,1,0)+
IF THEN ELSE("Maint (p) B">0,1,0)+
IF THEN ELSE("Maint (c) B">0,1,0)+
IF THEN ELSE("Maint (p) C">0,1,0)+
IF THEN ELSE("Maint (c) C">0,1,0)
```

- Component State (c) A

```
Initial Value = 100
```

It is important describe degradation behaviour on the basis of alarm conditions and correlation values. In this picture it is showed remaining life of all components, because they all affect themselves. When a component works in degraded condition, all correlated components degrade faster, if a failure comes, all degradation flows stop, if there is an inspection, the whole system stops too.



Graph 7.8 – Component State Trends

- <u>Component State (p) A</u>

  `Initial Value = 100`

- <u>TBM</u>

  `Initial Value = 0`

- <u>Number of Interventions</u>

  `Initial Value = 0`

7.2 - Spare Parts Module:

7.2.1 – Short simulation module graph label:

This section describes spare parts management module. The picture 6.12 was built connecting ‘Spare Parts Module’ with a basic view of variables of ‘Components Behaviour and Maintenance Module’ that are directly connected and included in mathematical equations of spare parts variables.

- Blue connections belong to this module
- Grey variables underline connections that come from other modules.
- Green auxiliary variables highlight inputs of module and they should be filled by customer to describe own plant situation and targets in stock management.
- Orange variables are outputs of the model

The picture below describes relationships of component A as an example, because the structure is the same also for the others.

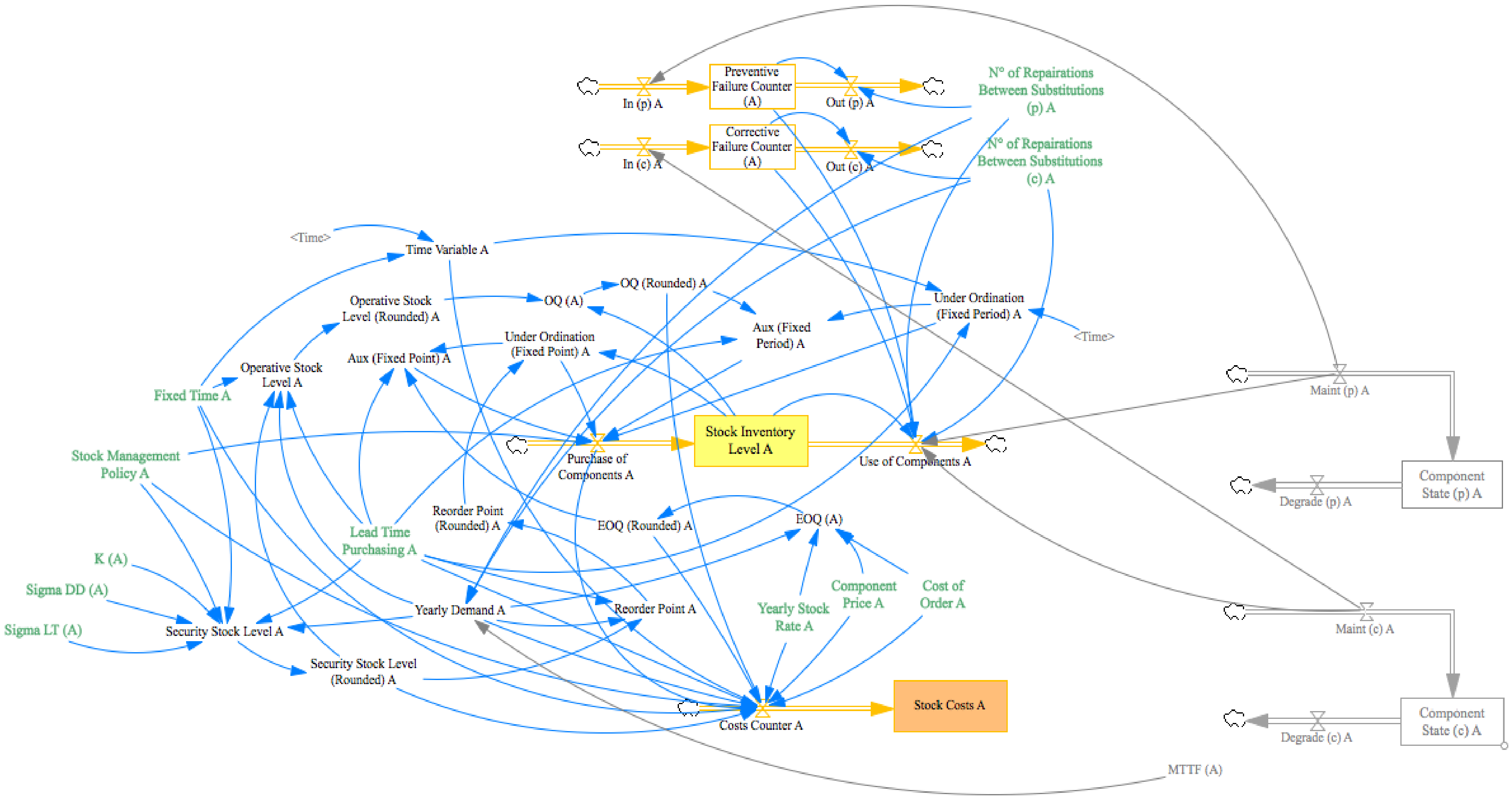


Figure 7.22 – Spare Parts Module

7.2.2 – Description of module features:

The ‘Spare Parts Module’ describes different stock policies and different conditions component by component. His structure is based on the use of a stock and flow mechanism that is able to simulate level and flows of a storage.

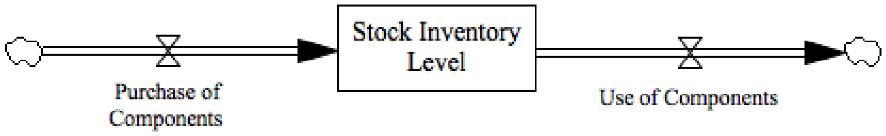


Figure 7.23 – Storage simulation

Outbound flow is activated by maintenance interventions defined in ‘Components Behaviour and Maintenance Module’, instead inbound flows are activated by the auxiliary variables define in this module that are able to define the batch dimension and the reorder time in accordance with stock management policies used from the customer. In that sense it is possible to choose between FIXED POINT and FIXED PERIOD reorder policies for each component of model. In the first case, there is a fixed quantity of reorder batch, calculated minimizing costs of stock handling and costs to handle orders. The reorder time is a variable that changes considering the usage of components, which means it changes following behaviour of components simulated in the main module. The reorder level is evaluated considering purchasing lead time, trying to guarantee the stock level above the security stock level. Indeed in the fixed period policy, customer chooses a fixed reordering interval and the quantity batch is calculated like difference between available stock level and target stock level.

Another feature of this module is the capability to implement the reparability or substitution mechanism presented in the previous module, handling effects that this choice involves in the stock handling simulation.

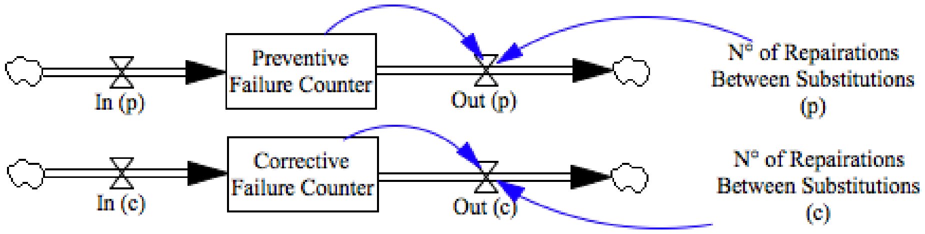


Figure 7.24 – Repairing or Substitution Handling structure

The stock and flows presented above allow counting the number of times that the component was repaired in both policy cases, in order to lead the if conditions that involve an inbound flow activation. It means that every time there is a failure, the module check if it is time to active the withdrawal of new components from the storage or if there is a reparation. The combination of modules mechanism allows setting a number of repairs that could be done before their replacement. Every component can be set in a different way. (i.e. it could be repaired a number of time in case of preventive action, and it could be changed in case of corrective). There is also the possibility to consider both cases (corrective and preventive) repairable for different times, but in a higher time and in a more expensive way in case of corrective actions (i.e. welding solutions on a framework).

The values estimation of variables to simulate policies are based on literature stock handling formulas.

Fixed point batch orders are defined on the basis of EOQ formula:

$$EOQ = \sqrt{\frac{2 * AD * OC}{PP * YSR}} \qquad (7.1)$$

AD = Annual Demand
OC = Order Cost
PP = Purchasing Price
YSR = Yearly Stock Rate

Indeed fixed period policy choices are defined on the basis of reorder point and the operative stock level formulas:

$$RP = DD * LT + SSL \qquad (7.2)$$

$$OSL = DD * (FT + LT) + SSL \qquad (7.3)$$

DD = Daily Demand
FT = Fixed Time
LT = Lead Time
SSL = Security Stock Level

The definition of security stock level is based on the policy choice and it follows these formulas:

$$\mathrm{SSL} = \mathrm{K} * \sqrt{LT * \sigma_{DD}{}^2 + DD * \sigma_{LT}{}^2} \qquad \text{(Fixed Point Policy)} \qquad (7.4)$$

$$\mathrm{SSL} = \mathrm{K} * \sqrt{(LT + FT) * \sigma_{DD}{}^{2} + DD * \sigma_{LT}{}^{2}} \quad \text{(Fixed Period Policy)} \qquad (7.5)$$

K = Service Level
LT = Lead Time
FT = Fixed Time
DD = Daily Demand

The output of the module is the amount of stock management costs for each component, defined by choices on the storage handling. The evaluation of the cost is based on the following literature formula:

$$\mathrm{C}_{\mathrm{TOT}} = \mathrm{YD} * \mathrm{PP} + \frac{YD}{OQ}\, OC + \frac{OQ}{2}\, PP * YSR \qquad (7.6)$$

YD = Yearly Demand
PP = Purchasing Price
OQ = Order Quantity
YSR = Yearly Stock Rate

7.2.3 – Summary of module capability:

Capabilities and features of the module are:

- Handle both fixed time and fixed period policies
- Evaluate purchasing costs of component
- Evaluate costs to handle the order (i.e. assurance, transportation, billing and packing charges costs)
- Evaluate the cost of stock handling (i.e. costs related to handle components in storage, assurance and obsolescence risk)
- Evaluate costs due spare parts lack (but they are described in costs evaluation module, because time spent waiting spare parts is added to down time, as it is described in that section)

7.2.4 – Input variables and measurement unit description:

In the table below there are all input module variables of components A, B and C. Data used are not referred to any kind of real situation but they are used to justified graphs showed in the section.

Variable Name	**Variable Meaning**	**Variable Value**	**Unit of measurement**
Stock Management Policy A	It's a Boolean variable that allows choosing between fixed point or fixed time reorder stock policy for component A.	1	1 = Fixed Point 0 = Fixed Time
Stock Management Policy B	It's a Boolean variable that allows choosing between fixed point or fixed time reorder stock policy for component B.	0	1 = Fixed Point 0 = Fixed Time
Stock Management Policy C	It's a Boolean variable that allows choosing between fixed point or fixed time reorder stock policy for component C.	1	1 = Fixed Point 0 = Fixed Time
K (A)	It's the service level required by customer for component A. It's calculated as the inverted Std Normal and it represents the demand level required avoiding stock out.	2.05	/
K (B)	It's the service level required by customer for component B. It's calculated as the inverted Std Normal and it represents the demand level	2.05	/

	required avoiding stock out.		
K (C)	It's the service level required by customer for component C. It's calculated as the inverted Std Normal and it represents the demand level required avoiding stock out.	2.05	/
Sigma DD (A)	Std deviation in daily demand A	0.8	/
Sigma DD (B)	Std deviation in daily demand B	0.3	/
Sigma DD (C)	Std deviation in daily demand C	0.9	/
Sigma LT (A)	Std deviation in Lead Time of purchasing of component A	1.3	Days
Sigma LT (B)	Std deviation in Lead Time of purchasing of component B	0.75	Days
Sigma LT (C)	Std deviation in Lead Time of purchasing of component C	0.75	Days
Lead Time Purchasing A	It's the average value of lead time in purchasing process of component A	7	Days
Lead Time Purchasing B	It's the average value of lead time in purchasing process of component B	5	Days
Lead Time Purchasing C	It's the average value of lead time in purchasing process of component C	3	Days
Fixed Time A	It's the interval between reordering process in fixed time policy of component A	200	Days
Fixed Time B	It's the interval between reordering process in fixed time policy of component B	100	Days
Fixed Time C	It's the interval between reordering process in fixed time policy of	80	Days

	component C		
Yearly Stock Rate A	It's the yearly rate to evaluate cost to leave stocked component A	0.12	%
Yearly Stock Rate B	It's the yearly rate to evaluate cost to leave stocked component B	0.12	%
Yearly Stock Rate C	It's the yearly rate to evaluate cost to leave stocked component C	0.12	%
Price of Component A	That is price to pay to get component A	7000	€
Price of Component B	That is price to pay to get component B	1250	€
Price of Component C	That is price to pay to get component C	830	€
Cost of Order A	It means cost to handle an order of A, including for example transportation, assurance, and billing.	2000	€
Cost of Order B	It means cost to handle an order of B, including for example transportation, assurance, and billing.	900	€
Cost of Order C	It means cost to handle an order of C, including for example transportation, assurance, and billing.	400	€
N° of Reparations Between Substitutions (c) A	It's the number of repair that could be done before a substitution of component A in corrective policy. The value 0 means that it doesn't possible repair in any case.	0	/
N° of Reparations Between	It's the number of repair that could be done before a substitution of	0	/

Substitutions (p) A	component A in preventive policy. The value 0 means that it doesn't possible repair in any case.		
N° of Reparations Between Substitutions (c) B	It's the number of repair that could be done before a substitution of component B in corrective policy. The value 0 means that it doesn't possible repair in any case.	0	/
N° of Reparations Between Substitutions (p) B	It's the number of repair that could be done before a substitution of component B in preventive policy. The value 0 means that it doesn't possible repair in any case.	1	/
N° of Reparations Between Substitutions (c) C	It's the number of repair that could be done before a substitution of component C in corrective policy. The value 0 means that it doesn't possible repair in any case.	0	/
N° of Reparations Between Substitutions (p) C	It's the number of repair that could be done before a substitution of component C in preventive policy. The value 0 means that it doesn't possible repair in any case.	2	/

Table 7.5 – Auxiliary Input Variables (Spare Parts Module)

7.2.5 – Auxiliary variables description:

The variables showed in next tables are related only to component A, because they contain equations with the same structure, so it's enough to replicate them.

Variable Name	Variable Meaning
Security Stock Level A	It means the security level should be in stock to avoid stop of production. It depends how much risk we want to avoid in accordance on the variability of the system.
Security Stock Level (Rounded) A	It's the rounded value of variable because it is necessary to use a discrete value.
Yearly Demand A	It is the Yearly Demand of Components in accordance with their Life Cycle.
Reorder Point A	It's the stock level that means it's time to order a batch of components.
Reorder Point (Rounded) A	It's the rounded value of variable because it is necessary to use a discrete value.
EOQ (A)	It's the optimized batch of components in accordance with the considered costs.
EOQ (Rounded) A	It's the rounded value of variable because it is necessary to use a discrete value.
Operative Stock Level A	It's the available stock level every fixed period, it is used to evaluate how much to reorder in fixed period policy.
Operative Stock Level (Rounded) A	It's the rounded value of variable because it is necessary to use a discrete value.
OQ (A)	It's the variable batch in case of fixed period policy.
OQ (Rounded) A	It's the rounded value of variable because it is necessary to use a discrete value.
Time Variable A	It's a variable built to describe the period between two

	orders in fixed time policy.
Under Ordination (Fixed Point) A	It's a Boolean variable used to describe time of simulation under ordination. When variable is 0 there isn't any ordination, instead 1 it means it's time to order. It is built in this way to simulate Lead Time and allow the use of the function FIXED DELAY. This variable is related to Fixed Point Policy.
Under Ordination (Fixed Period) A	It's a Boolean variable used to describe time of simulation under ordination. When variable is 0 there isn't any ordination, instead 1 it means it's time to order. It is built in this way to simulate Lead Time and allow the use of the function FIXED DELAY. This variable is related to Fixed Time Policy.
Aux (Fixed Point) A	It's an Auxiliary variable that describes how much should be the batch in accordance with the others and how much is the FIXED DELAY between the order and the arrive of components. This is related to Fixed Point Policy.
Aux (Fixed Period) A	It's an Auxiliary variable that describes how much should be the batch in accordance with the others and how much is the FIXED DELAY between the order and the arrive of components. This is related to Fixed Time Policy.

Table 7.6 – Auxiliary Variables (Spare Parts Module)

7.2.6 – Flow variables description:

Variable Name	Variable Meaning
Purchase of Component A	It's the variable that describe the purchase process about the components A.

Use of Components A	It describe the usage of components A.
Cost Counter A	It’s the flow variable that counts all costs in stock management of components A.
In (p) A	It’s the input flow that allows building a (preventive) counter of repairs between substitutions. The counter is used as logic condition to handle different calculations in repair case instead of the substitution.
In (c) A	It’s the input flow that allows building a (corrective) counter of repairs between substitutions. The counter is used as logic condition to handle different calculations in repair case instead of the substitution.
Out (p) A	It’s the output flow that allows building a (preventive) counter of repairs between substitutions. The counter is used as logic condition to handle different calculations in repair case instead of the substitution.
Out (c) A	It’s the output flow that allows building a (corrective) counter of repairs between substitutions. The counter is used as logic condition to handle different calculations in repair case instead of the substitution.

Table 7.7 – Flow Variables (Spare Parts Module)

7.2.7 – Stock variables description:

Variable Name	**Variable Meaning**
Preventive Failure Counter (A)	It’s the stock used to build a (preventive) counter of repairs between substitutions. The counter is used as logic condition to handle different calculations in repair case instead of the substitution.
Corrective Failure Counter (A)	It’s the stock used to build a (corrective) counter of repairs between substitutions. The counter is used as logic condition to handle different calculations in repair case instead of the substitution.

Stock Inventory Level A	It describes the level of components A.
Stock Costs A	It's the stock variable that counts the accumulation of stock management costs of components A.

Table 7.8 – Stock Variables (Spare Parts Module)

7.2.8 – Mathematical equations description:

- Time Variable

  This variable describe a periodic function on the basis of the fixed time chosen, it's used as logic value in the fixed time policy simulation.

  ```
  MODULO(Time,Fixed Time A)
  ```

- Under Ordination (Fixed Point) A

  The variable becomes 1 only when stock level reaches order point and remains 1 until the refill.

  ```
  IF THEN ELSE(Stock Inventory Level A>"Reorder Point
  (Rounded) A",0,1)
  ```

- Under Ordination (Fixed Period) A

  In that case variable is 1 for each fixed interval, using Time Variable as logic value.

  ```
  IF THEN ELSE(Time>Lead Time Purchasing A,
  IF THEN ELSE(Time Variable A<=Lead Time Purchasing
  A,1,0),0)
  ```

- Aux (Fixed Point) A

  This auxiliary variable Define how much big is the order and when it should arrive. The batch is equal to EOQ (Rounded) and it arrives with a delay calculated as Lead Time Purchasing.

  ```
  DELAY FIXED(("EOQ (Rounded) A"*"Under Ordination (Fixed
  Point) A"),Lead Time Purchasing A-1,0)
  ```

- Aux (Fixed Period) A

This variable is similar to the previous, but the batch quantity is evaluated on the basis of OQ (Rounded) A.

```
DELAY FIXED("OQ (Rounded) A"*"Under Ordination (Fixed
Period) A",Lead Time Purchasing A,0)
```

- Purchase of Component A

  Purchasing flow is described with aux variable multiplied with under ordination in both policies cases. The function is activated when under ordination became 1 and after the refill under ordination becomes zero again and Aux variable is immediately stopped. The use of Stock management policy variable allows using the right part of formula on the basis of chosen policy.

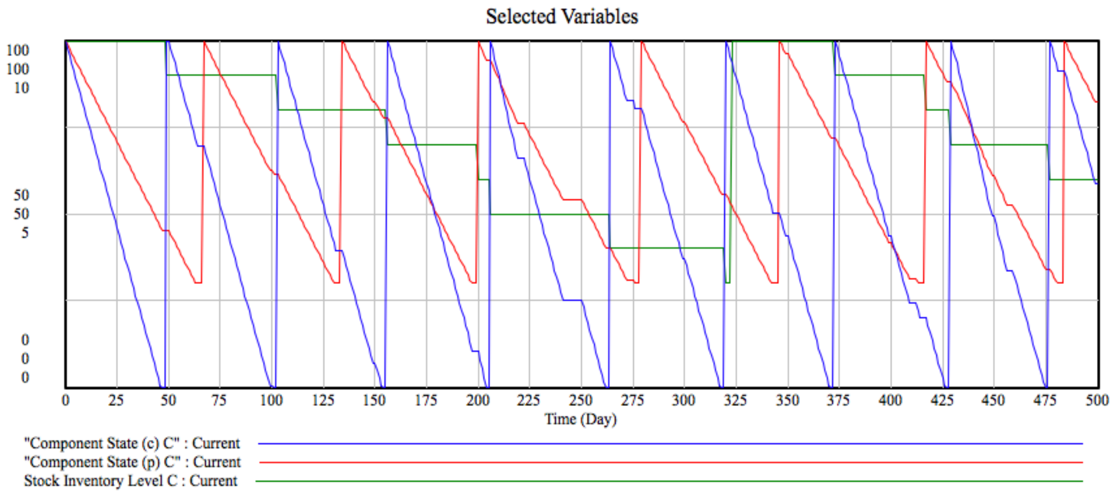
```
("Aux (Fixed Point) A"*"Under Ordination (Fixed Point)
A"*Stock Management Policy A)+("Aux (Fixed Period)
A"*"Under Ordination (Fixed Period) A"*(1-Stock Management
Policy A))
```

- Stock Inventory Level A

  It is initialized with Operative Stock Level (Rounded) A in case of fixed period reorder policy, else it is initialized with EOQ (Rounded) A value plus Reorder Point (Rounded) A.

```
Initial Value = ("EOQ (Rounded) A"+"Reorder Point (Rounded)
A")*Stock Management Policy A+("Operative Stock Level
(Rounded) A"*(1-Stock Management Policy A))
```

Below it is showed a graph of simulation of Stock Inventory Level C in accordance with Reliability in both cases preventive and corrective:



Graph 7.9 – Component State and Stock Inventory Level Trends

- <u>Use of Components A</u>

The use of components is simulated withdrawing them from storage only if it happens a substitution, so if there is a maintenance event and at the same time the failure counter is equal to the maximum repairing number, it means that the maintenance event is happening is a substitution, so the use of components A variable is activated.

```
IF THEN ELSE("Maint (c) A">0,
IF THEN ELSE("Corrective Failure Counter (A)"="N° of
Reparations Between Substitutions (c) A",MIN(Stock
Inventory Level A,1)
,0),0)
+
IF THEN ELSE("Maint (p) A">0,
IF THEN ELSE("Preventive Failure Counter (A)"="N° of
Reparations Between Substitutions (p) A",MIN(Stock
Inventory Level A,1)
,0),0)
```

- <u>Security Stock Level A</u>

```
"K (A)"*SQRT(((Lead Time Purchasing A+(Fixed Time A*(1-
Stock Management Policy A)))*("Sigma DD (A)"^2))+((Yearly
Demand A/365)*("Sigma LT (A)"^2)))
```

- <u>Security Stock Level (Rounded) A</u>

The variable is rounded to the nearest value.

```
IF THEN ELSE((Security Stock Level A-INTEGER(Security Stock
Level A))>0.5,INTEGER(Security Stock Level
A)+1,INTEGER(Security Stock Level A))
```

- Yearly Demand A

The yearly demand is calculated on the basis of MTTF of components, but considering the possibility to repair instead of replacement, that value is divided with the number of substitutions. Xidz function is used to avoid problems in case of denominator equal to zero.

```
xidz((365/"MTTF (A)"),("N° of Reparations Between
Substitutions (c) A"+"N° of Reparations Between
Substitutions (p) A"),365/"MTTF (A)")
```

- EOQ (A)

```
SQRT((2*Yearly Demand A*Cost of Order A)/(Component Price
A*Yearly Stock Rate A))
```

- EOQ (Rounded) A

It’s the rounded EOQ value to the nearest value.

```
IF THEN ELSE(("EOQ (A)"-INTEGER("EOQ
(A)"))>0.5,INTEGER("EOQ (A)")+1,INTEGER("EOQ (A)"))
```

- Reorder Point A

```
 ((Yearly Demand A/365)*Lead Time Purchasing A)+"Security
Stock Level (Rounded) A"
```

- Reorder Point (Rounded) A

```
IF THEN ELSE((Reorder Point A-INTEGER(Reorder Point
A))>0.5,INTEGER(Reorder Point A)+1,INTEGER(Reorder Point
A))
```

- Operative Stock Level A

```
 ((Yearly Demand A/365)*(Fixed Time A+Lead Time Purchasing
A))+"Security Stock Level (Rounded) A"
```

- Operative Stock Level (Rounded) A

```
IF THEN ELSE((Operative Stock Level A-INTEGER(Operative
Stock Level A))>0.5,INTEGER(Operative Stock Level
A)+1,INTEGER(Operative Stock Level A))
```

- OQ (A)

```
IF THEN ELSE("Operative Stock Level (Rounded) A"-Stock
Inventory Level A>0,"Operative Stock Level (Rounded) A"-
Stock Inventory Level A,0)
```

- OQ (Rounded) A

```
IF THEN ELSE(("OQ (A)"-INTEGER("OQ (A)"))>0.5,INTEGER("OQ
(A)")+1,INTEGER("OQ (A)"))
```

- Cost Counter A

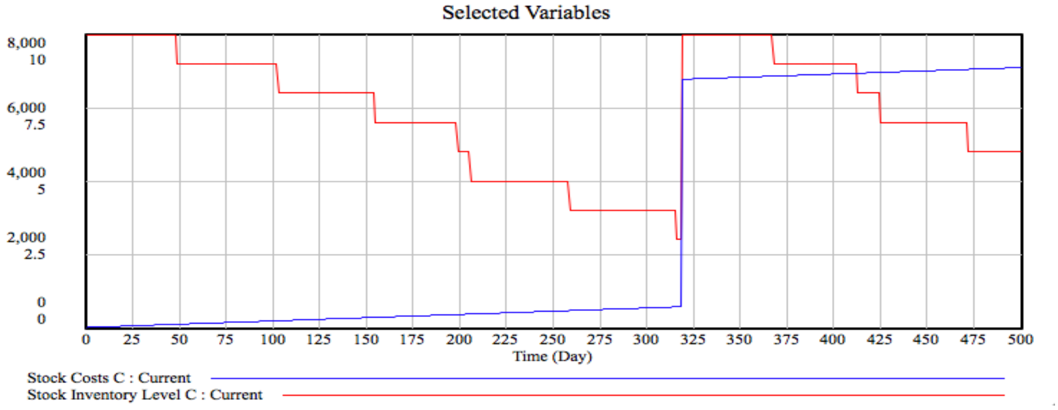
Every time there is a batch order it is added the order cost and purchasing costs to the output, by the counter flow. Handling stock cost is considered multiplying the yearly stock rate with the average stock level value.

```
((Purchase of Components A*Component Price A)+
IF THEN ELSE(Purchase of Components A="EOQ (Rounded)
A",Cost of Order A,0)+
(((("EOQ (Rounded) A"/2)+"Security Stock Level (Rounded)
A")*Component Price A*Yearly Stock Rate A)/365))*Stock
Management Policy A
+
((Component Price A*Purchase of Components A)+
IF THEN ELSE(Time Variable A=Lead Time Purchasing A,
IF THEN ELSE("OQ (Rounded) A">0,Cost of Order A,0),0)+
((((Yearly Demand A/365)*Fixed Time A)/2)+"Security Stock
Level (Rounded) A")*Component Price A*Yearly Stock Rate
A)*(1-Stock Management Policy A)
```

- Stock Costs A

```
Initial Value = 0
```

This variable has a linear (cumulative) function that describes handling costs of the storage, but when there is an order it is added the purchasing cost of the batch.



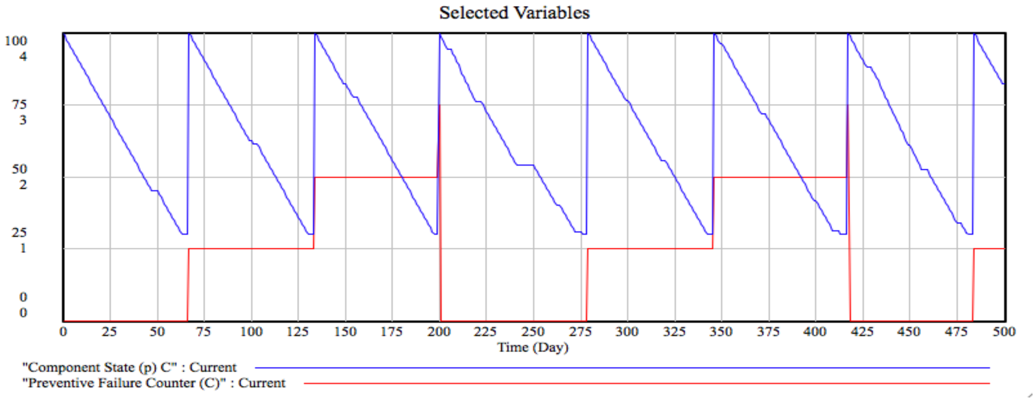
Graph 7.10 – Stock Costs and Stock Inventory Level Trends

- <u>Preventive Failure Counter (A)</u>

This failures counter allow counting how much time a component is repaired and when it is substituted.

`Initial Value = 0`

It is showed the case of component C:



Graph 7.11 Component State and Preventive Failure Counter Trends

- <u>Corrective Failure Counter (A)</u>

`Initial Value = 0`

- <u>In (p) A</u>

This flow is activated every time there is a maintenance event.

```
IF THEN ELSE("Maint (p) A">0,1,0)
```

- In (c) A

```
IF THEN ELSE("Maint (c) A">0,1,0)
```

- Out (p) A

It means after a substitution the counter must restart from zero.

```
IF THEN ELSE("Preventive Failure Counter (A)"="N° of
Reparations Between Substitutions (p) A"+1,"N° of
Reparations Between Substitutions (p) A"+1,0)
```

- Out (c) A

```
IF THEN ELSE("Corrective Failure Counter (A)"="N° of
Reparations Between Substitutions (c) A"+1,"N° of
Reparations Between Substitutions (c) A"+1,0)
```

7.3 - Service Module:

7.3.1 – Short simulation module graph label:

This section presents ‘Service Module’ that is described in the figure below, where purple auxiliary variables highlight inputs of module that come from a technical database filled from technical staff, instead blue connections are referred to this module.

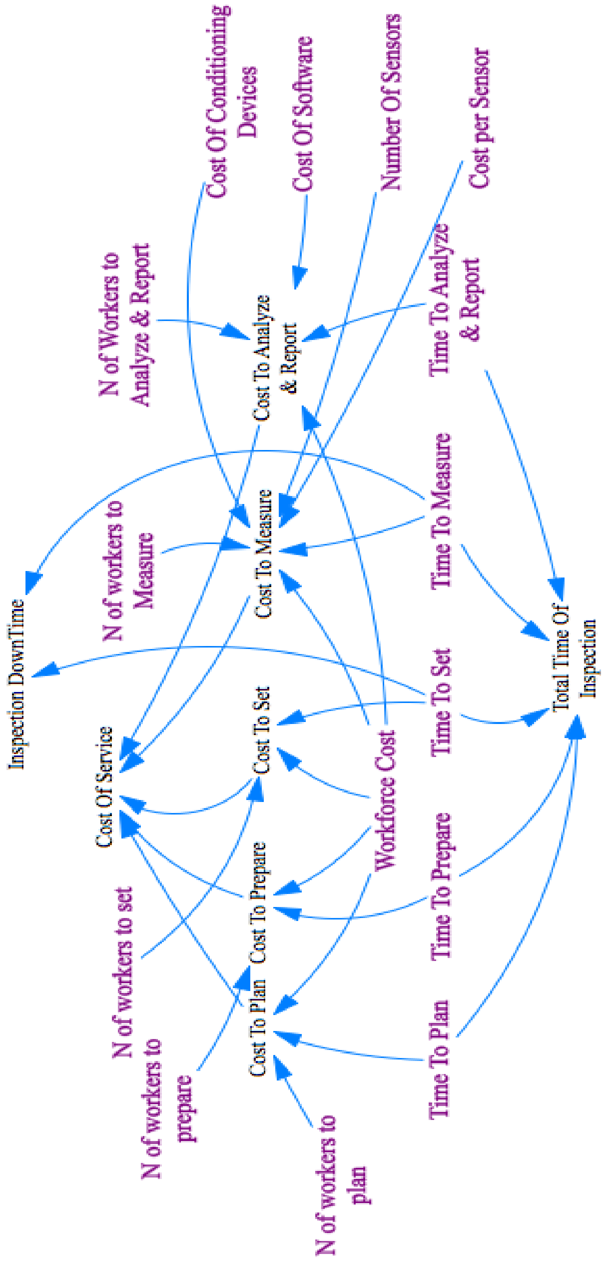


Figure 7.25 – Service Module

7.3.2 – Description of module features:

The service module is pretty simple, it handles technical and economic data specifically related to the measurement service chosen and it translates them in time, costs and requirements. The description of variables that affect the estimation of technical and economic variables were defined following the provider measurement process analyzed in VTT and showed below:

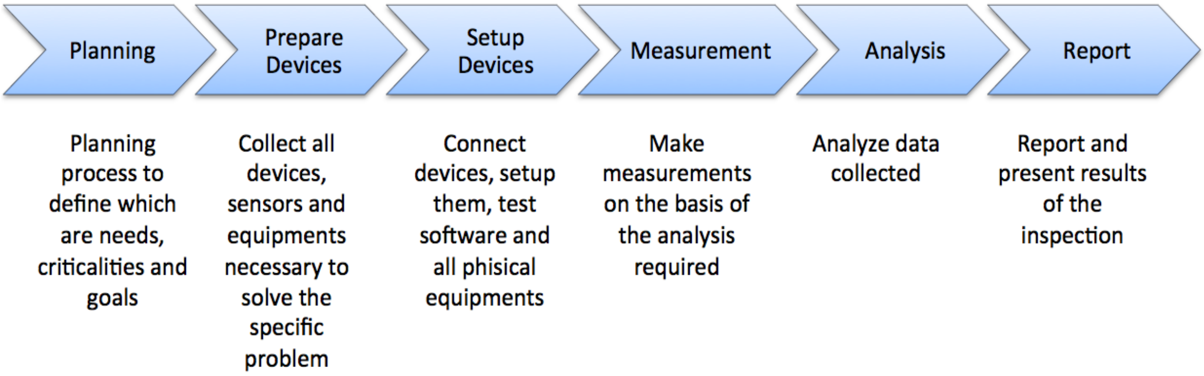


Figure 7.26 – Inspection Process

The relationship between customer and supplier can be characterized with these two scenarios. In both cases customer wants to understand how the service can help him:

- Customer knows fault, because it happened often, but doesn’t know causes
- Customer noticed symptoms, but it doesn’t know what it will happen

So customer managers should evaluate the specific case and they should cross it with information about the measurement process. Initializing the module with this information, it would be possible to describe needs to implement the solution. Anyway considering that customer managers cannot handle this kind of data without to be supported, it is developed a database to initialize the module. Database, filled by technical staff, is explored with customer before the usage of simulation model, so the customer manager can make a query with main information of his customer and to find out the right service setup.

The Class Diagram of database, presented in chapter 1, is showed in the figure below to present further details:

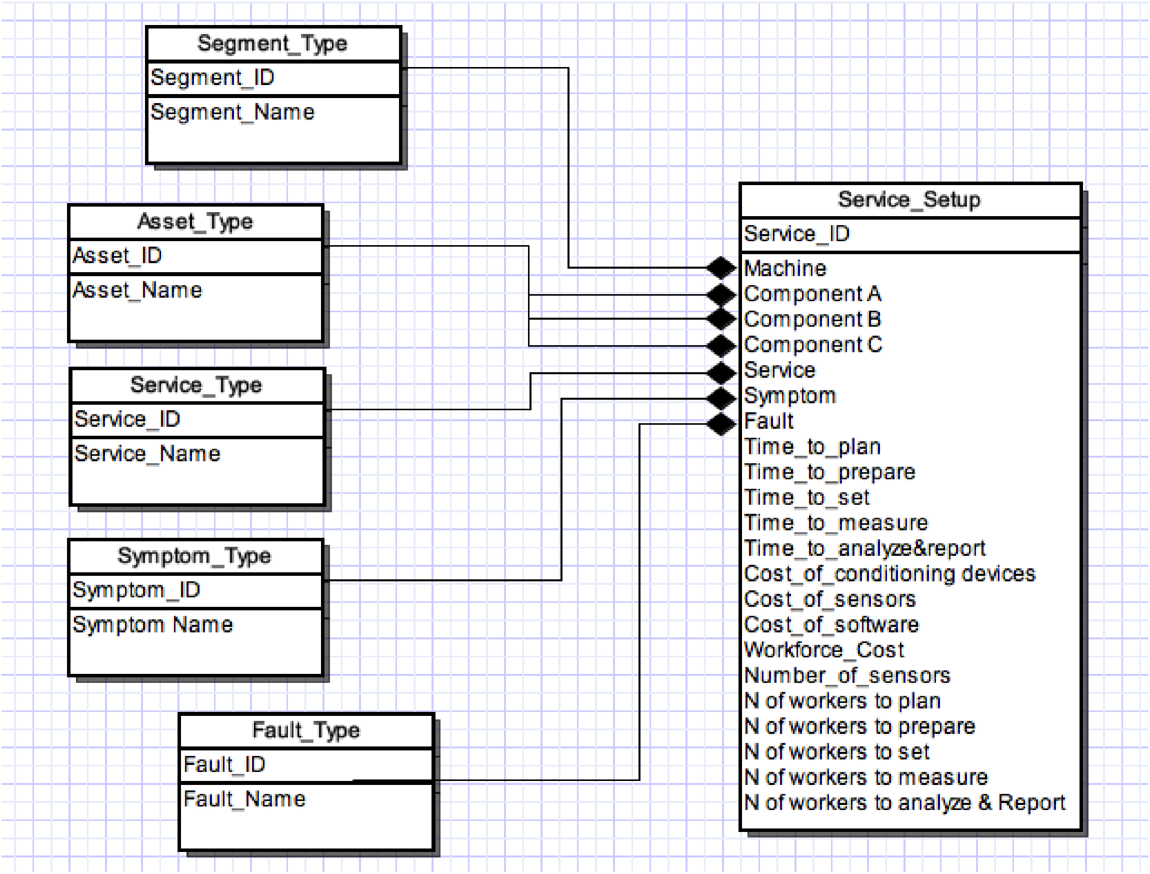


Figure 7.27 – Technical Data Base Class Diagram

Despite this would be the best solution, it could not be possible to connect directly database with model, the simulation software does not have predisposition to make a directly connection to the initialization of data using a query of a database. Nevertheless, there are two ways to solve the problem:

- Copy and paste the array founded out with database query in an excel page, directly connected to the simulation model.
- Build a software (i.e. with a programming language like C++), that is able to make the connection between the model and the database.

In both cases the input software would be the interface of application level used to communicate with customers, so it would handle customer inputs and present simulation results.

7.3.3 – Summary of module capability:

The module capabilities are:

- Handle data of the technical database
- Handle the technical needs of the service (i.e. sensors, devices, software, number of worker per step) following measurement process
- Provide an estimation of necessary time to make an inspection
- Provide the estimation of costs to make an inspection

7.3.4 – Input variables and measurement unit description:

Variable Name	Variable Meaning	Variable Value	Unit of measurement
Time To Plan	It's time to plan the inspection	2	Days
Time To Prepare	It's time to collect all devices there will used in measurement step	2	Days
Time To Set	It's time spent to set devices on the machines testing them and verifying all it is working in the right condition	1	Days
Time To Measure	It's time spent in measurement work	1	Days
Time To Analyze & Report	It's time spent to analyzing data and reporting results	5	Days
Workforce Cost	It's the cost of workforce	800	€/Day per Person
Number of Sensors	It's the number of sensors to be used on the basis of machine, components, dimensions and measurement kind	3	/
Cost of Sensors	It's cost of use of a sensor, calculated as a % of purchasing	1.4	€

	price per day		(0,14% Purchasing Price per Day)
Cost of Conditioning Devices	It's cost of use of conditioning devices, calculated as a % of purchasing price per day	30.8	€ (0,14% Purchasing Price per Day)
Cost of Software	It's cost of software used to analyze data, calculated as a % of purchasing price per day	2.8	€ (0,14% Purchasing Price per Day)
N of workers to plan	It's the number of workers used in plan step	2	/
N of workers to prepare	It's the number of workers used in prepare step	1	/
N of workers to set	It's the number of workers used in set step	2	/
N of workers to measure	It's the number of workers used in measurement step	2	/
N of workers to analyze & report	It's the number of workers used in analysis & report step	1	/

Table 7.9 – Auxiliary Input Variables (Service Module)

7.3.5 – Auxiliary variables description:

Variable Name	Variable Meaning
Cost To Plan	It's the cost to plan an inspection
Cost To Prepare	It's the cost to collect devices

Cost To Set	It’s the cost to set and verify devices
Cost To Measure	It’s the cost to make measurements
Cost To Analyze & Report	It’s the cost to analysis and report data
Total Time Of Inspection	It’s the total time spent for each inspection
Inspection Down Time	It’s inspection time requires machine stopped
Cost Of Service	It’s the cost for each inspection

Table 7.10 – Auxiliary Variables (Service Module)

7.3.6 – Mathematical equations description:

- Cost To Plan

```
Workforce Cost*Time To Plan*N of workers to plan
```

- Cost To Prepare

```
Time To Prepare*Workforce Cost* N of workers to prepare
```

- Cost To Set

```
Time To Set*Workforce Cost* N of workers to set
```

- Cost To Measure

```
Cost Of Conditioning Devices+(Cost per Sensor*Number Of Sensors)+(Time To Measure*Workforce Cost* N of workers to measure)
```

- Cost To Analyze & Report

```
Cost Of Software+("Time To Analyze & Report"*Workforce Cost* "N of workers to analyze & Report")
```

- Total Time Of Inspection

```
"Time To Analyze & Report"+Time To Measure+Time To Plan+Time To Prepare+Time To Set
```

- Inspection Down Time

```
Time To Measure+Time To Set
```

- Cost Of Service

```
"Cost To Analyze & Report"+Cost To Measure+Cost To
Plan+Cost To Prepare+Cost To Set
```

7.4 - Costs Evaluation Module:

7.4.1 – Short simulation module graph label:

This section describes costs evaluation module. The picture below was built connecting it with a basic view of variables of modules directly connected and included in mathematical equations of component behaviour and maintenance variables.

- Blue connections belong to this module
- Grey variables underline connections that come from other modules.
- Green auxiliary variables highlight inputs of module and they should be filled from customer to describe own plant situation and targets in costs evaluation.
- Orange variables are outputs of the model

Since the high complexity does not allow explaining well the model, it is highlighted only relationship of component A, anyway it includes light grey variables of other components B and C correlated with the first one and connected with dotted lines. In a similar way of components behaviour and maintenance module, understanding the single component framework, it's simple to build the whole module, just replicating the same structure for each other.

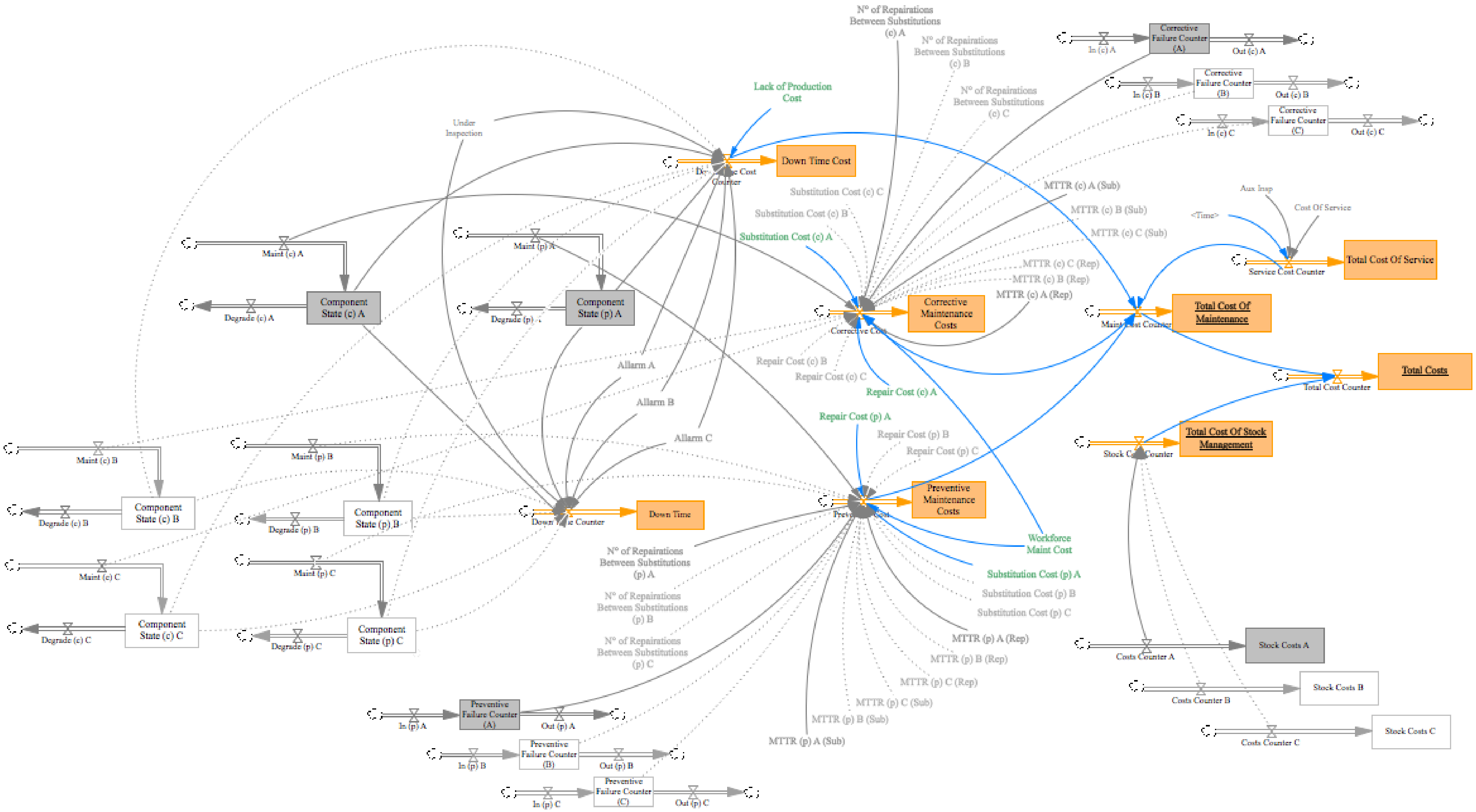


Figure 7.28 - Cost Evaluation Module

7.4.2 – Description of module features:

This module has a simple calculation structure, but it seems complex because it summarizes a lot of information from other modules translating in cost language. Stocks represent the accumulation of cost flows along the simulation time.

Costs included in the module are:

- Direct Maintenance Costs
- Down Time Costs
- Service Costs
- Spare Parts Costs

Maintenance costs are divided on the basis of policy to show them in details. In both cases, if there is the possibility to repair a component an amount of time, it’s possible to set different costs of repairing instead of substitution. Anyway repairing or replacement costs do not include purchasing cost of new component, because it is considered in spare parts module.

Down time stock and flow counts all time wasted on repairing and replacing components, but also waiting stock refill in case of spare parts lack. So down time costs are calculated on the basis of time and lack of production costs set from customer.

Anyway total cost of maintenance includes corrective and preventive costs, down time cost and also cost of inspection service supplied. However the evaluation of whole simulation costs includes total cost of maintenance and costs related to spare parts modules called total cost of stock management.

7.4.3 – Summary of module capability:

- Evaluate costs centers
- Count Down Time Hours

7.4.4 – Input variables and measurement unit description:

In the table below there are all input module variables of components A, B and C. Data used are not referred to any kind of real situation but they are used to justified graphs showed in the section.

Variable Name	Variable Meaning	Variable Value	Unit of measurement
Repair Cost (c) A	It’s the repair cost of component A in case of corrective policy	4000	€
Repair Cost (p) A	It’s the repair cost of component A in case of preventive policy	3500	€
Repair Cost (c) B	It’s the repair cost of component B in case of corrective policy	600	€
Repair Cost (p) B	It’s the repair cost of component B in case of preventive policy	600	€
Repair Cost (c) C	It’s the repair cost of component C in case of corrective policy	430	€
Repair Cost (p) C	It’s the repair cost of component C in case of preventive policy	430	€
Substitution Cost (c) A	It’s the replacement cost of component A in case of corrective policy	500	€
Substitution Cost (p) A	It’s the replacement cost of component A in case of preventive policy	50	€
Substitution Cost (c) B	It’s the replacement cost of component B in case of corrective policy	200	€
Substitution Cost (p) B	It’s the replacement cost of component B in case of	20	€

	preventive policy		
Substitution Cost (c) C	It's the replacement cost of component C in case of corrective policy	200	€
Substitution Cost (p) C	It's the replacement cost of component C in case of preventive policy	20	€
Lack of Production Cost	It's the cost to stop production for customer	500	€/Day
Workforce Maint Cost	It's the HR maintenance operations cost	640	€/Day

Table 7.11 – Auxiliary Input Variables (Cost Evaluation Module)

7.4.5 – Flow variables description:

The variables showed in next tables are related only to component A, because they contain equations with the same structure, so it's enough to replicate them.

Variable Name	Variable Meaning
Corrective Cost	It's the sum of all direct corrective maintenance costs
Preventive Cost	It's the sum of all direct preventive maintenance costs
Maint Cost Counter	This variable count all maintenance costs
Service Cost Counter	This variable count service costs
Stock Cost Counter	This variable count spare parts costs
Total Cost Counter	This variable count whole system costs
Down Time Counter	This variable count down time

Down Time Cost Counter	This variable count down time costs

Table 7.12 – Flow Variables (Cost Evaluation Module)

7.4.6 – Stock variables description:

Variable Name	Variable Meaning
Corrective Maintenance Costs	It’s the amount of direct corrective costs
Preventive Maintenance Costs	It’s the amount of direct preventive costs
Total Cost Of Maintenance	It’s the amount of maintenance costs
Total Cost Of Service	It’s the amount of service costs
Total Cost Of Stock Management	It’s the amount of spare parts costs
Total Costs	It’s the amount of whole system costs
Down Time	It’s the amount of down time
Down Time Cost	It’s the amount of down time costs

Table 7.13 – Stock Variables (Cost Evaluation Module)

7.4.7 – Mathematical equations description:

- Corrective Cost

  The fallowing formula is divided in 3 parts referred to component A, B and C. Analyzing the first part, it means that every time there is a maintenance event, and it is really time to replace the component, because it is not any more repairable or at all, it is time to consider costs of corrective maintenance. Those costs are substitution cost and workforce cost multiplied for time required to replace it, or else it’s necessary to consider the same kind of costs but referred to a repair event.

```
IF THEN ELSE("Maint (c) A">0,
IF THEN ELSE("Corrective Failure Counter (A)"="N° of
Reparations Between Substitutions (c) A",
```

```
"Substitution Cost (c) A"+("MTTR (c) A (Sub)"*Workforce
Maint Cost),
"Repair Cost (c) A"+("MTTR (c) A (Rep)"*Workforce Maint
Cost)),0)
+
IF THEN ELSE("Maint (c) B">0,
IF THEN ELSE("Corrective Failure Counter (B)"="N° of
Reparations Between Substitutions (c) B",
"Substitution Cost (c) B"+("MTTR (c) B (Sub)"*Workforce
Maint Cost),
"Repair Cost (c) B"+("MTTR (c) B (Rep)"*Workforce Maint
Cost)),0)
+
IF THEN ELSE("Maint (c) C">0,
IF THEN ELSE("Corrective Failure Counter (C)"="N° of
Reparations Between Substitutions (c) C",
"Substitution Cost (c) C"+("MTTR (c) C (Sub)"*Workforce
Maint Cost),
"Repair Cost (c) C"+("MTTR (c) C (Rep)"*Workforce Maint
Cost)),0)
```

- Preventive Cost

The formula is strictly similar to the upper one, but it includes variables related to preventive policy case.

```
IF THEN ELSE("Maint (p) A">0,
IF THEN ELSE("Preventive Failure Counter (A)"="N° of
Reparations Between Substitutions (p) A",
"Substitution Cost (p) A"+("MTTR (p) A (Sub)"*Workforce
Maint Cost),"Repair Cost (p) A"+("MTTR (p) A
(Rep)"*Workforce Maint Cost)),0)
+
IF THEN ELSE("Maint (p) B">0,
IF THEN ELSE("Preventive Failure Counter (B)"="N° of
Reparations Between Substitutions (p) B",
"Substitution Cost (p) B"+("MTTR (p) B (Sub)"*Workforce
Maint Cost),"Repair Cost (p) B"+("MTTR (p) B
(Rep)"*Workforce Maint Cost)),0)
```

```
+
IF THEN ELSE("Maint (p) C">0,
IF THEN ELSE("Preventive Failure Counter (C)"="N° of
Reparations Between Substitutions (p) C",
"Substitution Cost (p) C"+("MTTR (p) C (Sub)"*Workforce
Maint Cost),"Repair Cost (p) C"+("MTTR (p) C
(Rep)"*Workforce Maint Cost)),0)
```

- Maint Cost Counter

```
Corrective Cost+Preventive Cost+Down Time Cost
Counter+Service Cost Counter
```

- Service Cost Counter

```
IF THEN ELSE(Time>0,IF THEN ELSE(Aux Insp=0,Cost Of
Service,0),0)
```

- Stock Cost Counter

```
Costs Counter A+Costs Counter B+Costs Counter C
```

- Total Cost Counter

```
Maint Cost Counter+Stock Cost Counter
```

- Down Time Counter:

Down time formula consider wasted time every step of simulation spent with components reliability = 0 in case of corrective policy and = alarm condition in preventive. There is also time spent in inspections defined with variable “Under Inspection” that is = 1 only during inspections.

```
IF THEN ELSE("Component State (c) A"=0,1,0)+
IF THEN ELSE("Component State (c) B"=0,1,0)+
IF THEN ELSE("Component State (c) C"=0,1,0)+
IF THEN ELSE("Component State (p) A"=Alarm A,1,0)+
IF THEN ELSE("Component State (p) B"=Alarm B,1,0)+
IF THEN ELSE("Component State (p) C"=Alarm C,1,0)+
Under Inspection
```

- Down Time Cost Counter:

The following formula is similar to the previous but it adds “Lack of Production Cost” to the counter every time there is down time.

```
    IF THEN ELSE("Component State (c) A"=0,Lack of Production
Cost,0)+
    IF THEN ELSE("Component State (c) B"=0,Lack of Production
    Cost,0)+
    IF THEN ELSE("Component State (c) C"=0,Lack of Production
Cost,0)+
    IF THEN ELSE("Component State (p) A"=Alarm A,Lack of
    Production Cost,0)+
    IF THEN ELSE("Component State (p) B"=Alarm B,Lack of
    Production Cost,0)+
    IF THEN ELSE("Component State (p) C"=Alarm C,Lack of
    Production Cost,0)+
    (Under Inspection*Lack of Production Cost)
```

- Corrective Maintenance Costs:

  `Initial Value = 0`

- Preventive Maintenance Costs:

  `Initial Value = 0`

- Total Cost Of Maintenance:

  `Initial Value = 0`

- Total Cost Of Service:

  `Initial Value = 0`

- Total Cost Of Stock Management:

  `Initial Value = 0`

- Total Costs:

  `Initial Value = 0`

- Down Time:

  `Initial Value = 0`

- <u>Down Time Cost:</u>

  `Initial Value = 0`

Reference:

CONTENTS	REFERENCES	PUBLICATION YEAR	WORK CONTRIBUTION
A supporting tool for the evaluation of CBM impact in After Sales Services.	Farrukku K., Gasparetti M., DIG, Politecnico di Milano.	2010	Politecnico di Milano background reference on maintenance simulation field

Chapter 8 – Case of Study

Although the conceptual model was validated by a number of experts (basing the assessment on the evaluation of its correctness and checking if requirements were met) it is presented a case of study, in order to evaluate the tool behaviour in a real case. In this chapter it is presented the case in anonymous way, because of confidential data are included in it.

After the case of study presentation and discussion it is done a sensitivity analysis on some parameters of the tool. The purpose of this analysis is to understand tool behaviour on variables variation, having the possibility to better evaluate the case and how stable is the solution proposed by the model.

Graphs presented in this chapter represent the average of data collected with 20 runs.

8.1 – Case Presentation

The case of study is related to maintenance interventions on public transportation vehicles. The tool evaluates 3 components that require to be monitored. Each vehicle has 16 hours of working time per day.

- Component A = braking system
- Component B = transmission
- Component C = wheels

As usual, in transportation field, components degradation depends on several elements, for example how the driver dives, how much he usually uses the brake, on the basis of weather conditions, rails conditions, lubrication of rail junctions, but also considering the kind of route for each vehicle. So the degradation is affected by high variability.

The case of study provides four scenarios that try to face maintenance problems:

1. To make an inspection every 60 days
2. To make an inspection every 120 days
3. To make an inspection every 180 days
4. To never make inspections

So the use of the tool can evaluate each scenario, comparing them.

In the following tables are presented input values to initialize the tool with the case of study data. First four rows describes interval between inspections and related CBM detection rates case by case. These data are estimated by experts, so it is not possible to investigate scenarios that have different interval between inspections instead of case of study available data, because of the lack of possibility to describe CBM detection rates in those situations.

Components behaviour and maintenance module case of study data:

Variable Name	Insp. 60	Insp. 120	Insp. 180	Never Insp.
CBM Detection Rate A	0.72	0.49	0.31	0
CBM Detection Rate B	0.97	0.82	0.66	0
CBM Detection Rate C	0.84	0.61	0.52	0
Interval Between Inspections	60	120	180	Never
MTTF (A)	187	187	187	187
MTTF (B)	437	437	437	437
MTTF (C)	312	312	312	312
Dev Std TTF (A)	4	4	4	4
Dev Std TTF (B)	5	5	5	5
Dev Std TTF (C)	7	7	7	7
Alarm A	45	45	45	45
Alarm B	20	20	20	20
Alarm C	15	15	15	15
Collateral Damage BA	0	0	0	0
Collateral Damage CA	0	0	0	0
Collateral Damage AB	0.094	0.094	0.094	0.094
Collateral Damage CB	0.205	0.205	0.205	0.205
Collateral Damage AC	0.117	0.117	0.117	0.117
Collateral Damage BC	0.413	0.413	0.413	0.413
MTTR (c) A (Rep)	0	0	0	0
MTTR (c) B (Rep)	0	0	0	0
MTTR (c) C (Rep)	0	0	0	0
MTTR (p) A (Rep)	0	0	0	0
MTTR (p) B (Rep)	0	0	0	0
MTTR (p) C (Rep)	0	0	0	0
MTTR (c) A (Sub)	5	5	5	5
MTTR (c) B (Sub)	7	7	7	7
MTTR (c) C (Sub)	3	3	3	3
MTTR (p) A (Sub)	1	1	1	1
MTTR (p) B (Sub)	1	1	1	1
MTTR (p) C (Sub)	1	1	1	1

Table 8.1 - Components Behaviour and Maintenance Module Input Data

Spare Parts Module Data:

Variable Name	Insp. 60	Insp. 120	Insp. 180	Never Insp.
Stock Management Policy A	1	1	1	1
Stock Management Policy B	1	1	1	1
Stock Management Policy C	1	1	1	1
K (A)	2.05	2.05	2.05	2.05
K (B)	2.05	2.05	2.05	2.05
K (C)	2.05	2.05	2.05	2.05
Sigma DD (A)	0.8	0.8	0.8	0.8
Sigma DD (B)	0.3	0.3	0.3	0.3
Sigma DD (C)	0.9	0.9	0.9	0.9
Sigma LT (A)	1.3	1.3	1.3	1.3
Sigma LT (B)	0.75	0.75	0.75	0.75
Sigma LT (C)	0.75	0.75	0.75	0.75
Lead Time Purchasing A	5	5	5	5
Lead Time Purchasing B	7	7	7	7
Lead Time Purchasing C	6	6	6	6
Fixed Time A	0	0	0	0
Fixed Time B	0	0	0	0
Fixed Time C	0	0	0	0
Yearly Stock Rate A	0.12	0.12	0.12	0.12
Yearly Stock Rate B	0.12	0.12	0.12	0.12
Yearly Stock Rate C	0.12	0.12	0.12	0.12
Price of Component A	1870	1870	1870	1870
Price of Component B	4630	4630	4630	4630
Price of Component C	643	643	643	643
Cost of Order A	960	960	960	960
Cost of Order B	1344	1344	1344	1344
Cost of Order C	416	416	416	416
N° of Reparations Between Substitutions (c) A	0	0	0	0
N° of Reparations Between Substitutions (p) A	0	0	0	0
N° of Reparations Between Substitutions (c) B	0	0	0	0
N° of Reparations Between Substitutions (p) B	0	0	0	0
N° of Reparations Between Substitutions (c) C	0	0	0	0
N° of Reparations Between Substitutions (p) C	0	0	0	0

Table 8.2 – Spare Parts Module Input Data

Costs Evaluation Module Data:

Variable Name	Insp. 60	Insp. 120	Insp. 180	Never Insp.
Repair Cost (c) A	0	0	0	0
Repair Cost (p) A	0	0	0	0
Repair Cost (c) B	0	0	0	0
Repair Cost (p) B	0	0	0	0
Repair Cost (c) C	0	0	0	0
Repair Cost (p) C	0	0	0	0
Substitution Cost (c) A	200	200	200	200
Substitution Cost (p) A	20	20	20	20
Substitution Cost (c) B	500	500	500	500
Substitution Cost (p) B	50	50	50	50
Substitution Cost (c) C	200	200	200	200
Substitution Cost (p) C	20	20	20	20
Lack of Production Cost	1840	1840	1840	1840
Workforce Maint Cost	640	640	640	640

Table 8.3 – Costs Evaluation Module Input Data

Service Module Data:

Variable Name	Insp. 60	Insp. 120	Insp. 180	Never Insp.
Time To Plan	2	2	2	2
Time To Prepare	2	2	2	2
Time To Set	0	0	0	0
Time To Measure	1	1	1	1
Time To Analyze & Report	5	5	5	5
Workforce Cost	350	350	350	350
Number of Sensors	3	3	3	3
Cost of Sensors	1.4	1.4	1.4	1.4
Cost of Conditioning Devices	30.8	30.8	30.8	30.8
Cost of Software	2.8	2.8	2.8	2.8
N of workers to plan	2	2	2	2
N of workers to prepare	1	1	1	1
N of workers to set	2	2	2	2
N of workers to measure	1	1	1	1
N of workers to analyze & report	1	1	1	1

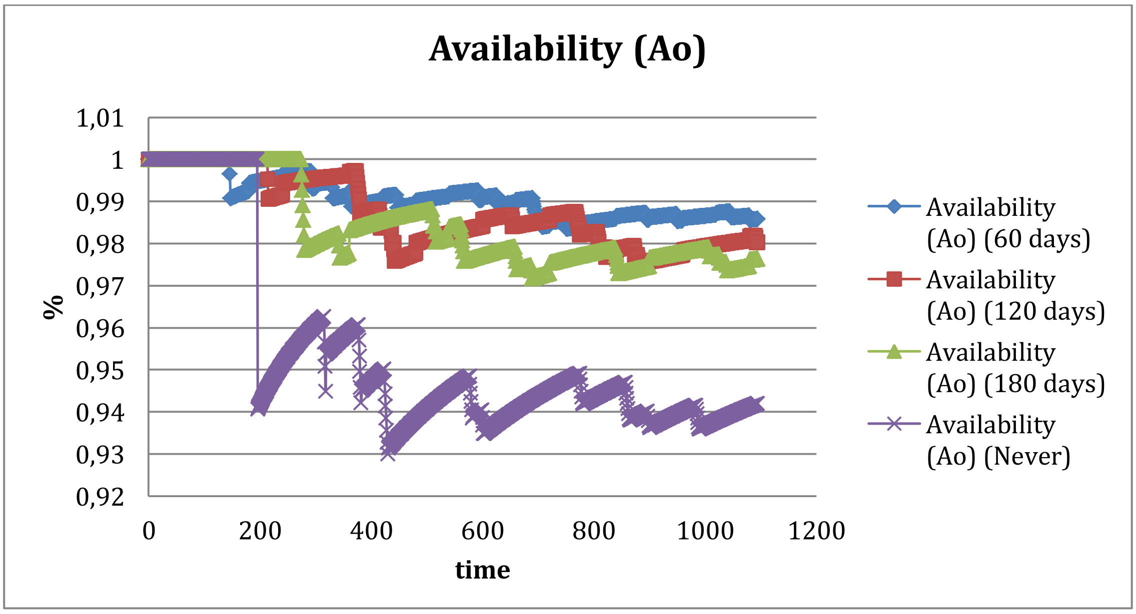
Table 8.4 – Service Module Input Data

8.2 – Scenarios Evaluation

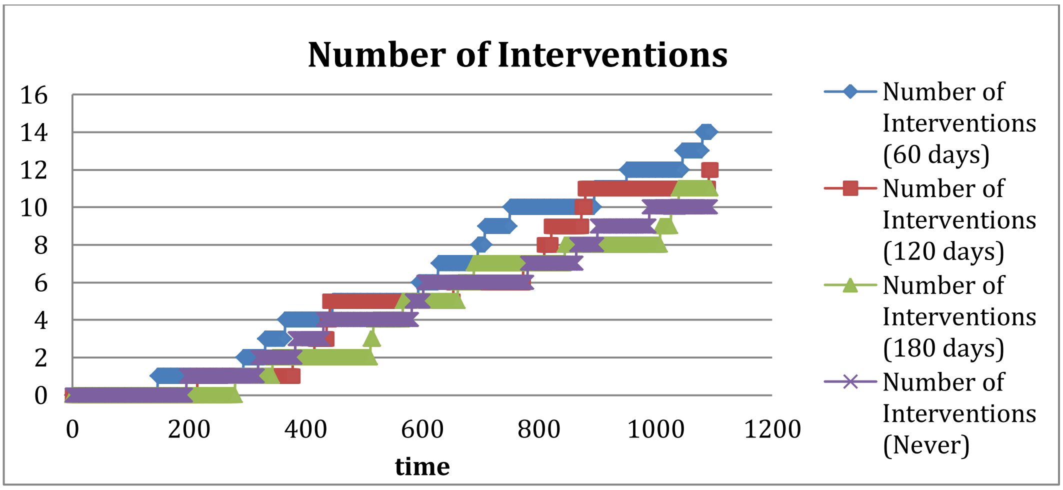
In that section it is presented an overview on outputs provided by the tool. They are evaluated during simulation time (3 years: 1095 days) underlining differences on the basis of scenarios. The outputs of the model are:

- Availability of the system
- Number of interventions
- Down Time (hours)
- Number of inspections
- Corrective maintenance costs
- Preventive maintenance costs
- Down time costs
- Total cost of service
- Total cost of stock management
- Total cost

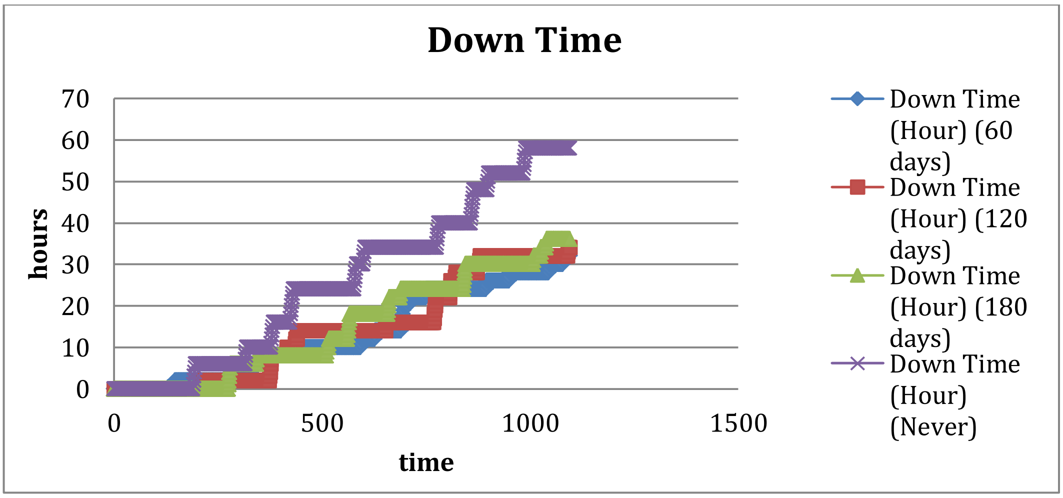
In the following pictures they are presented:



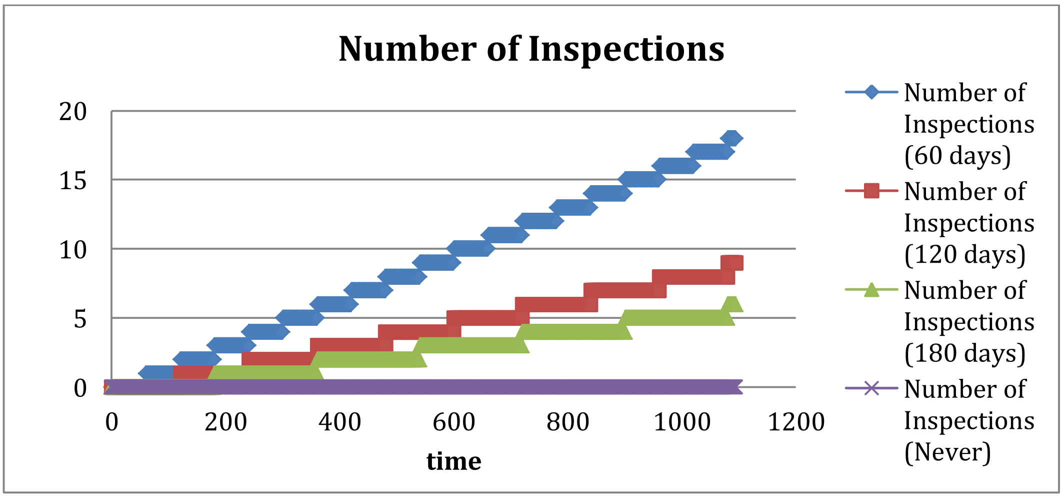
Graph 8.1 – Availability simulation on four scenarios



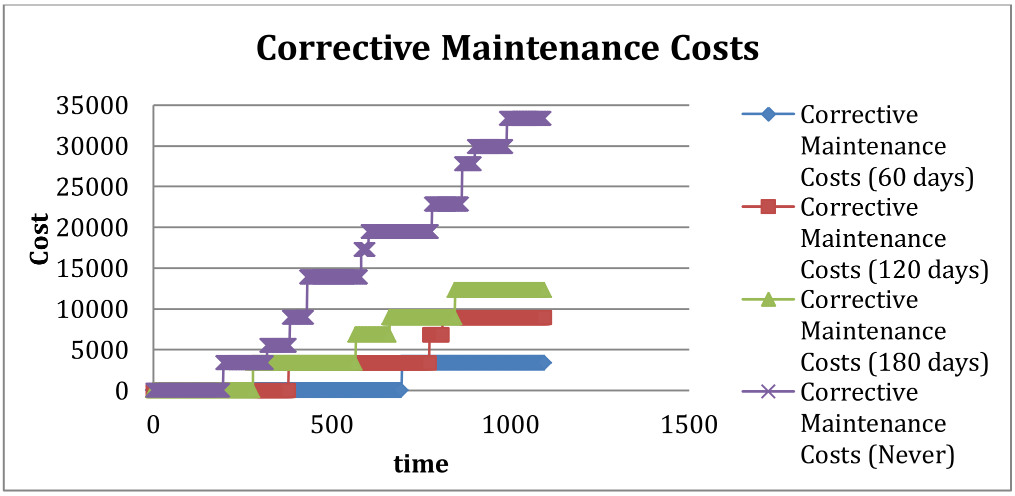
Graph 8.2 – Number of interventions simulation on four scenarios



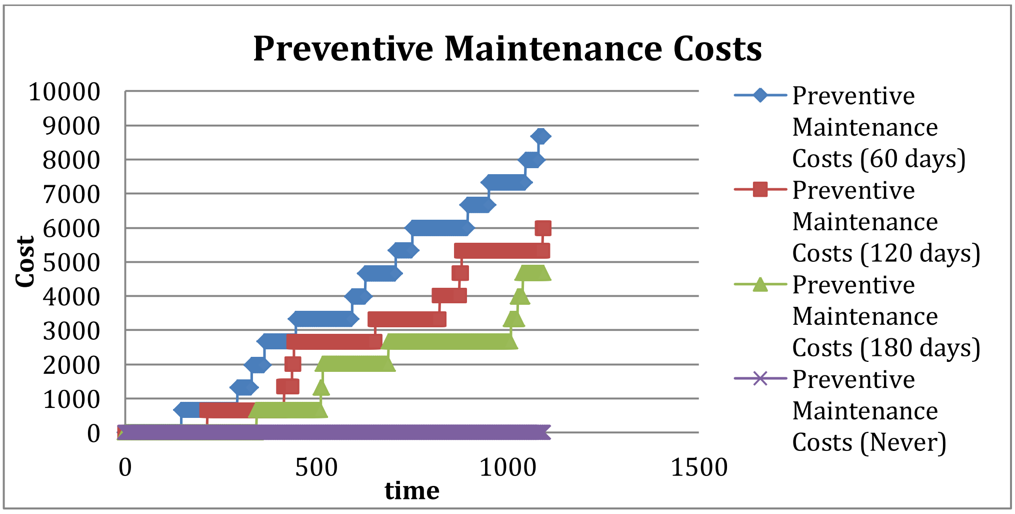
Graph 8.3 – Down time simulation on four scenarios



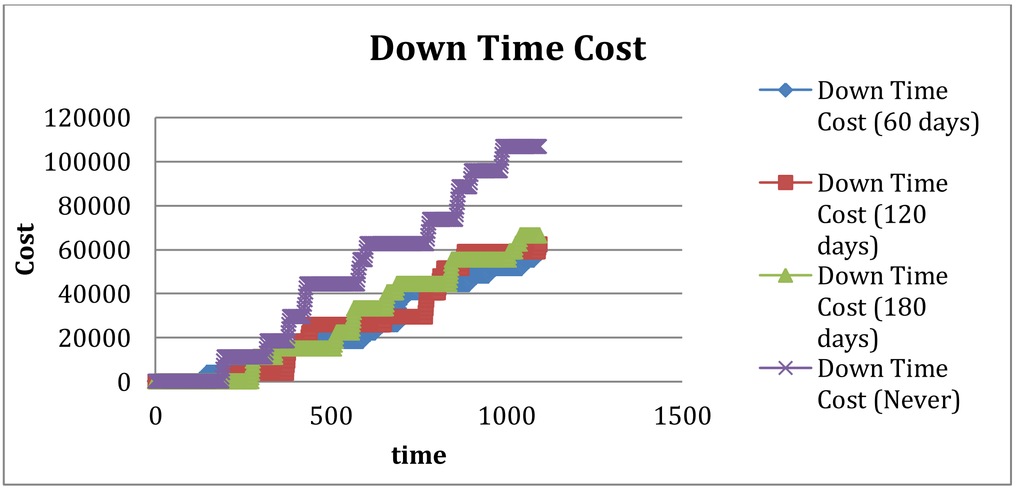
Graph 8.4 – Number of inspections simulation on four scenarios



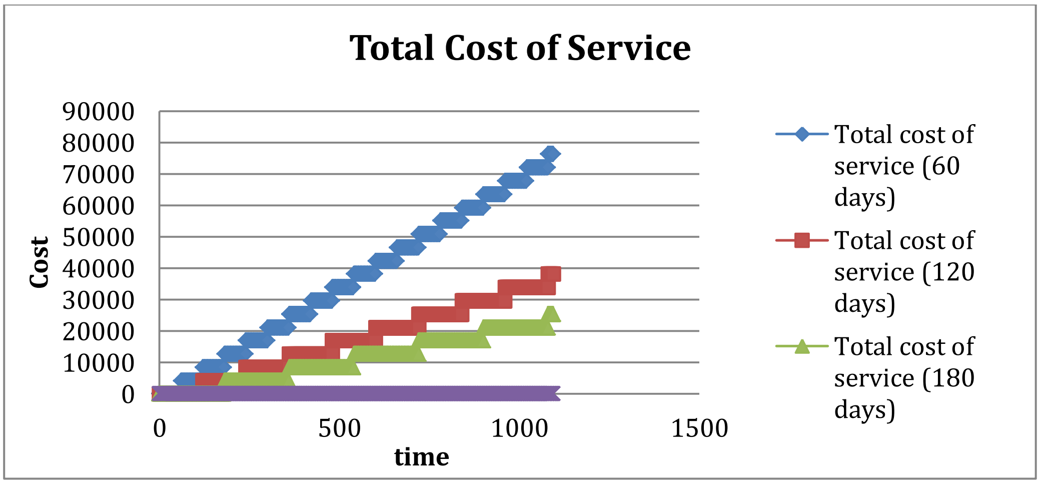
Graph 8.5 – Corrective maintenance costs simulation on four scenarios



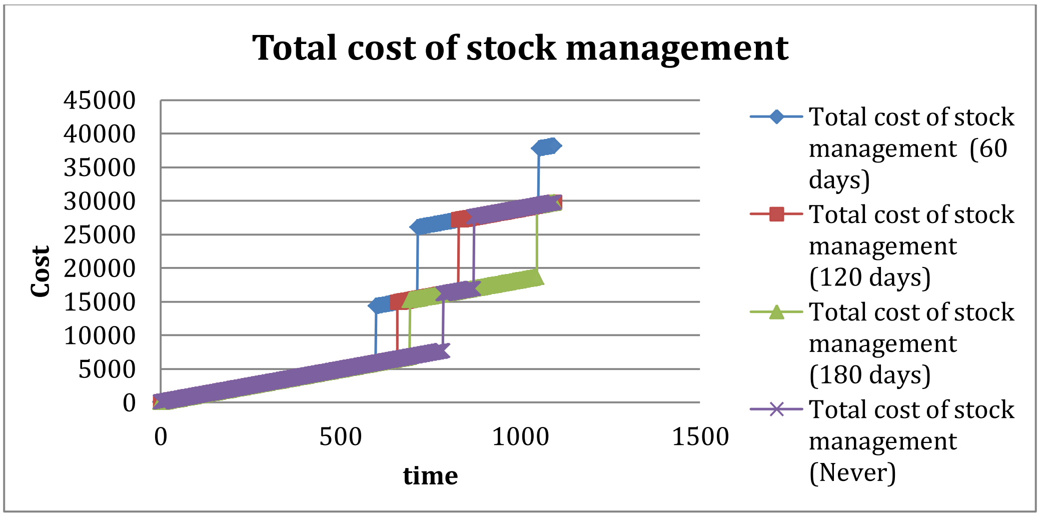
Graph 8.6 – Preventive maintenance costs simulation on four scenarios



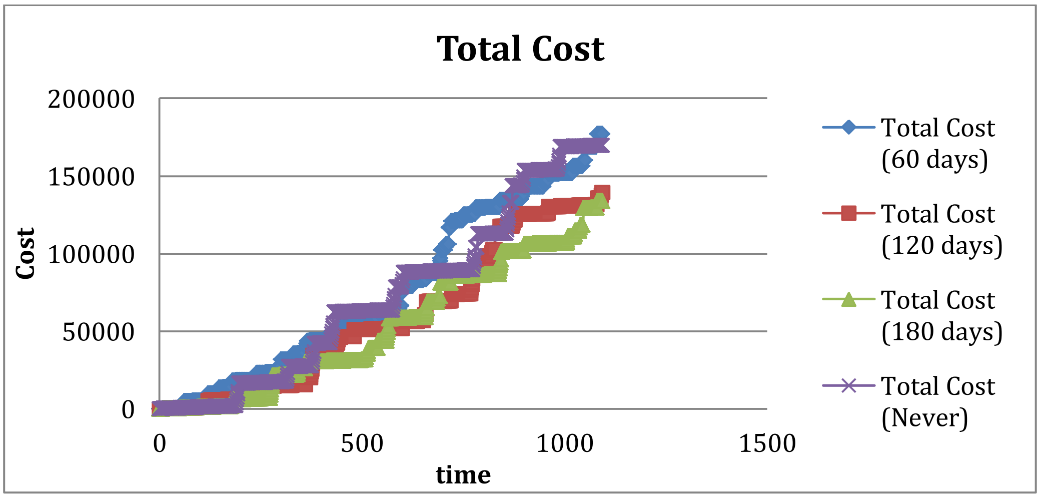
Graph 8.7 – Down time costs simulation on four scenarios



Graph 8.8 – Total cost of service simulation on four scenarios



Graph 8.9 – Total cost of stock management simulation on four scenarios



Graph 8.10 – Total cost simulation on four scenarios

Output graphs describe in detail benefits and criticalities of each scenario, underlining features of each choice and summarizing all different effect in total cost evaluation. It is interesting to underline how all trends of scenarios 180 and 120 days are often similar; in some cases also 60 days scenario is not so different. Instead never inspection scenario is always far to the others. Availability increases with the increasing of inspections; at the same way also the number of interventions increases, instead down time became worst as much as inspections are reduced. Costs have different behaviour, clearly more inspections amplify preventive maintenance and service costs, but they reduce significantly corrective maintenance and down time costs. Moreover, total cost of stock management became significantly bad only in case of high level of inspections.

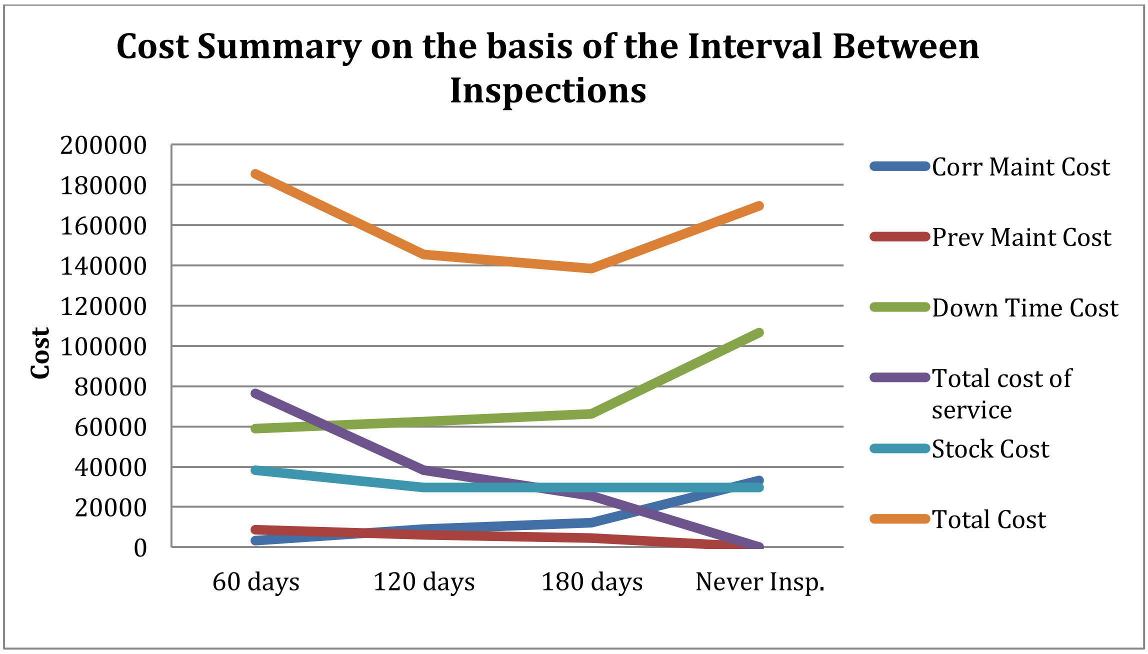
Although all these cost outputs knowledge can be a great instrument to investigate on what happens on specific cost centers, they cannot help to choose between scenarios. Total costs graph summarizes all these feature weighing them. So evaluating this output it is possible to understand that 180 days scenario is the best economic choice. Anyway other outputs, especially availability, can help decision maker to understand which is the price to pay to reduce costs, in order to guarantee a certain service level. In this case, the economic optimum solution does not require to loose significant level of availability, so it can be considered the best choice. Probably it would be possible to optimize that solution choosing further scenarios, but as explained in the previous chapter, this evaluation was not possible due to the lack of additional case of study data. More details on scenarios evaluation are showed in graphs and table below.

	60 days	120 days	180 days	Never Insp.
Corr Maint Cost	**3400**	**8920**	**12320**	**33320**
Prev Maint Cost	**8670**	**6000**	**4680**	**0**
Down Time Cost	**58880**	**62560**	**66240**	**106720**
Total cost of service	**76280,4**	**38140,2**	**25426,8**	**0**
Stock Cost	**38143,7**	**29703,8**	**29703,8**	**29703,8**
Total Cost	**185374,1**	**145324**	**138370,6**	**169743,8**

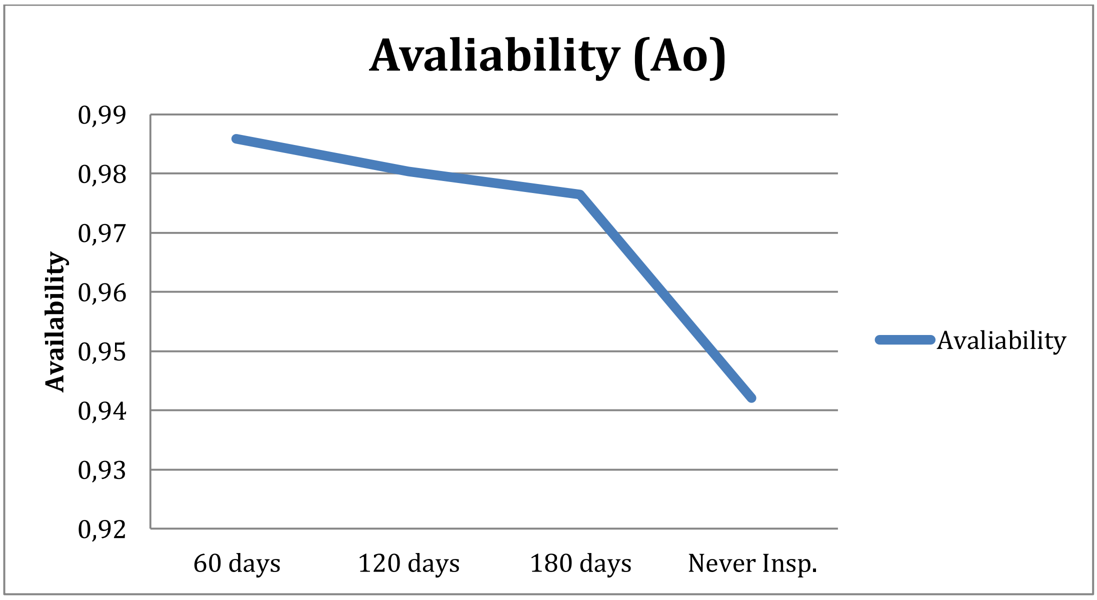
	60 days	**120 days**	**180 days**	**Never Insp.**
N° Interventions (total number)	14	12	11	10
N° Corrective Interventions	1	3	4	10
N° Preventive Interventions	13	9	7	0
Down Time (h)	32	34	36	58
N° Insp.	18	9	6	0

	60 days	120 days	180 days	Never Insp.
Avaliability	0,985849	0,980385	0,976436	0,942042

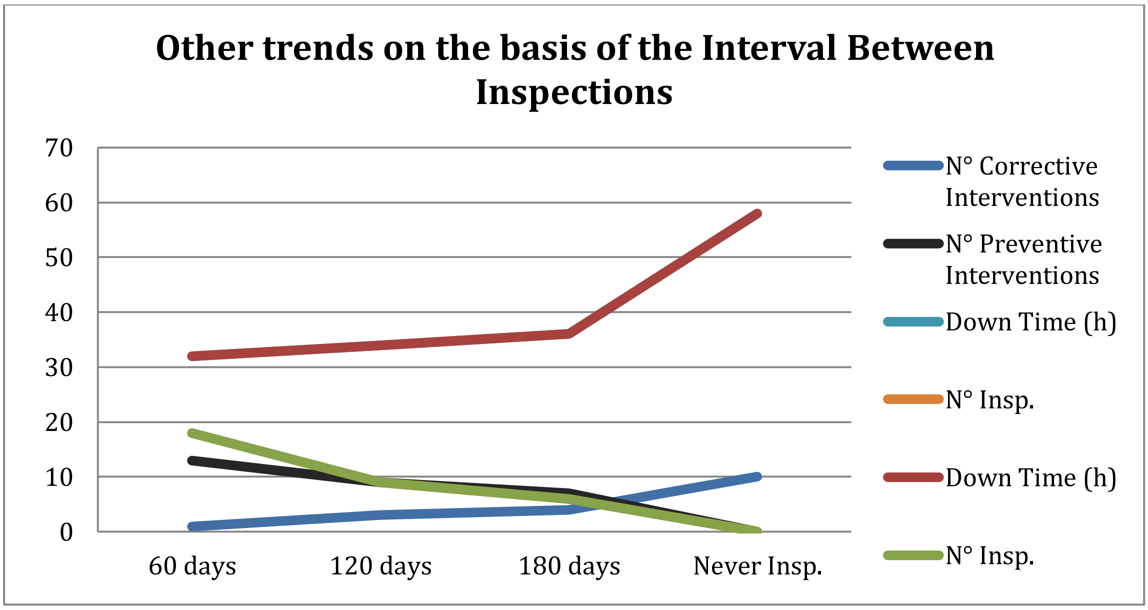
Table 8.5 – Outputs/scenarios at time = 1095 days



Graph 8.11 – Costs output/scenarios comparison at time = 1095



Graph 8.12 – Costs Availability/scenarios comparison at time = 1095



Graph 8.13 – Other outputs/scenarios comparison at time = 1095

8.3 – Sensitivity Analysis

In that section it is presented a sensitivity analysis on sensible input parameters. A sensible parameter is that one affects significantly on outputs; they are presented below:

- Alarm level (Alarm level A)
- Down time cost (Lack of Production Cost)
- Failure correlation (Collateral Damage AC)

As demonstrated in the previous section, case of study results underline that the best solution is to implement 180 days scenario. So sensitivity analysis wants to evaluate how much stable is this solution, even if parameters listed above change.

Moreover it is also underlined how the parameter variation affects each scenario, pointing out the relationship between outputs trend and inspection efforts.

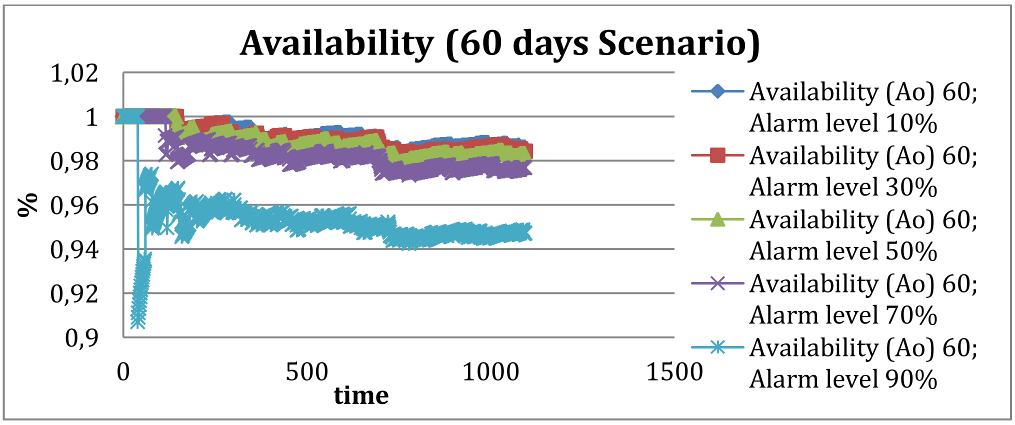
These effects are evaluated only on four outputs:

- Availability of the system
- Number of interventions
- Down Time (hours)
- Total cost

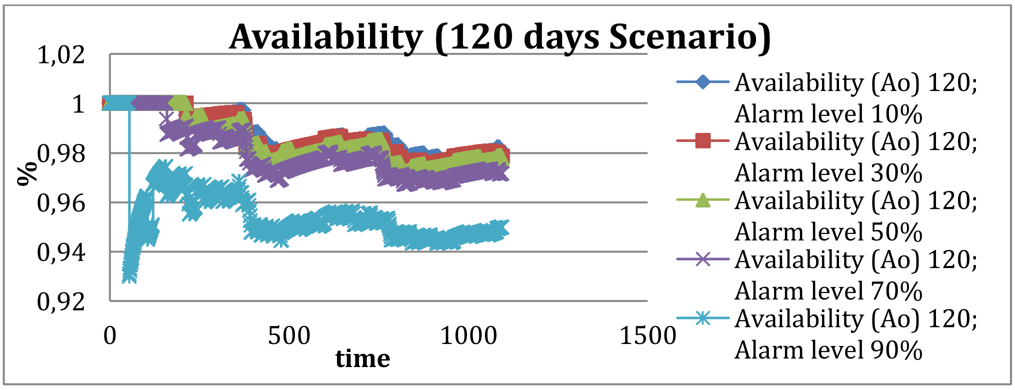
Indeed customer is mostly interested in understanding outputs that summarize the whole system behaviour, because they really communicate what happens. Anyway it does not mean that other outputs are not considered in the analysis, they are aggregated in those chosen. In that sense, the number of inspection is already included in the evaluation of the number of interventions and total cost already includes all detailed costs and their effects.

8.3.1 – Alarm level sensitivity analysis

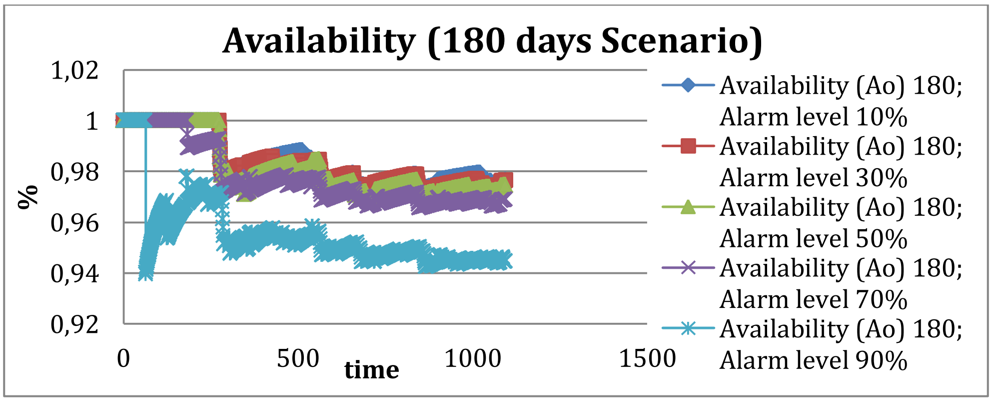
In this section it is presented an overview of alarm A variation effects on each scenario. It is evaluated how the use of a not congruent alarm level affects results in each scenario.



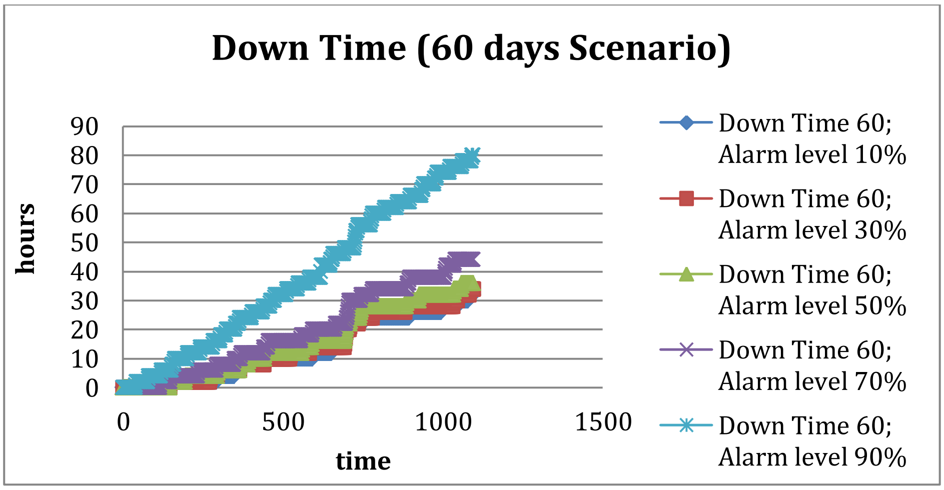
Graph 8.14 – Availability on 60 days scenario (Alarm Sensitivity)



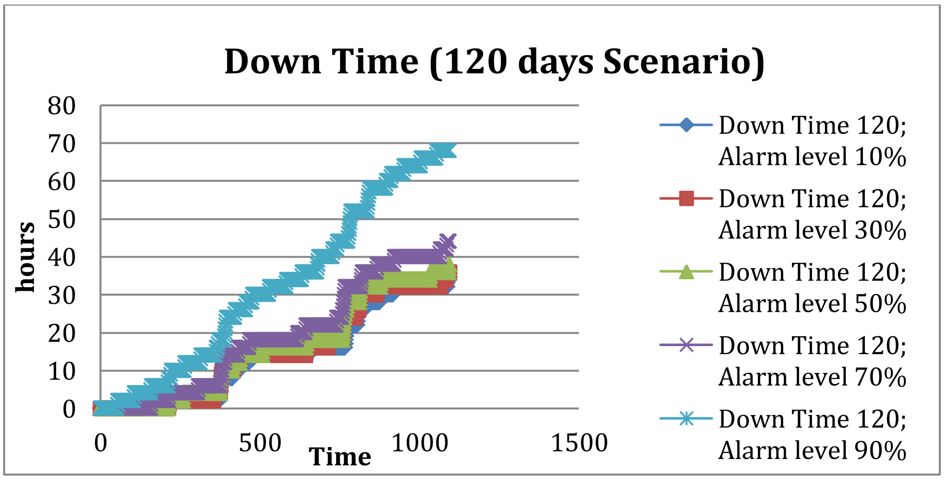
Graph 8.15 – Availability on 120 days scenario (Alarm Sensitivity)



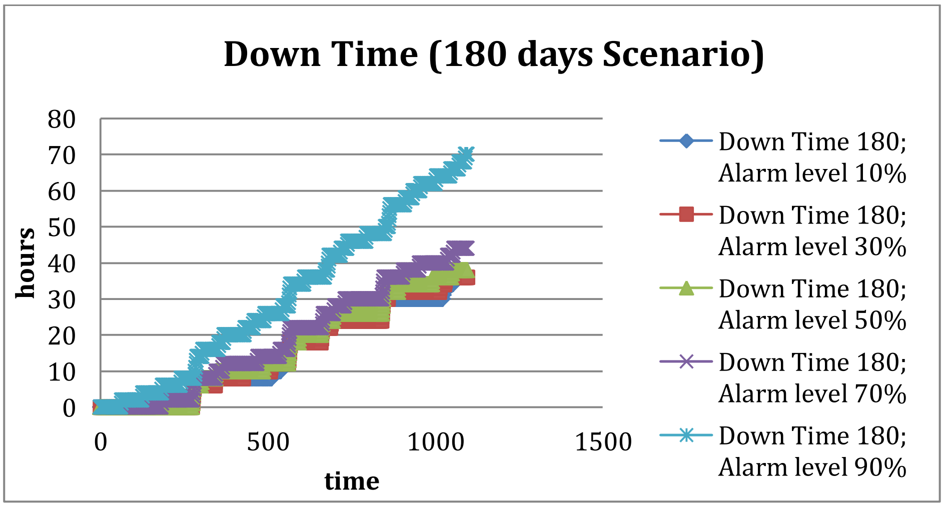
Graph 8.16 – Availability on 180 days scenario (Alarm Sensitivity)



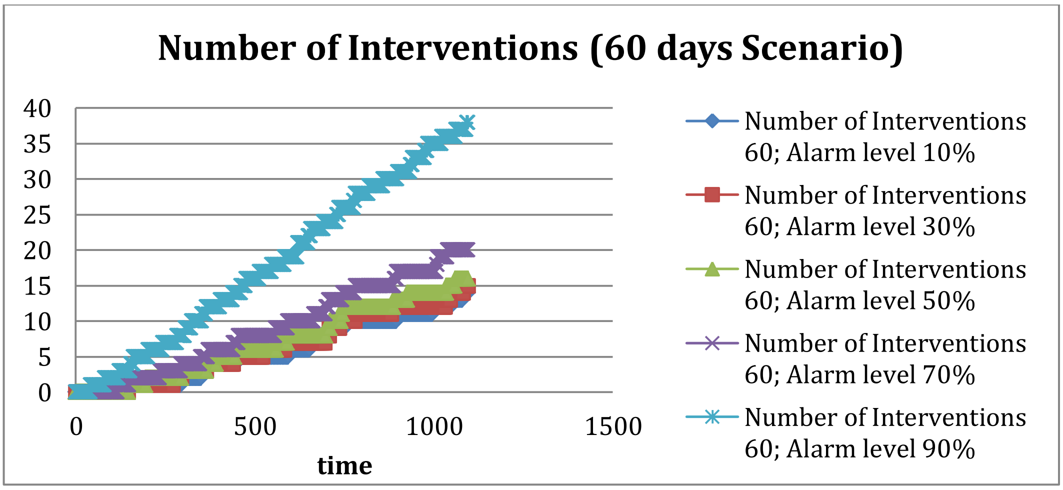
Graph 8.17 – Down time on 60 days scenario (Alarm Sensitivity)



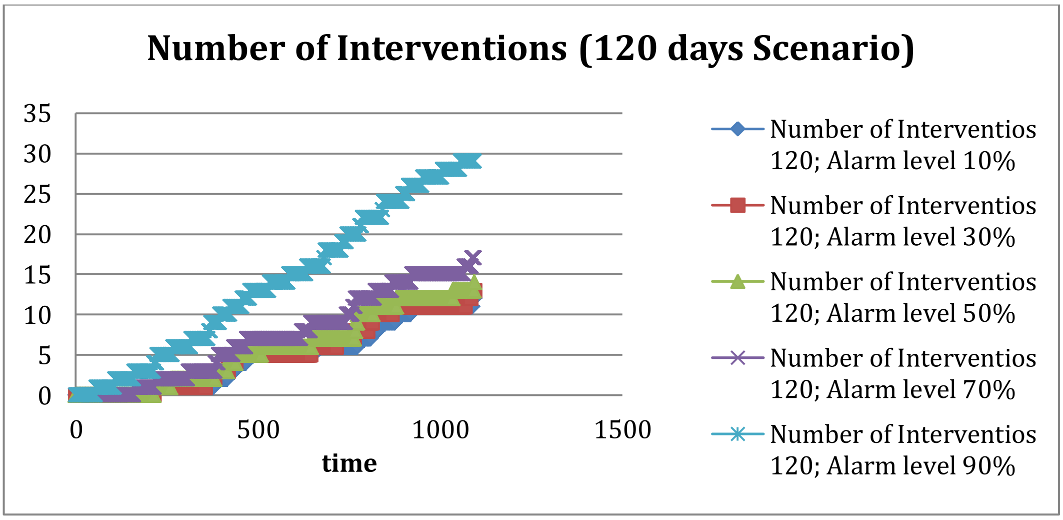
Graph 8.18 – Down time on 120 days scenario (Alarm Sensitivity)



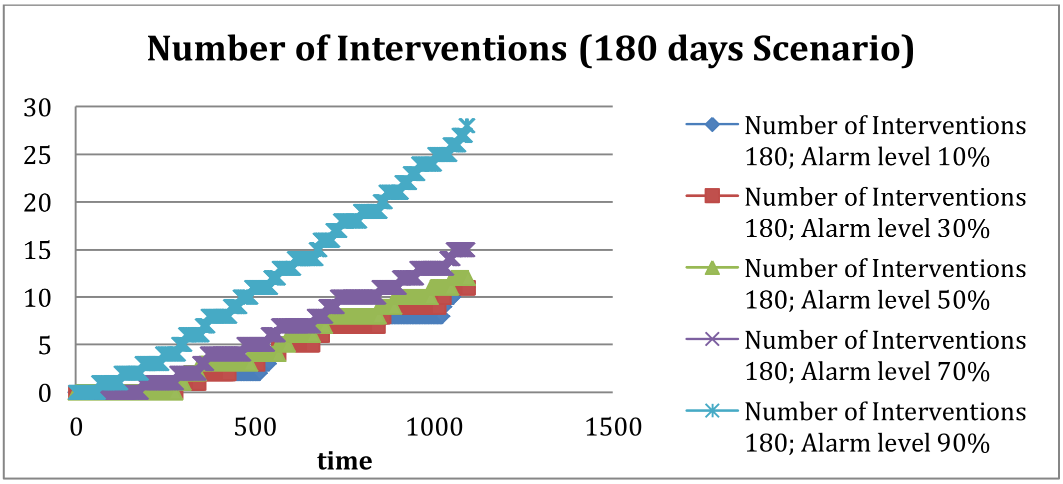
Graph 8.19 – Down time on 180 days scenario (Alarm Sensitivity)



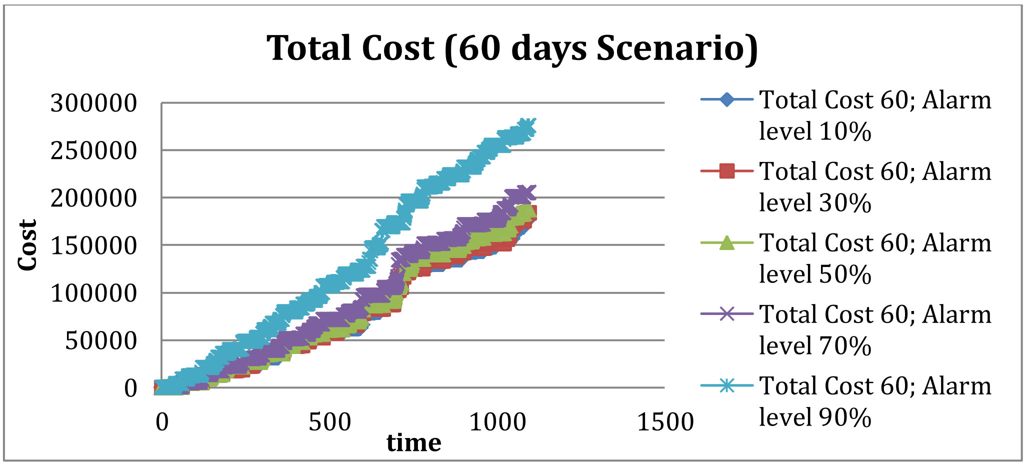
Graph 8.20 – Number of interventions on 60 days scenario (Alarm Sensitivity)



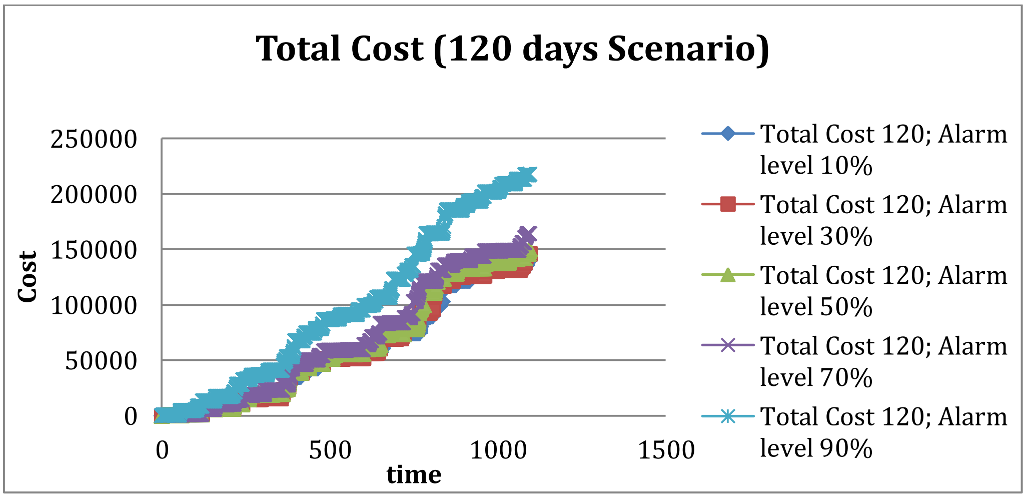
Graph 8.21 – Number of interventions on 120 days scenario (Alarm Sensitivity)



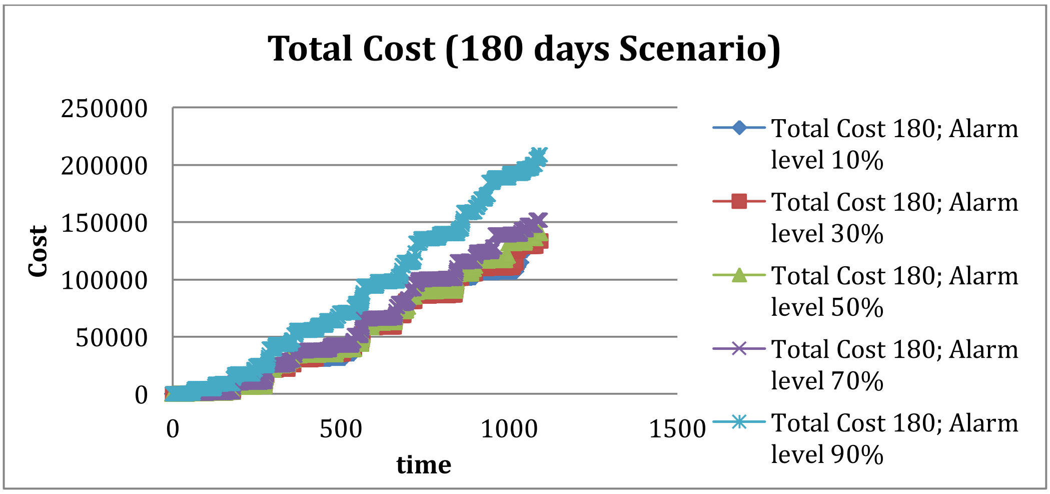
Graph 8.22 – Number of interventions on 180 days scenario (Alarm Sensitivity)



Graph 8.23 – Total Cost on 60 days scenario (Alarm Sensitivity)



Graph 8.24 – Total Cost on 120 days scenario (Alarm Sensitivity)



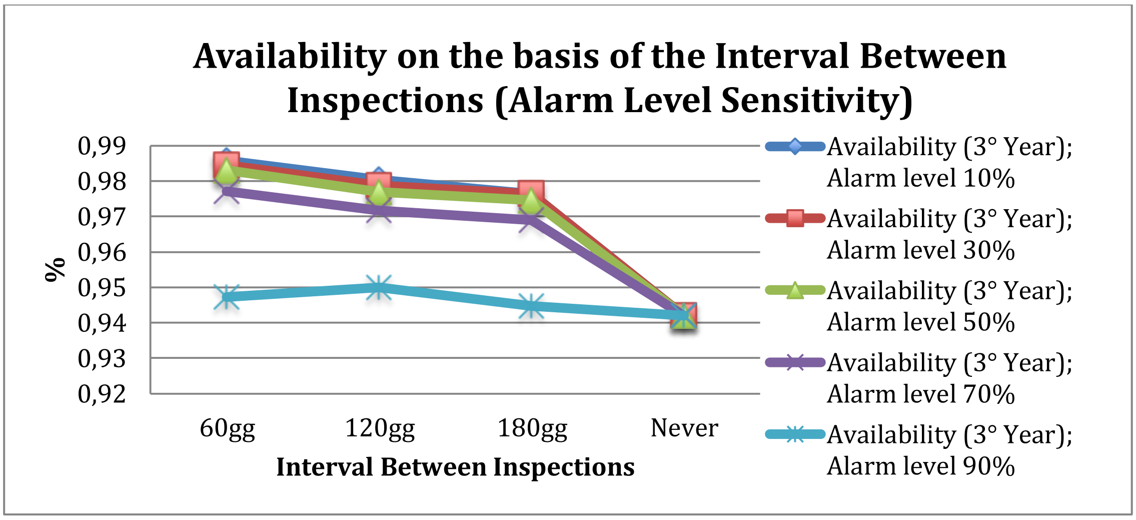
Graph 8.25 – Total Cost on 180 days scenario (Alarm Sensitivity)

Graphs show that the alarm level increasing affects availability, reducing it. At the end of simulation time, this behaviour is underlined in each scenario; even if in short-term trend shape can be different. Indeed availability is influenced from down time, so considering that higher alarm level involves the increasing of preventive intervention required, down time increases too.

Anyway, although trends are clear, it is interesting to underline some scenarios features. The alarm level increasing involves on the outputs trends amplifying or reducing them. The difference between down time with alarm level = 10% to down time with alarm level = 90% is reduced as much as the interval between inspections increases. In that sense also the difference between number of interventions with alarm level = 10% to number of interventions with alarm level = 90% follows the same behaviour, that is also confirmed by total costs.

It means that outputs variability, due to alarm level increasing, is reduced more and more it is moved to a corrective maintenance scenario. In other words preventive interventions, expected when it is reached the alarm level, means to change components before their complete failure, wasting part of their life. So if alarm level increases the benefit to avoid bad effect of degraded state (i.e. failure correlation) would be completely covered by costs to waste most of components life. It means that with an increasing of the alarm level it would be better to move to a corrective policy, avoiding inspections.

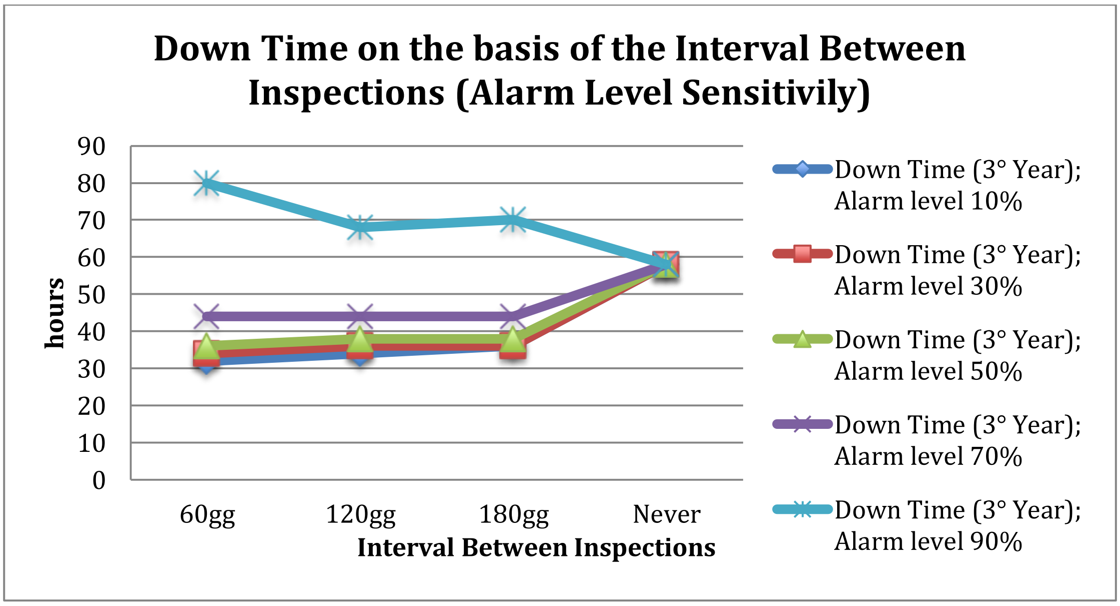
This effect is also underlined by following graphs that represent outputs state at the end of simulation time (t=1095); comparing them on the basis of inspection efforts variation. In case of alarm level = 90% every outputs demonstrates that it would be better to chose a corrective maintenance. In particular total costs graph would has the minimum level on the never inspection scenario, but it is demonstrated that optimum level would move to a closer interval between inspections as much as the alarm level decreases. Optimum values are underlined in the total cost table.



Graph 8.26 – Availability/scenarios comparison at time = 1095 (Alarm Sensitivity)

	Availability (3° Year);				
	Alarm level 10%	**Alarm level 30%**	**Alarm level 50%**	**Alarm level 70%**	**Alarm level 90%**
60 days	0,985849	0,984441	0,983003	0,977002	0,947176
120 days	0,980385	0,978648	0,976899	0,971597	0,949907
180 days	0,976436	0,976436	0,974552	0,968917	0,94465
Never	0,942042	0,942042	0,942042	0,942042	0,942042

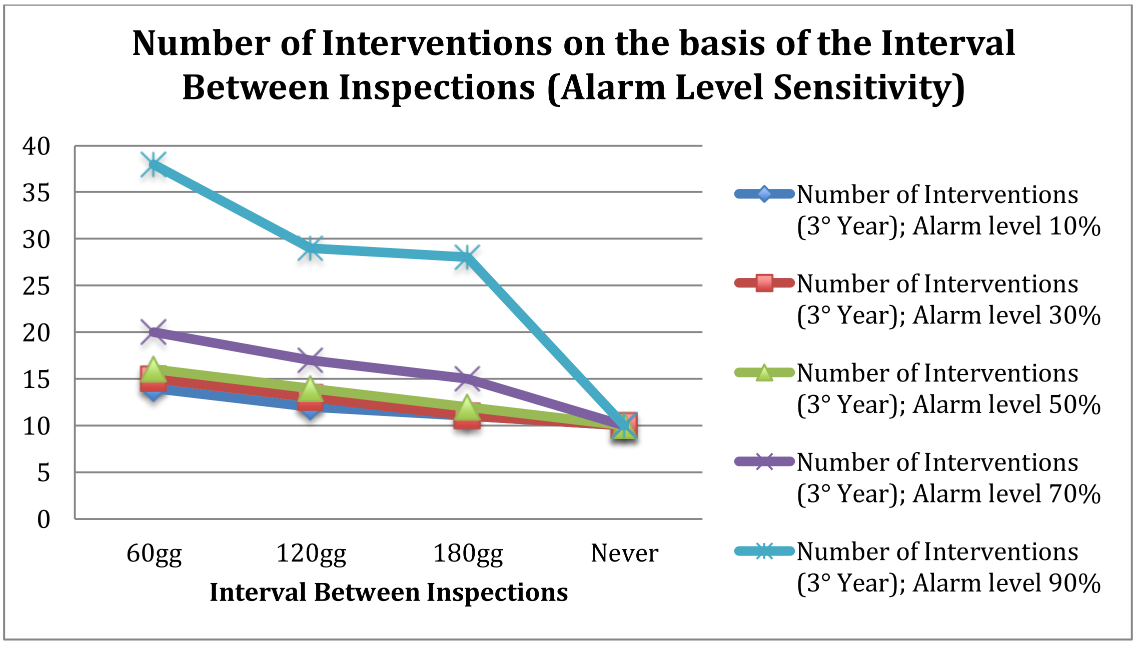
Table 8.6 – Availability/scenarios comparison at time = 1095 (Alarm Sensitivity)



Graph 8.27 – Down time/scenarios comparison at time = 1095 (Alarm Sensitivity)

	Down Time (3° Year);				
	Alarm level 10%	**Alarm level 30%**	**Alarm level 50%**	**Alarm level 70%**	**Alarm level 90%**
60 days	32	34	36	44	80
120 days	34	36	38	44	68
180 days	36	36	38	44	70
Never	58	58	58	58	58

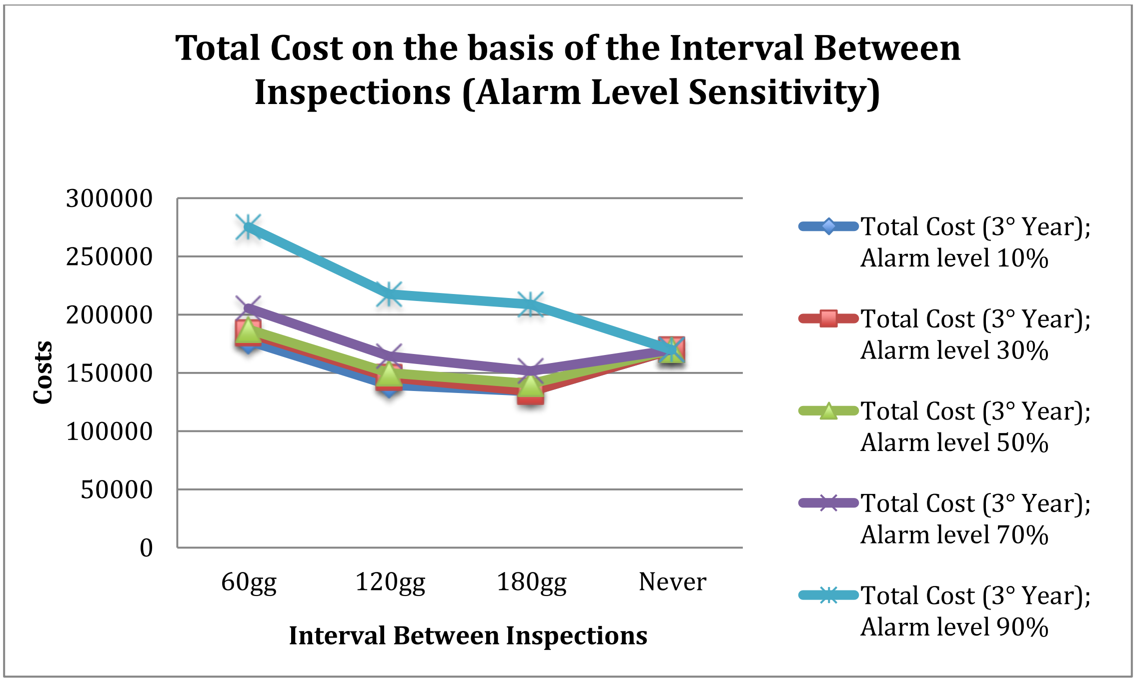
Table 8.7 – Down time/scenarios comparison at time = 1095 (Alarm Sensitivity)



Graph 8.28 – N° interventions/scenarios comparison at time = 1095 (Alarm Sensitivity)

	Number of Interventions (3° Year);				
	Alarm level 10%	**Alarm level 30%**	**Alarm level 50%**	**Alarm level 70%**	**Alarm level 90%**
60 days	14	15	16	20	38
120 days	12	13	14	17	29
180 days	11	11	12	15	28
Never	10	10	10	10	10

Table 8.8 – N° interventions/scenarios comparison at time = 1095 (Alarm Sensitivity)



Graph 8.29 – Total cost/scenarios comparison at time = 1095 (Alarm Sensitivity)

	Total Cost (3° Year);				
	Alarm level 10%	**Alarm level 30%**	**Alarm level 50%**	**Alarm level 70%**	**Alarm level 90%**
60 days	177054	183742	187442	205230	275343
120 days	139564	146252	149952	164040	217403
180 days	**133890**	**133890**	**140578**	**151678**	208742
Never	169743	169743	169743	169743	**169743**

Table 8.9 – Total cost/scenarios comparison at time = 1095 (Alarm Sensitivity)

In the next table it is underlined how interventions (referred to all 3 components) are divided on the basis of the policy, demonstrating the specific effect of the alarm level increasing on preventive interventions.

The expected number of preventive interventions should be lower or equal to the number of inspections. This number depends on the basis of scenarios.

- 60 days: 18 inspections in 3 years
- 120 days: 9 inspections in 3 years
- 180 days: 6 inspections in 3 years
- Never Inspections: No inspections in 3 years

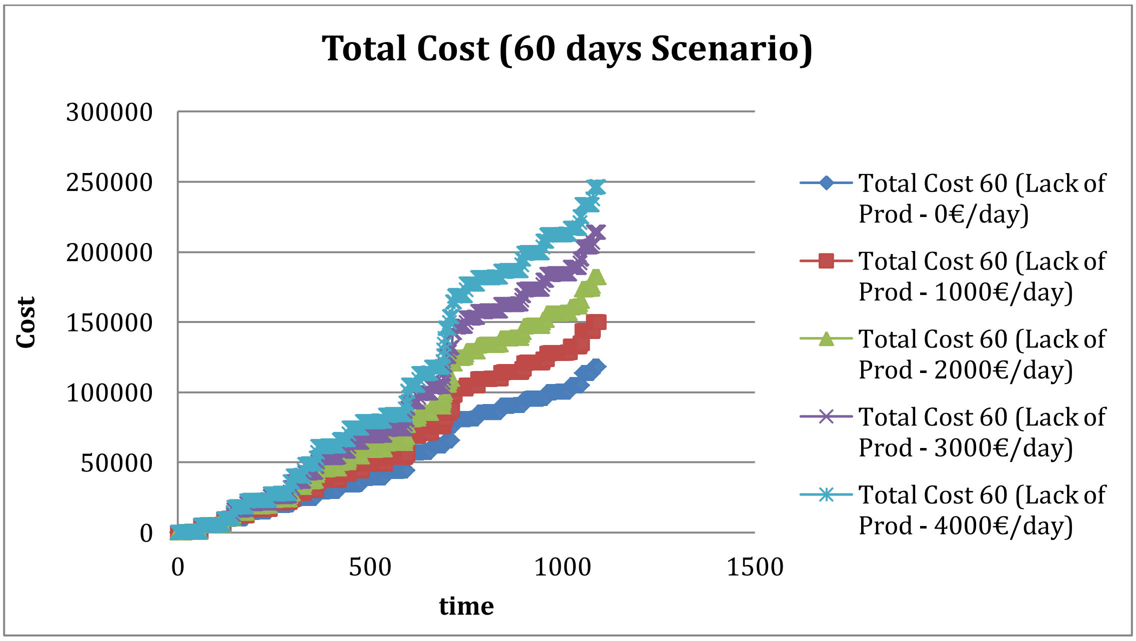
	Number of Preventive Interventions on Component A (3° Year);				
	Alarm level 10%	**Alarm level 30%**	**Alarm level 50%**	**Alarm level 70%**	**Alarm level 90%**
60 days	4	5	8	13	37
120 days	3	3	5	9	22
180 days	1	2	3	5	17
Never	0	0	0	0	0

Table 8.10 – Number of preventive interventions on component A (with alarm level variation)

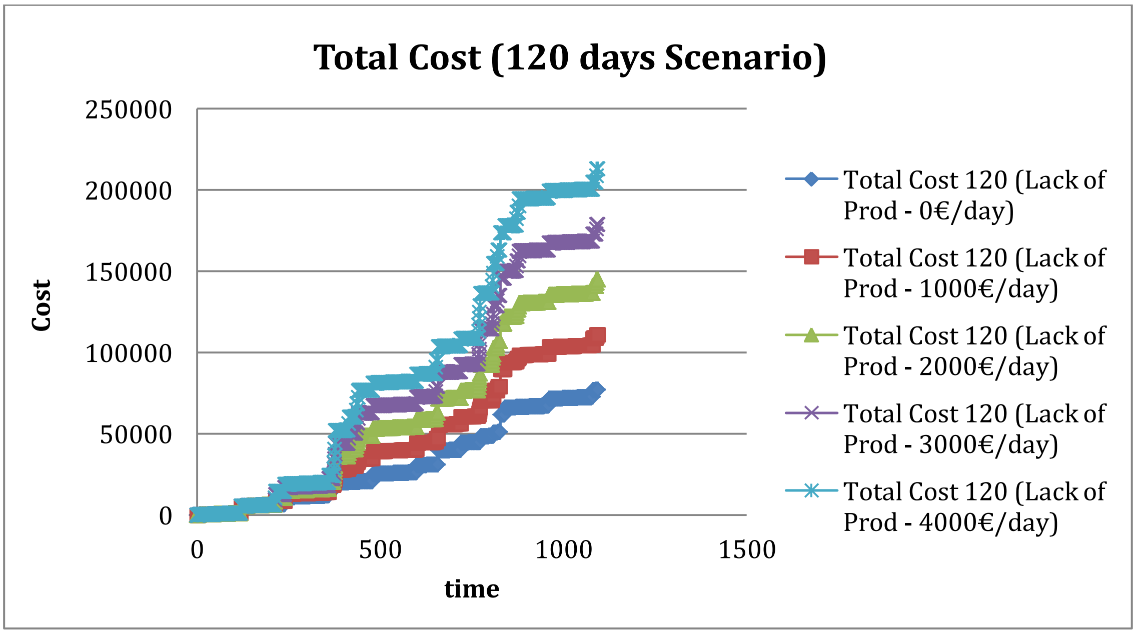
As much as the alarm level increases in a not congruent way, as much the number of interventions becomes anomalous. It means that the preventive intervention number increases without to make more inspections. Surely it would not make sense. Anyway sensitivity analysis demonstrates that despite alarm level variation pushes results in a wrong case, results are not modified, and 180 days scenario remains often the best solution. In most of cases the variation of alarm level in a not congruent way does not significantly affect the stability of results, indeed until alarm level is between 10 to 70% the solution is acceptable. The number of inspections becomes higher to the number of interventions if it is used a 90% level compromising results, but it is an unrealistic case. So the expert has to make a big mistake to compromise simulation results.

8.3.2 – Down time cost sensitivity analysis

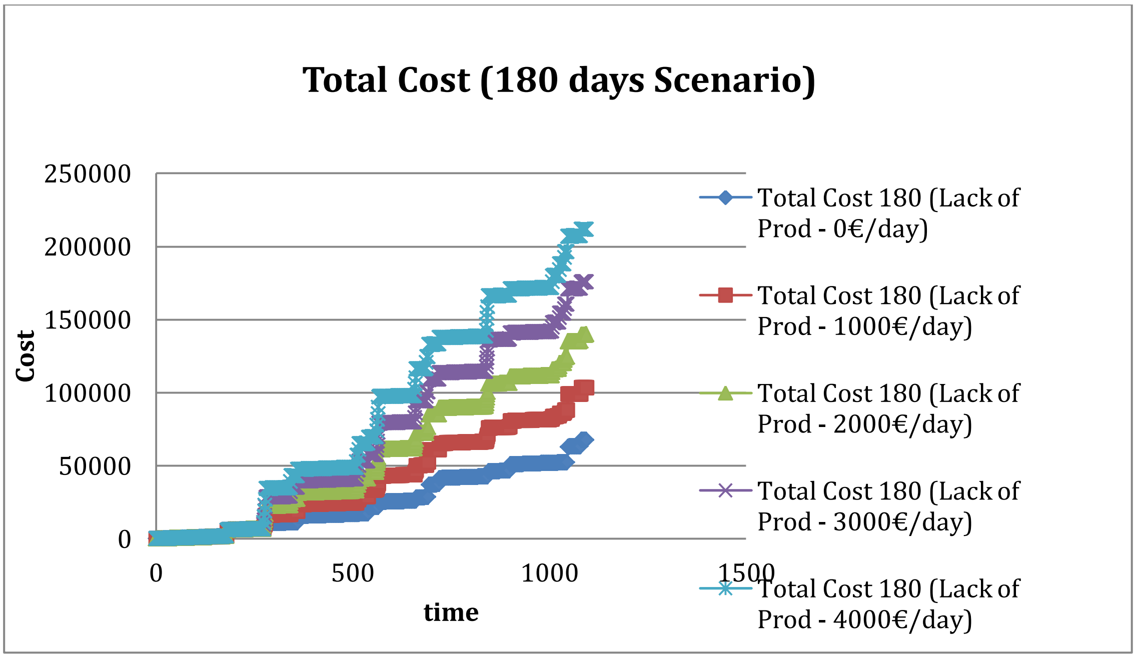
In this section it is presented an overview of lack of production cost variation effects on each scenario. The only one output that is affected by the changing of down time cost is total cost, indeed other outputs do not depend on it.



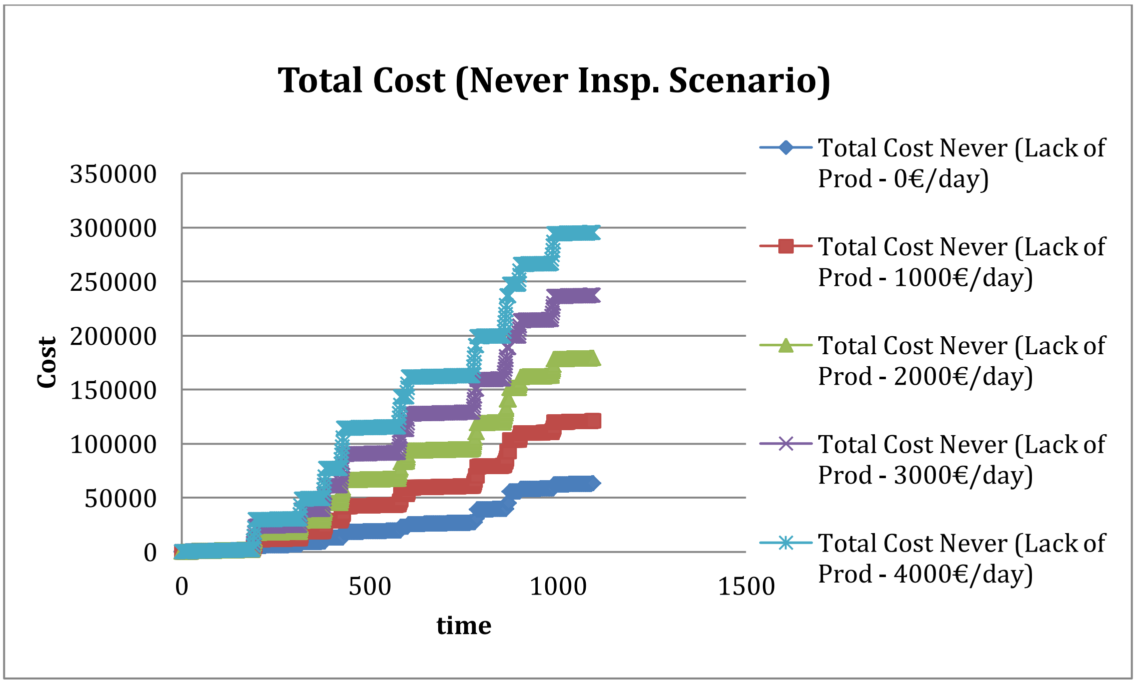
Graph 8.30 – Total cost on 60 days scenario (Down Time Cost Sensitivity)



Graph 8.31 – Total cost on 120 days scenario (Down Time Cost Sensitivity)



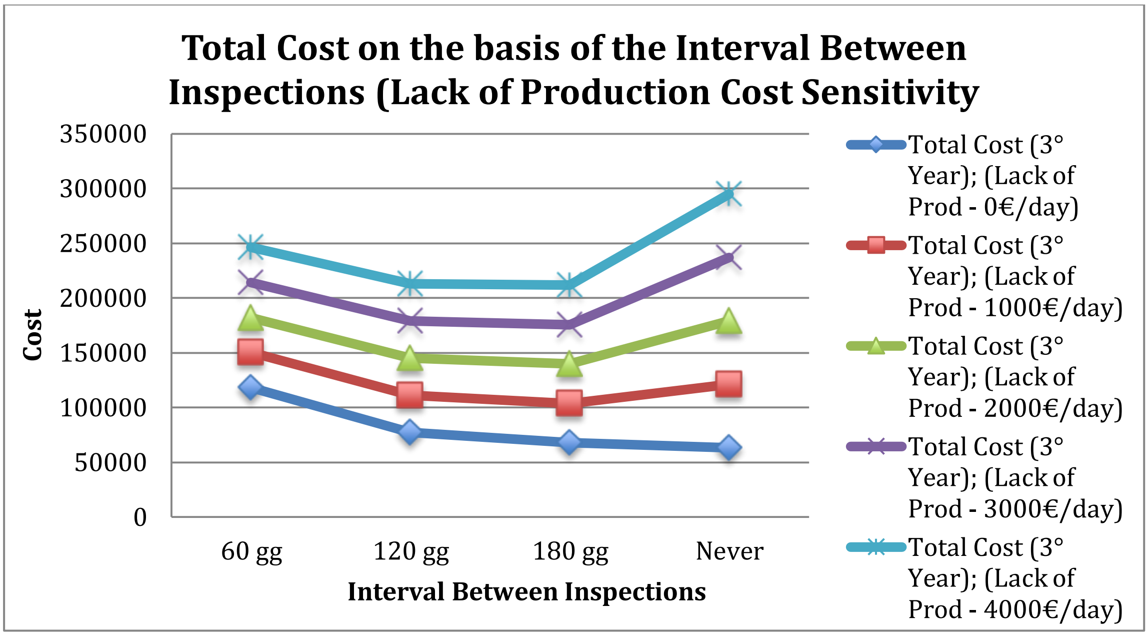
Graph 8.32 – Total cost on 180 days scenario (Down Time Cost Sensitivity)



Graph 8.33 – Total cost on never inspections scenario (Down Time Cost Sensitivity)

Graphs underlines how in each case the increasing of lack of production cost makes higher total costs. They also show that the difference between total costs with the higher lack of production cost and the lower one increases as much as inspections are avoided. It means that the lack of inspections amplify total costs caused by lack of production costs increasing.

In other words it is important to evaluate which is the best scenario in relationship of lack of down time cost. Indeed looking at the following graph it is clear that optimum case moves from never inspections scenario, in case of free down time cost, to more and more inspections as much as down time cost increases.



Graph 8.34 – Total cost/scenarios comparison at time = 1095 (Down Time Cost Sensitivity)

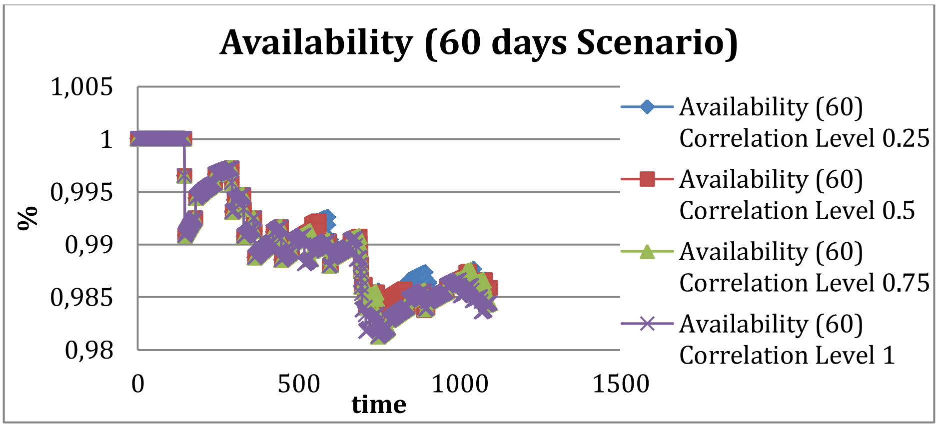
	Total Cost (3° Year);				
	(Lack of Prod; 0€/day)	(Lack of Prod; 1000€/day)	(Lack of Prod; 2000€/day)	(Lack of Prod; 3000€/day)	(Lack of Prod; 4000€/day)
60 days	118174	150174	182174	214174	246174
120 days	77003,7	111004	146004	179004	213004
180 days	67650,4	**103650**	**139650**	**175650**	**211650**
Never insp	**63023,5**	121023	179023	237023	295026

Table 8.11 – Total cost/scenarios comparison at time = 1095 (Down Time Cost Sensitivity)

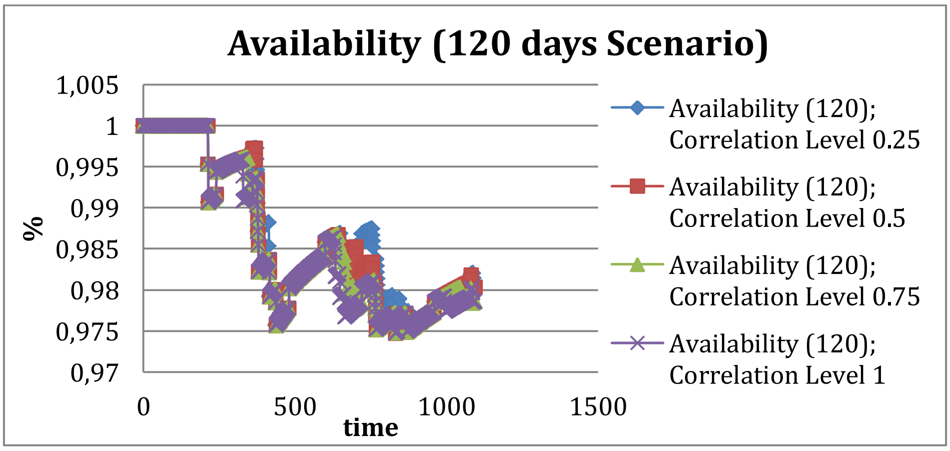
Anyway also changing this parameter until 4000€ per day, 180 days scenario is the best choice in most of cases.

8.3.3 – Failure correlation sensitivity analysis

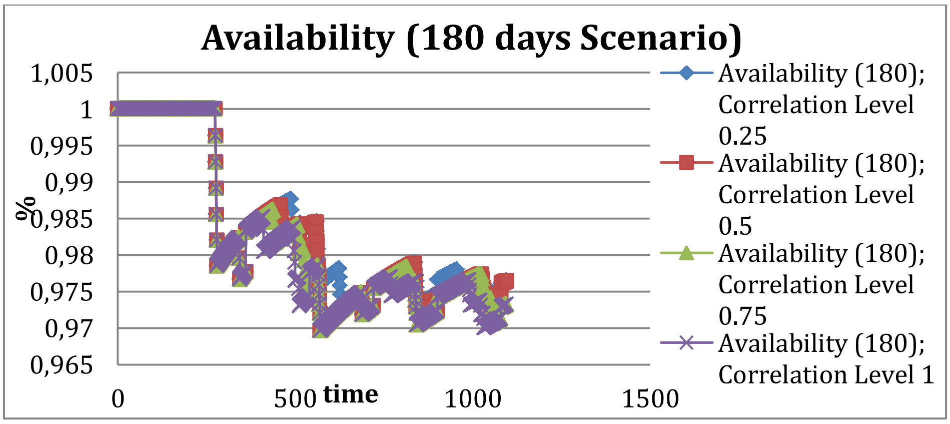
In this section it is presented an overview of lack of production cost variation effects on each scenario. All outputs are showed in following graphs:



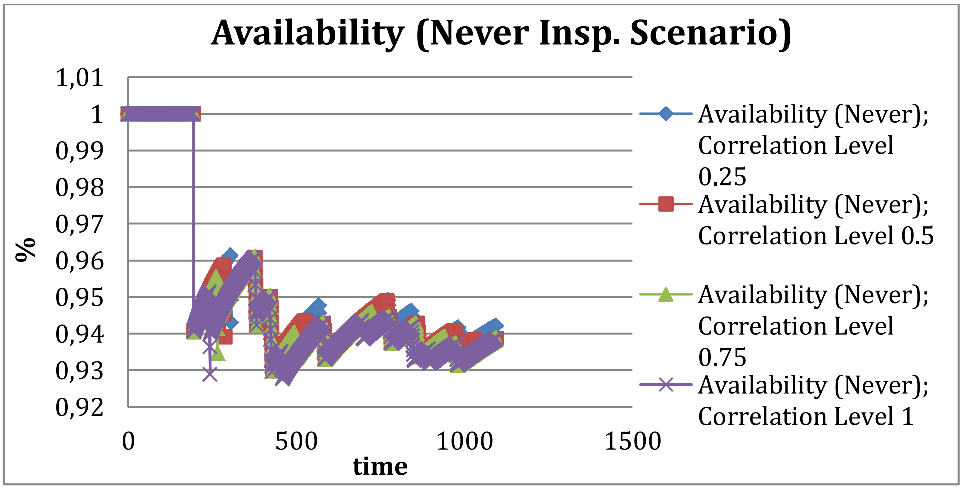
Graph 8.35 – Availability on 60 days scenario (Correlation Level Sensitivity)



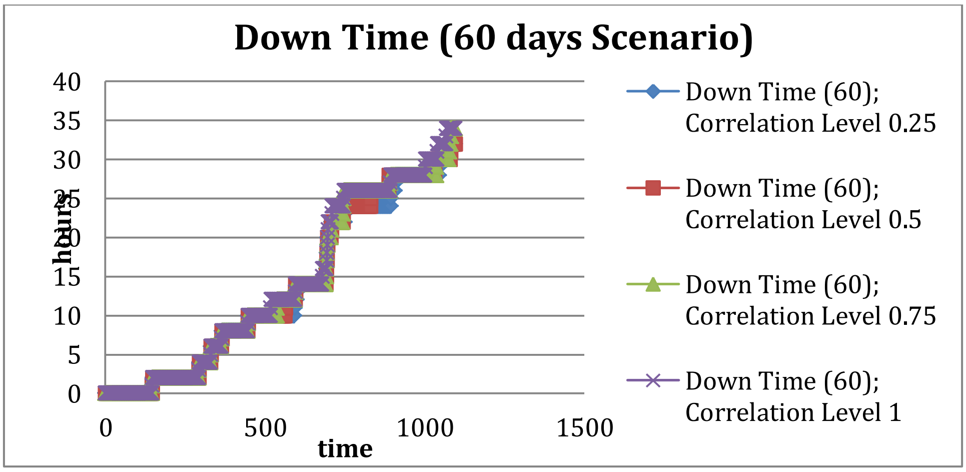
Graph 8.36 – Availability on 120 days scenario (Correlation Level Sensitivity)



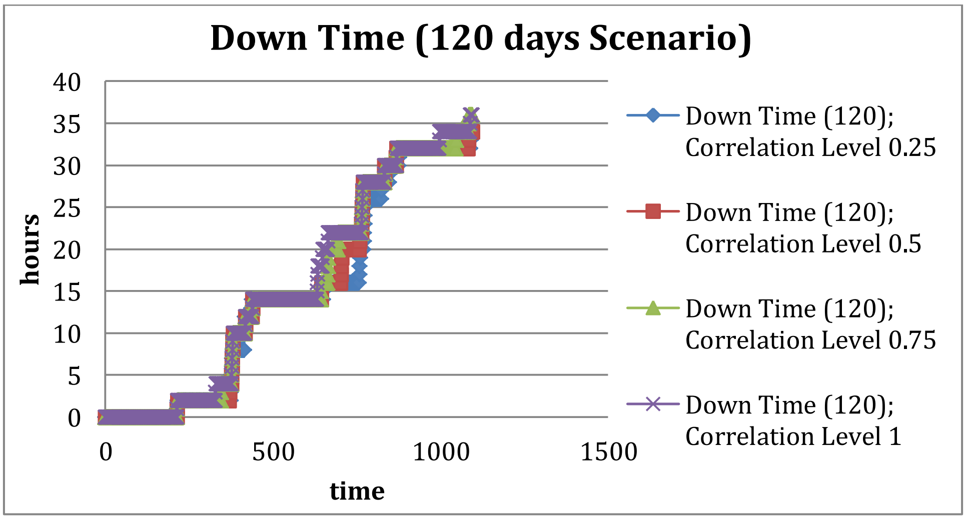
Graph 8.37 – Availability on 180 days scenario (Correlation Level Sensitivity)



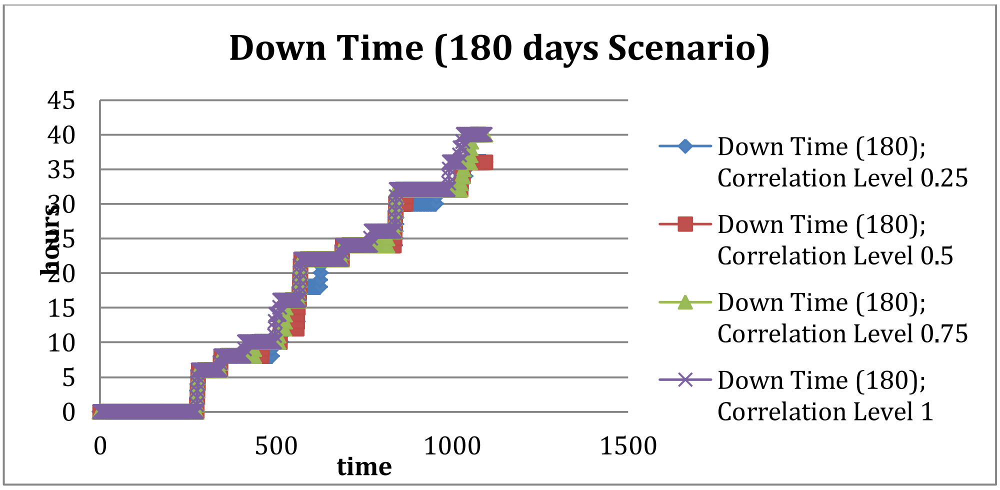
Graph 8.38 – Availability on Never inspections scenario (Correlation Level Sensitivity)



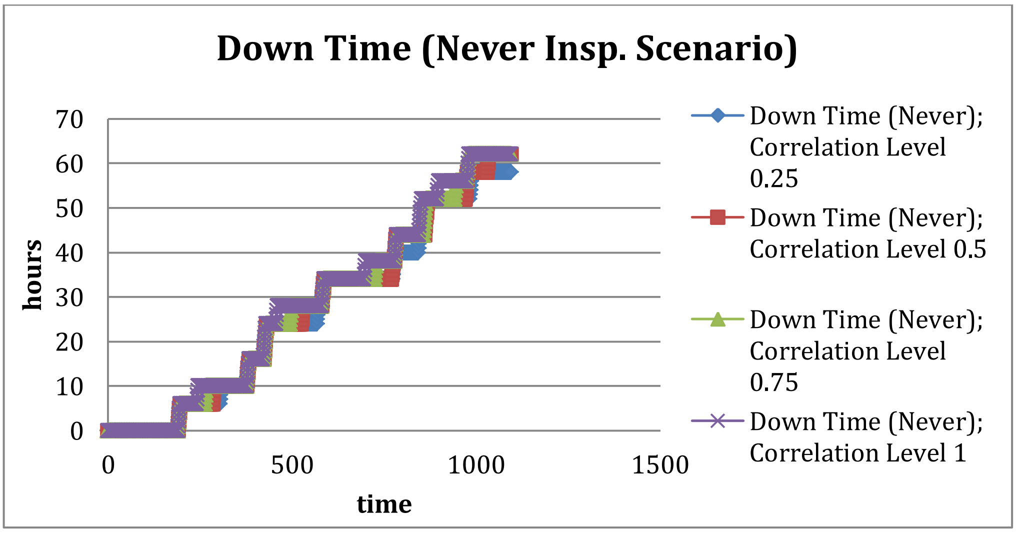
Graph 8.39 – Down time on 60 days scenario (Correlation Level Sensitivity)



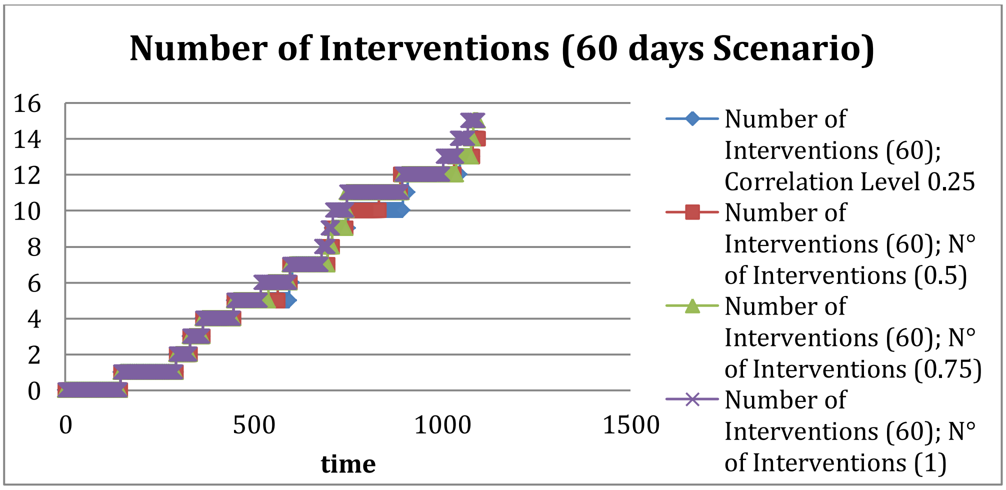
Graph 8.40 – Down time on 120 days scenario (Correlation Level Sensitivity)



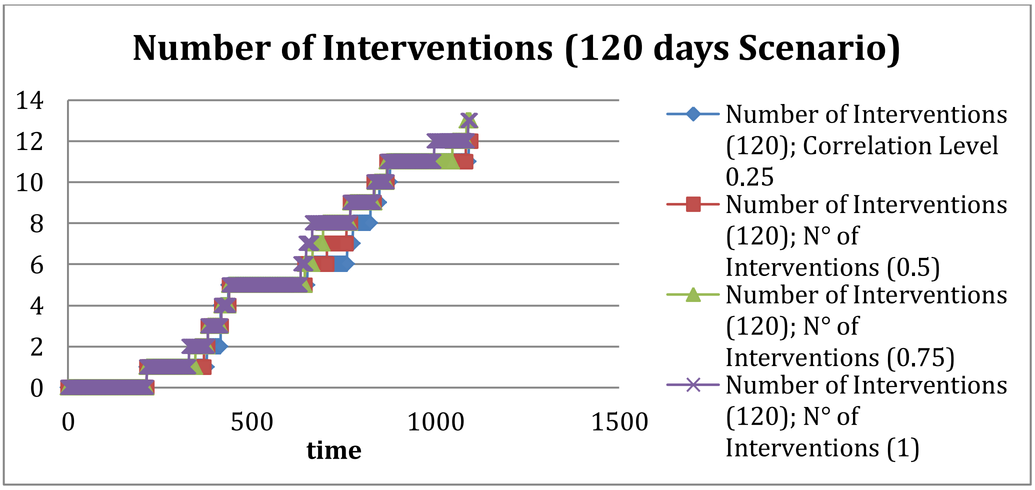
Graph 8.41 – Down time on 180 days scenario (Correlation Level Sensitivity)



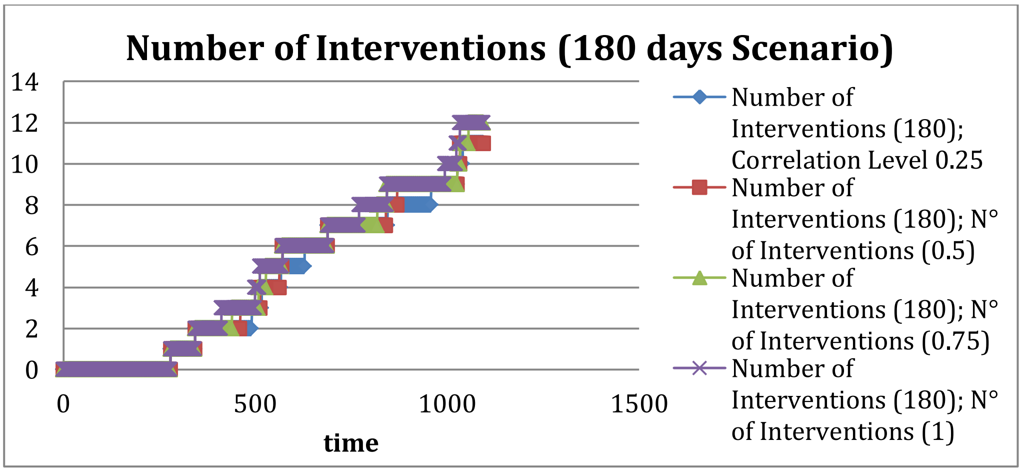
Graph 8.42 – Down time on Never inspections scenario (Correlation Level Sensitivity)



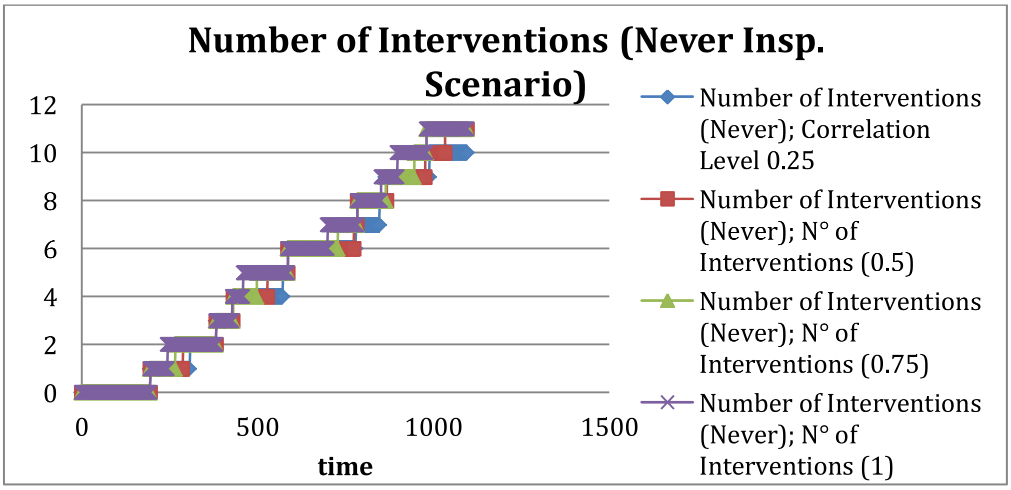
Graph 8.43 – N° of inspections on 60 days scenario (Correlation Level Sensitivity)



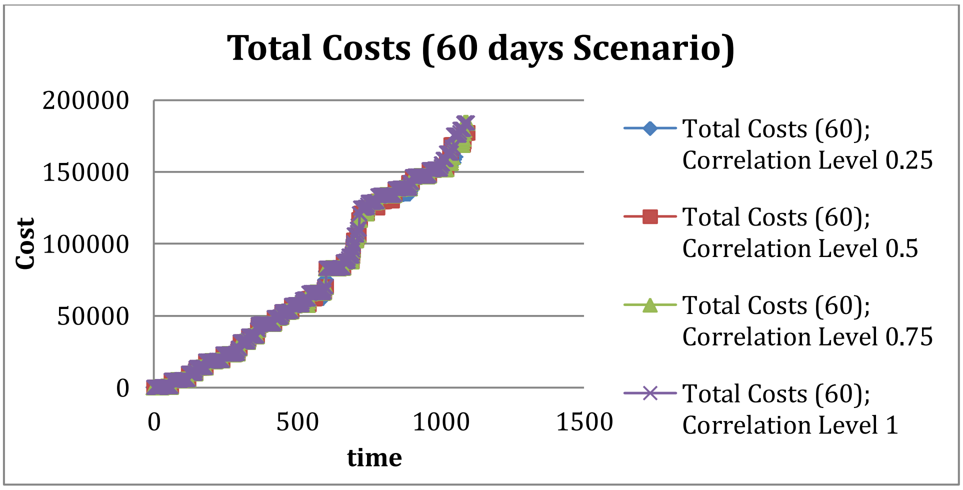
Graph 8.44 – N° of inspections on 120 days scenario (Correlation Level Sensitivity)



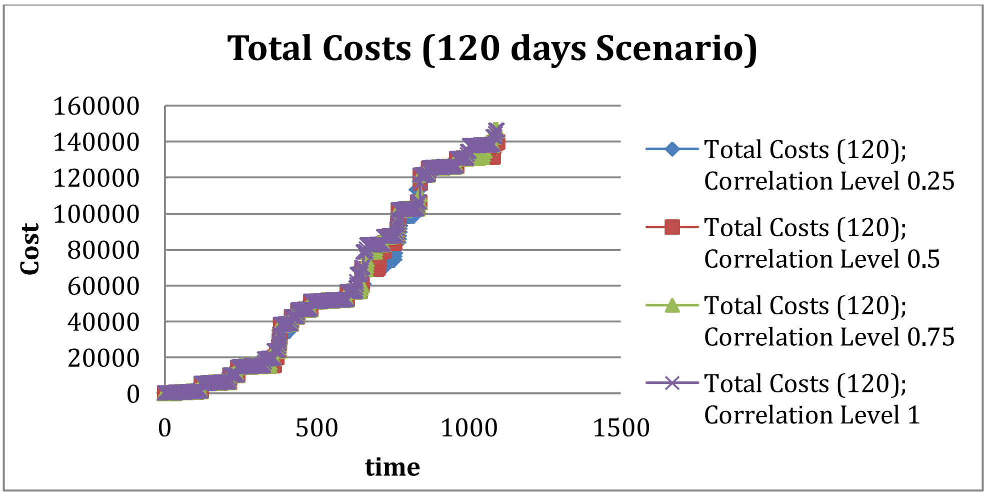
Graph 8.45 – N° of inspections on 180 days scenario (Correlation Level Sensitivity)



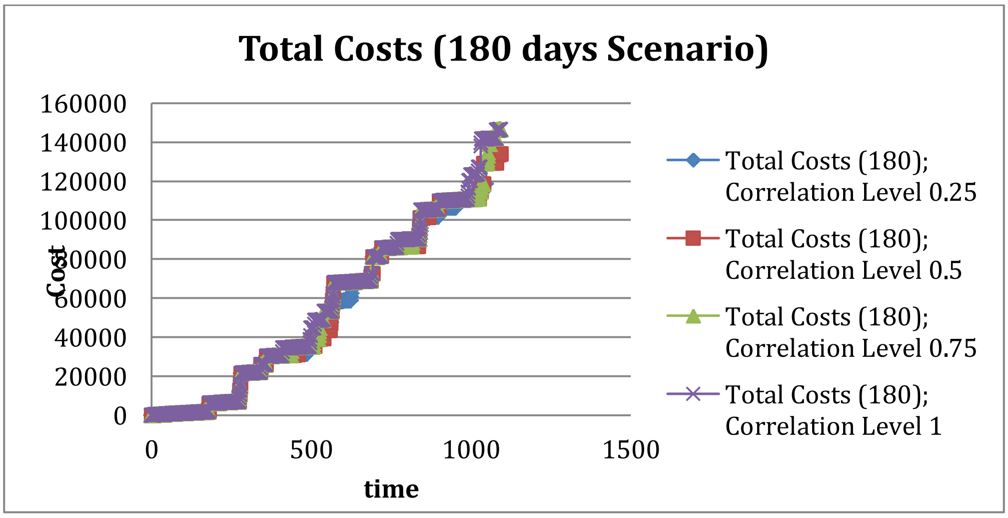
Graph 8.46 – N° of intervention on Never inspections scenario (Correlation Level Sensitivity)



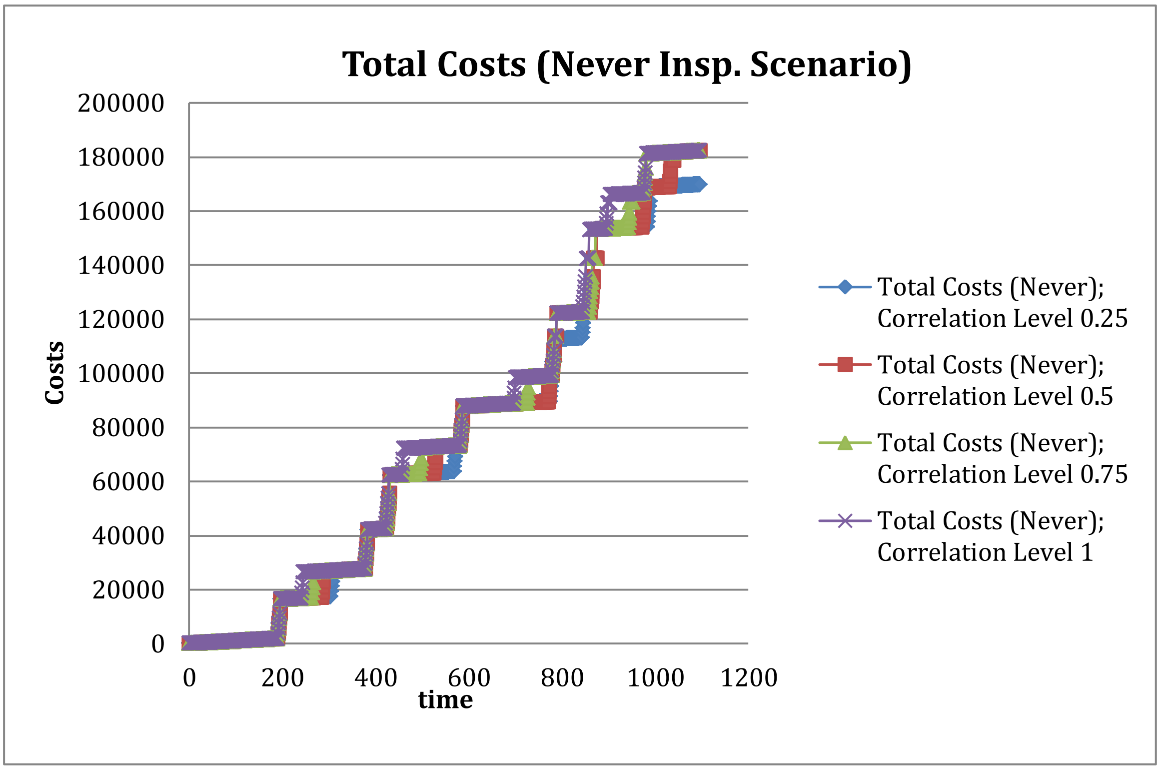
Graph 8.47 – Total costs on 60 days scenario (Correlation Level Sensitivity)



Graph 8.48 – Total costs on 120 days scenario (Correlation Level Sensitivity)



Graph 8.49 – Total cost on 180 days scenario (Correlation Level Sensitivity)

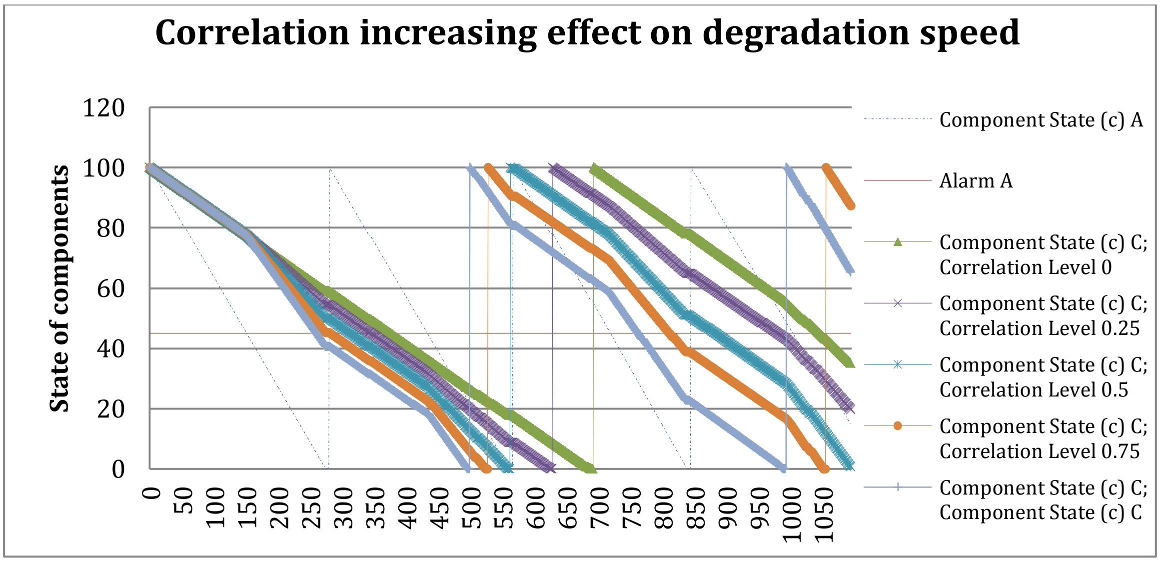


Graph 8.50 – Total costs on Never inspections scenario (Correlation Level Sensitivity)

Graphs underlines that there is not significant difference between outputs values on the variation of failure correlation AC.

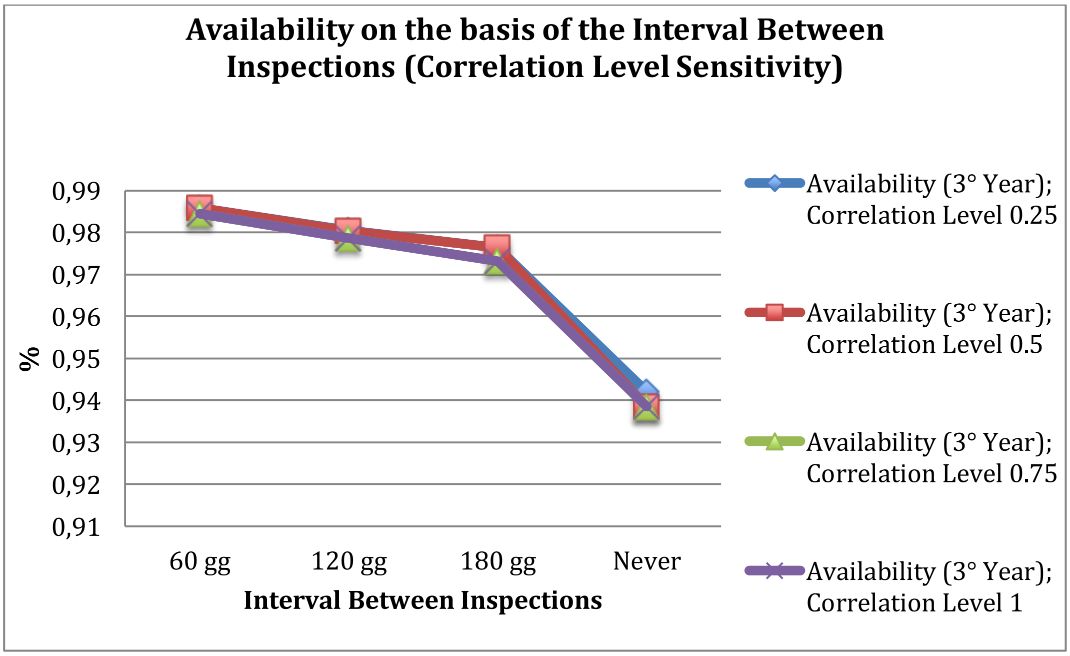
Anyway it does not means that correlation has not an high impact on outputs, it depends on the specific scenarios described by case of study. In that sense the mean lifecycle of components is too big in relationship to 3 years of simulation time. In other words correlation effect would be more visible on outputs in a long-term view or in case of shorter lifecycle of components. Anyway it is possible to point out correlation effect looking at degradation of components in each scenario.

Graph below can clarify this point.



Graph 8.51 – Correlation increasing effect on degradation speed

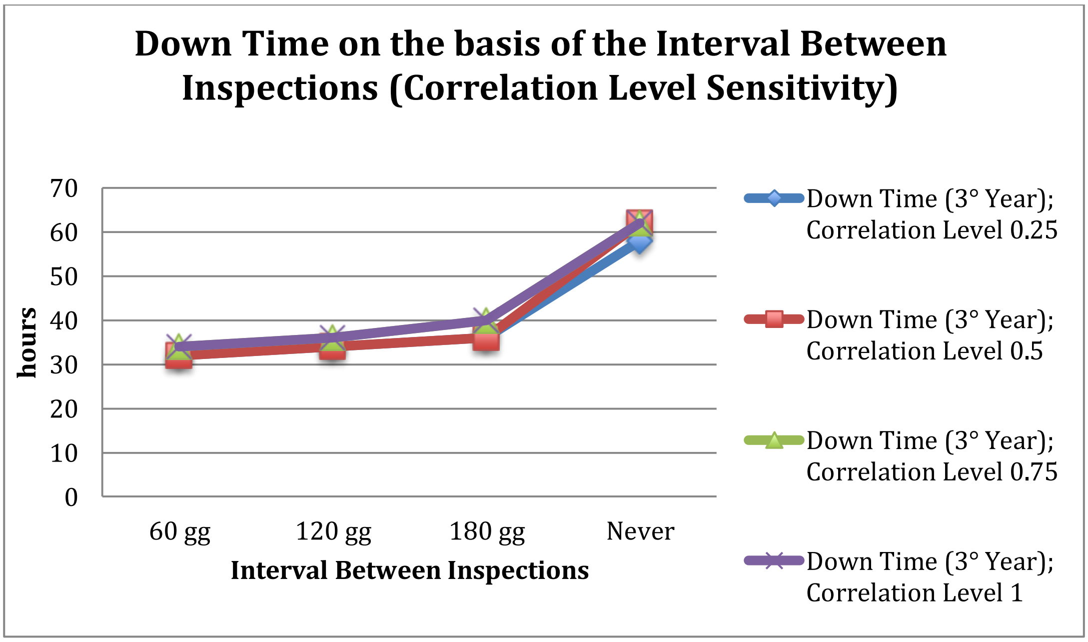
In graphs below indeed it is presented the relationship between outputs and scenarios at time t=1095, comparing different correlation levels and summarizing effects on the basis of inspections efforts.



Graph 8.52 – Availability/scenarios comparison at time = 1095 (Correlation Level Sensitivity)

	Availability (3° Year);			
	Correlation Level 0.25	**Correlation Level 0.5**	**Correlation Level 0.75**	**Correlation Level 1**
60 days	0,985849	0,985849	0,984441	0,984441
120 days	0,980422	0,980385	0,978648	0,978648
180 days	0,976436	0,976436	0,973199	0,973199
Never	0,942042	0,938548	0,938548	0,938548

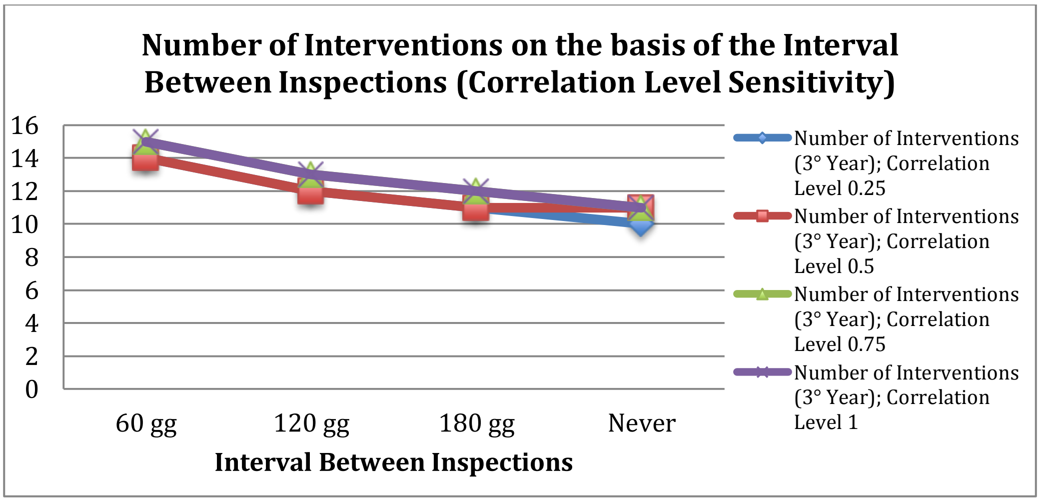
Table 8.12 – Availability/scenarios comparison at time = 1095 (Correlation Level Sensitivity)



Graph 8.53 – Down time/scenarios comparison at time = 1095 (Correlation Level Sensitivity)

	Down Time (3° Year);			
	Correlation Level 0.25	**Correlation Level 0.5**	**Correlation Level 0.75**	**Correlation Level 1**
60 days	32	32	34	34
120 days	34	34	36	36
180 days	36	36	40	40
Never	58	62	62	62

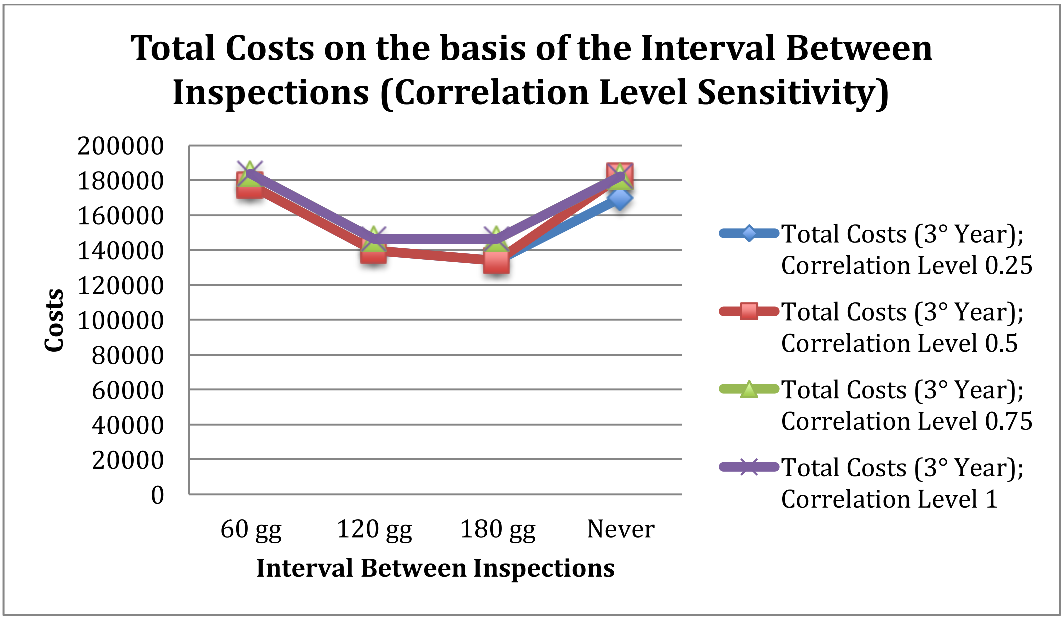
Table 8.13 – Down time/scenarios comparison at time = 1095 (Correlation Level Sensitivity)



Graph 8.54– N° of interventions/scenarios comparison at time = 1095 (Correlation Level Sensitivity)

	Number of Interventions (3° Year);			
	Correlation Level 0.25	Correlation Level 0.5	Correlation Level 0.75	Correlation Level 1
60 days	14	14	15	15
120 days	12	12	13	13
180 days	11	11	12	12
Never	10	11	11	11

Table 8.14 – N° of interventions/scenarios comparison at time = 1095 (Correlation Level Sensitivity)



Graph 8.55– Total costs/scenarios comparison at time = 1095 (Correlation Level Sensitivity)

	Total Costs (3° Year);			
	Correlation Level 0.25	**Correlation Level 0.5**	**Correlation Level 0.75**	**Correlation Level 1**
60 days	177054	177054	183742	183742
120 days	139564	139564	**146252**	**146252**
180 days	**138370**	**138370**	146358	146358
Never	169743	182211	182211	182211

Table 8.15 – Total costs/scenarios comparison at time = 1095 (Correlation Level Sensitivity)

Total costs graph demonstrates how correlation variation pushes the optimum scenario from 180 days to more frequent inspections case.

8.3.3 – Sensitivity Conclusions

Sensitivity analysis confirms that 180 days scenario is the best solution to face case of study problems and that it is a stable solution also in case of variation of sensible parameters. Surely the analysis done underlines that in case of increasing of correlation or lack of production cost, more inspections can reduce failures or down time, optimizing costs. Instead in case of increasing of component alarm level, inspections begin to be less effective, so it can be better to move in the direction of corrective maintenance.

Chapter 9 – Conclusions

Model proposed meets research targets indeed it is able to face most of criticalities and uncertainties underlined by literature. It was built combining main maintenance modules, that describe features of this field and assuring a complete view of maintenance. It underlines policy implications, spare parts handling, degradation modeling, measurement service evaluation, cost analysis and performance measurement through some values like the availability of the system or number of failures. It is able to be a precious support of decision maker, highlighting how and in which case the increasing preventive maintenance trend is the right choice, but also underlining problems, improving the comprehension of the whole systemic behaviour, thanks to the use of a dynamic simulation. In that sense it supports service development, helping its to reach benefits that require its correct functioning and its quality guarantee.

Model has been tested and it provided interesting results demonstrating its usefulness. Company data allowed to evaluate the model and to make a sensitivity analysis, confirming goodness of results. However it is not used to provide a consultant service to that company. So future researches could use it in order to make several maintenance services assessment and to improve it on the basis of features more required from customers.

Annex 1 – Vibration Analysis

Vibration measured parameters to investigate on components are:

- Displacement (m)
- Velocity (m/s)
- Acceleration (m/s^2)
- Frequency (Hz)
- Bandwidth (Hz)
- Spike Energy (gSE)
- Power spectral density
- Peak Value
- Root Mean Square (RMS)
- Crest Factor (CF)
- Arithmetic Mean (AM)
- Geometric Mean (GM)
- Standard Deviation (SD)
- Kurtosis
- Phase

In the picture below there is the representation of some parameters:

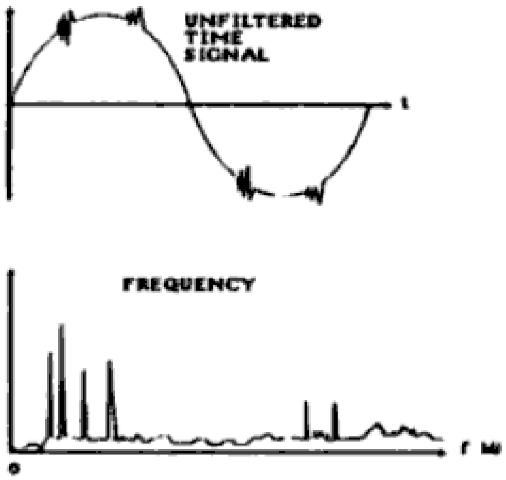


Figure A1.1 – Unfiltered Time Signal and Frequency (Rao B. (1996))

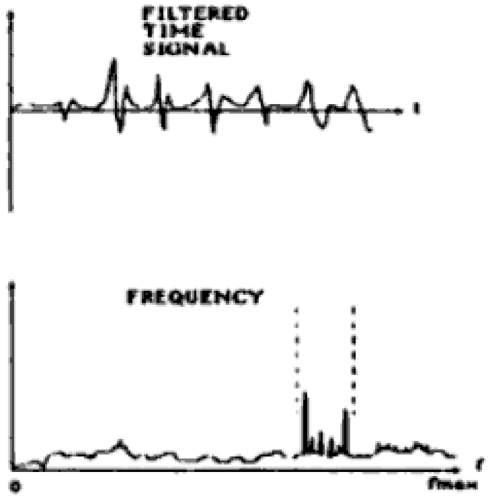


Figure A1.2 – Filtered Time Signal and Frequency (Rao B. (1996))

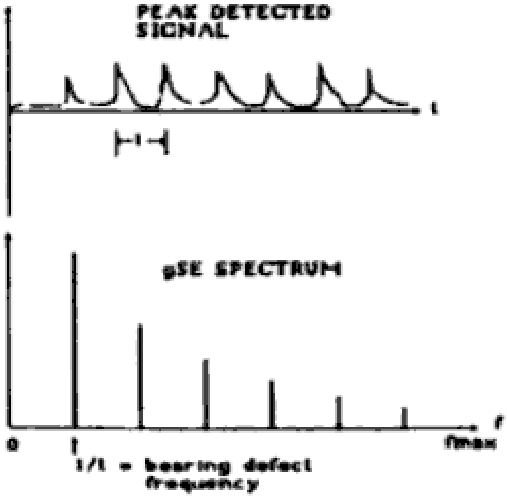


Figure A1.3 – Peak Detected Signal and Spectrum graph (Rao B. (1996))

It is not simple to investigate on machinery vibration signature because of a mixture of sinusoidal waveform of different amplitude, frequencies and phase gives to the graph an impossible reading. To analyze frequency distribution or spectrum it is fundamental to transform the signal from the domain of time to frequency domain using a Fast Fourier Transform (FTT). It allows obtaining for example a clear spectrum analysis, which is able to communicate the state of component, because an incoming failure corresponds to a specific graph shape.

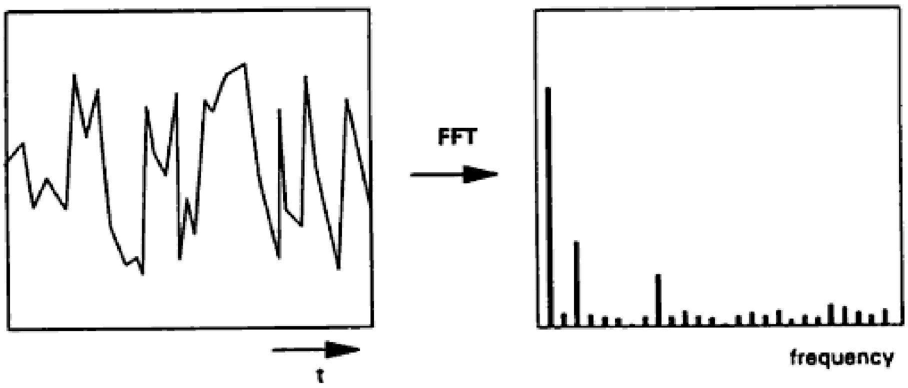


Figure A1.4 – Transformation from Time Domain to Frequency Domain (Rao B. (1996))

Annex 2 – System Dynamics

In system dynamics the structure of the system is described with a combination of causal loop diagrams with stock and flow diagrams and auxiliary variables. These diagrams represent the qualitative part of the model, in which the mathematical model (i.e. differential equations) is hidden. Mathematical model is separated from the framework, and hidden to focus on interactions and feedbacks of the whole system instead of specific formula to describe it.

Feedback

Feedback is an essential concept in system dynamics. The word feedback means that input affects the state of the system that affects the input too. Basically, there are two types of feedbacks: negative and positive. Plus and minus signs refer to the link polarity and the direction of the influence. Plus sign means that an increase in independent variable increases the dependent variable. Minus sign means that an increase in independent variable decreases the dependent variable. Loop polarity is determined by the overall effect of the feedback loop. Negative feedback can be called self-correcting and positive feedback self-reinforcing. The importance of the concept is emphasized in system dynamics because the complex dynamic behaviour of system is determined mostly by different feedbacks, not by the complexity of individual components, Sterman (2000).

Causal Loop Diagram

Causal loop diagram is a useful tool to capture the structure of a feedback system. These diagrams describe the causal connections between components. They can give a clear image of system cause-effect relationships. Therefore, they have an important role in the system conceptualization phase when information about the structure of system is put together. Despite their power to capture the interrelations of systems components, they are never enough to form a system dynamics model just by themselves. This is because, causal loop diagrams cannot represent the stock and flow structure of dynamic systems, as explained in Sterman (2000).

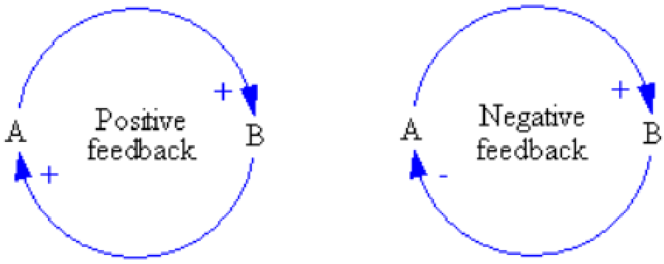


Figure A2.1 - Causal loop diagrams of positive and negative feedback. Plus and minus signs refer to the direction of the in influence (Sterman (2000))

Stocks and Flows

Stocks, also known as state variables or accumulations, represent accumulations of material, money, information etc. Flows refer to rate at which the level of the stock is changing. The general structure of stock and flow represents the following integral equation:

$$Stock(t) = Stock(t_0) + \int_{t_0}^{t} [Inflow(s) - Outfolw(s)]\, ds \qquad (A2.1)$$

Stocks characterize the state of the system and act as sources of information for decision making. Furthermore, stocks create inertia and memory to the system, as

Figure A2.2 - Stock and flow diagram (Sterman (2000))

They are accumulations of past events and can be changed only through in flow and out flow. They create disequilibrium dynamics as they allow inflows and outflows differ, Sterman (2000).

Time Delays

Time delays are the essential sources of dynamics. In negative feedback loops they create instability and oscillations to the system. Moreover, they hinder people from understanding the behavior of the system and learning from experience, Sterman (2000).

<u>Structure and Behavior of Dynamic Systems</u>:

This section discusses the connection between structure and dynamic behavior. System characteristic behavior depends directly from its structure which consists of components and looped causal connections. In system dynamics these feedback loops are modeled mathematically.

Fundamental Modes of Dynamic Behavior

Most of the dynamic behavior can be explained as a combination of three most fundamental modes of behavior, Sterman (2000). They are described in the following sections as simple feedback structures that are dominating when these modes are observed in the behavior. These modes of behavior include: exponential growth, goal seeking and oscillation. Additionally, there are three other basic modes of behavior that are derived from the most fundamental ones: S-shaped growth, growth with overshoot, along with overshoot and collapse. The figures adopted come from Sterman (2000).

Positive feedback generates exponential growth. As the state of the system grows as well the net increase rate grows, which eventually leads to ever accelerating exponential growth.

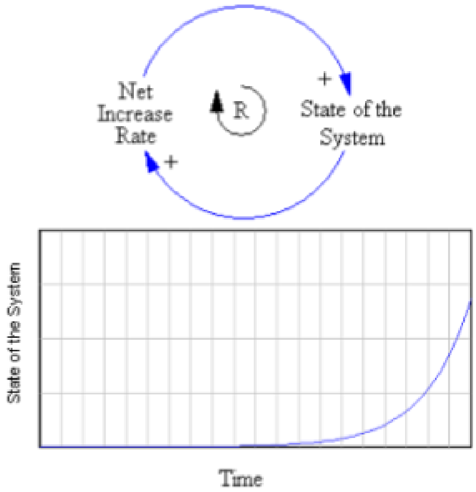


Figure A2.3 - Exponential growth (Sterman (2000))

Goal seeking behavior is generated by a negative feedback. System tries to stay near the desired state of the system. As disturbances occur and system state deviates from its goal value, corrective actions are taken. Corrective actions are taken on the grounds of discrepancy between the desired and the current state of the system.

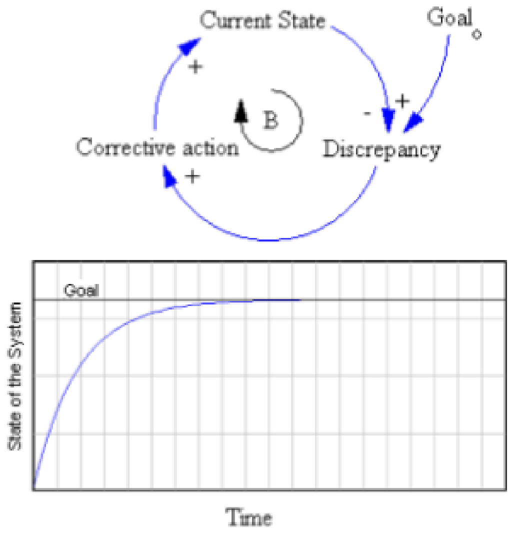


Figure A2.4 - Goal seeking behaviour (Sterman (2000))

Oscillation is generated by negative feedback loop in which there are significant time delays. Basically oscillations derivate from goal seeking system as corrective actions, due to delays, continue beyond the goal value. Subsequently, corrective actions are taken to the opposite direction with similar consequences.

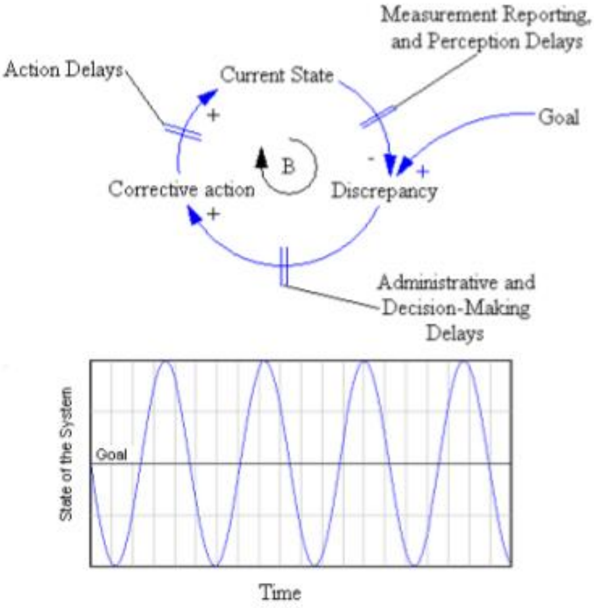


Figure A2.5 - Oscillation and different types of time delays (Sterman (2000))

S-shaped growth is a combination of exponential growth and goal seeking behavior. It represents growth and limits to the growth. In the beginning, growth is exponential until system closes on its carrying capacity. Growth slows down and, eventually stops when the state of the system reaches its equilibrium level.

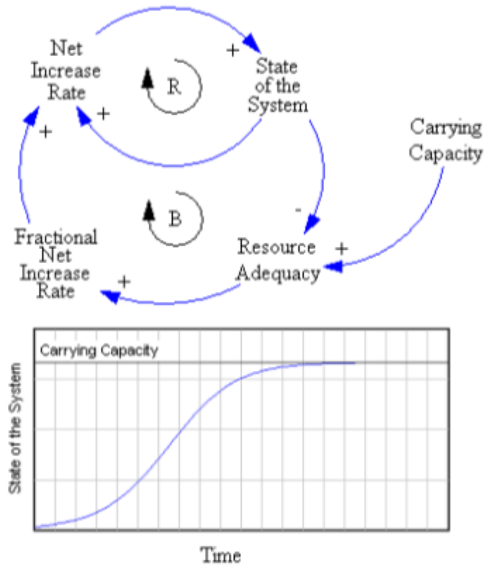


Figure A2.6 - S-shaped growth (Sterman (2000))

S-shaped growth with overshoot is a combination of exponential growth and goal seeking behavior including significant time delay in the negative feedback loop

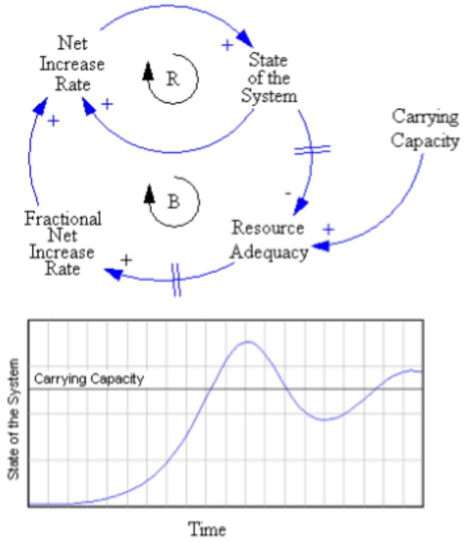


Figure A2.7 – S-shaped growth with overshoot (Sterman (2000))

Overshoot and collapse is basically similar to s-shaped growth with the difference that carrying capacity is not fixed. In this case carrying capacity can drop through excessive consumption, erosion etc. by the over grown state of the system. The collapse of carrying capacity will eventually cause the state of the system to fall as well.

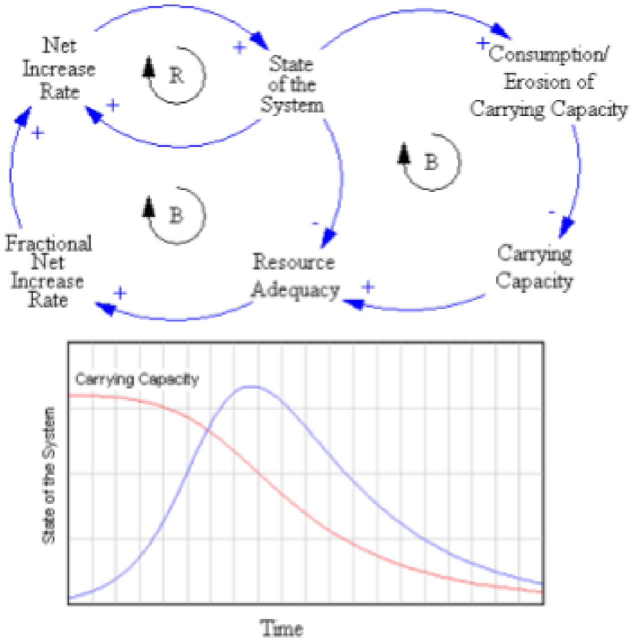


Figure A2.8 – Exponential growth with overshoot and collapse (Sterman (2000))

Loop Dominance

As mentioned before, most of the systems dynamic behaviour is instances of small set of fundamental modes of behaviour. It is characteristic to systems that the relative significance of their modes of behavior and structural components varies over the time. This change in structural significance affects the behavior and the changed behavior, leads to changing structural significance. Alexander et. Al (1981) defines dominant loop as "a loop that is primarily responsible for model behavior over some time interval". For example, S-shaped growth can be seen as a result of loop dominance shift from reinforcing to balancing feedback loop. In order to understand the connection between system's structure and behavior, it is necessary to understand the loop dominance shifts.

Levers in systems

Levers are areas in the system where even small changes can improve the system behavior significantly. Peter M. Senge (1990) said that handling a difficult problem, it is often a matter to see where the high leverage lies. He also points out that high leverage areas are usually highly not clear. System dynamics offers a good way to spot the levers in the structure.

Reference:

CONTENTS	REFERENCES	PUBLICATION YEAR	WORK CONTRIBUTION
Introduction to System Dynamics.	Alexander L. Pugh George P. Richardson, Cambridge: MIT Press; 1981	1981	Technical knowledge about system dynamics
Business Dynamics: System Thinking and Modeling for a Complex World.	John D. Sterman, Irwin McGraw-Hill, 2000	2000	Technical knowledge about system dynamics
The fifth Discipline: The Art & Practice of the Learning Organization.	Peter M. Senge, Century Business.	1990	Technical knowledge about system dynamics