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Development and analysis of an opportunistic maintenance policy

Supervisor: Prof. Marcello COLLEDANI

Andrea SOMASCHINI
ID 863392

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Abstract

Nowadays it is crucial to optimize as much as possible all the aspects of a manufacturing system, as in the case of production and maintenance. The complex interactions present in modern factories make available many opportunity of improvement, even in the case of these two historically contrasting fields.

In this work an opportunistic maintenance policy is developed, which, beside the theoretical modelling, is also tested with simulation in order to demonstrate that can bring real benefits to production.

A description is provided about how the policy is modelled in Matlab though a Markov chain, and how this model can be used to analyze a system in order to set policy parameters in the best way.

It is showed how, in a two stage production line with an intermediate buffer, the non-perfect reliability of the downstream machine and the buffer generate opportunity windows which, through the application of an opportunistic maintenance policy, can be exploited to carry out minor maintenance interventions on the upstream machine. The execution of these interventions exposes the system to a risk of losing throughput, with respect to a baseline case without policy applied. However, performing these tasks during opportunities coming up along shifts, makes available a certain amount of additional time for production, that is the time which would be otherwise dedicated to the execution of the minor maintenance actions. This additional time allows a greater total production over the period considered.

To implement this policy, it’s necessary to guide the operator behavior whenever an opportunity arises, suggesting him the action to carry out or providing information to support his selection. Therefore an interface is studied, which should be installed at machine location in order to make possible a real application of what described in this thesis.

The proposed model is suitable to be implemented in real cases, and leads to new research possibilities on the analysis of the advantages of opportunistic maintenance policies.

Keywords: Manufacturing Systems, Maintenance Opportunity Window, Opportunistic Maintenance, Discrete Time Markov Chain, Interface

Abstract

Al giorno d’oggi è cruciale ottimizzare nella migliore maniera possibile tutti gli aspetti di un sistema produttivo, come nel caso della produzione e della manutenzione. Le complesse interazioni presenti nelle fabbriche moderne rendono disponibili molte opportunità di miglioramento, anche nel caso di due campi come questi, storicamente in contrasto.

In questo lavoro viene sviluppata una politica di manutenzione opportunistica che, a parte la modellazione teorica, è anche testata tramite simulazione per mostrare i benefici che può realmente portare alla produzione.

E’ fornita una descrizione della modellazione della politica in Matlab attraverso una catena di Markov e di come questo modello possa essere utilizzato per analizzare un sistema con conseguente impostazione dei parametri della politica stessa nel migliore dei modi.

Viene mostrato come, in una linea di produzione composta da due macchine e un buffer intermedio, la non totale affidabilità della macchina a valle e il buffer generino delle finestre di opportunità che, attraverso una politica di manutenzione opportunistica, possono essere sfruttate per eseguire degli interventi di manutenzione minore sulla macchina a monte. L’esecuzione di questi interventi espone il sistema a un rischio di perdita di produttività rispetto a un caso base in cui la politica non è applicata. Comunque, svolgere queste operazioni durante le opportunità che nascono lungo i turni, rende disponibile una certa quantità addizionale di tempo per la produzione, che sarebbe altrimenti dedicata all’esecuzione delle attività di manutenzione minore. Questo tempo addizionale permette di ottenere un incremento della produzione totale alla fine del periodo considerato.

Per implementare questa politica è necessario guidare il comportamento dell’operatore ogni qualvolta sorge un’opportunità, suggerendogli quale azione eseguire o fornendogli informazioni per aiutarlo nella selezione. Si è quindi studiata una interfaccia, da posizionare vicino alla macchina, che renda possibile un’applicazione reale di quanto descritto in questa tesi.

Il modello proposto si presta ad essere implementato in casi reali e apre le strade a nuove possibilità di ricerca sull’analisi dei vantaggi delle politiche di manutenzione opportunistica.

Keywords: Manufacturing Systems, Maintenance Opportunity Window, Opportunistic Maintenance, Discrete Time Markov Chain, Interface

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Chapter 1

Introduction

1.1 Context

Manufacturing companies are widespread all over the world, and their success and effective functioning is crucial for the continuous development of themselves, their industry and the hosting countries. The functioning of a manufacturing company is a very mazy subject, as it has plenty of factors affecting its behavior.

There can be many external factors like the actual trend of the related industry, the countries where it operates, market demand, raw materials or semi-finished parts availability and cost, the introduction of environmental regulations, the positioning with respect to customers. Internal factors as well greatly influence the results of a company, for example planning and decision methods used to cope with the demand, inventory management, management of the workforce, choice of technologies exploited. These factors can be more or less subject to a company control, because for example it may be easier to invest in new technologies or implement a lean organization than modify the trend of the demand from the market. By the way usually a relationship between all the factors exists and each aspect of a company is somehow related to the others (for example enhance a process quality could attract new customers towards improved or more reliable products).

To deal with all the issues of a company, usually a strategy is developed, which can be divided in three main categories:

- Corporate level strategy: it’s the highest level and provides long-range guidance for the whole organization.
- Business level strategy: it’s related to how to offer products and services in the target markets. Markets are defined at corporate level.
- Functional level strategy: it’s the level concerned with making corporate, and consequently business, objectives concretely achievable, exploiting every working day in the factory in the best possible way.

The great complexity of modern manufacturing systems makes it very hard to have an effective approach to each one of the numerous influencing factors, so in companies it’s not hard to find a large waste of resources and there are very often large margins of improvement under the most various perspectives.

1.2 Problem statement

This study will be focused on an internal point of view and will be placed at the previously described ‘functional level’, aiming to optimize some classical internal performances of a manufacturing company, such as throughput and starvation probability. This will be done involving one of the most historically underrated field of lots of companies, maintenance. The difficulty consists in the fact that maintenance and production usually pursue contrasting objectives, because, in a simplified way, a production responsible would like to produce as much as possible, therefore minimizing the stops, and a maintenance responsible would instead stop the machine as much as possible to guarantee its correct functioning.

Therefore cutting waste and exploiting better the resources available in order to improve the value created by maintenance, by a production perspesctive, are the motivations that guide this work.

As will be better described in the literature review, maintenance has some main policy types, but actually can take into account a very large number of factors, making possible to combine an infinite number of parameters regarding, for example, machines, buffers, maintenance costs, workforce costs and availability, products nature (e.g. perishable items) and production stoppages. Therefore it’s clear that, in real cases, a policy tends to be fitted to the manufacturing system under consideration as much as possible, focusing on the most critical parameters of the specific context.

Moving back the focus from maintenance to the system itself, it’s well know from literature the use of buffers to decouple machines different reliabilities effects, in order to avoid that the failure of a single machine stops the whole production. Beside this, opportunistic maintenance philosophy pretends to transform an undesirable event, in this case the failure, into a valuable occasion.

Obviously a failure is something that is always undesirable but, since real machines are not perfectly reliable, it’s worth to develop some solutions which allow to create value from that free time that a machine operator has available, suddenly and more or less unexpectedly, when something goes wrong in the manufacturing system, and his workstation is affected by this situation due to the production line configuration and layout.

Even if this opportunistic idea seems quite simple from a logical point of view and at the same time looks like a big chance for a company enhancement, this kind of maintenance is absolutely not common in real factories.

1.3 Objective

The objective of this study is developing a tool that can help the decision maker, who could be for example a supervisor or even directly an operator, to exploit in the best way the time windows that happen to be available during production time. More specifically the basic idea is to execute during these opportunity intervals some minor maintenance tasks, which are usually carried out before or after production time or even require, when needed, a stop of the machine during production time.

The result should therefore be a better manufacturing system overall performance, in terms of real production gain thanks to the time needed to execute the activities saved, as they will be directly done, as much as possible, during the opportunities that arise during standard production time. This will push maintenance toward an higher frequency of activation, guaranteeing also, on average, a better system condition.

The downside of this opportunistic concept is the intentional acceptance of creating a risk for production, because will come up the possibility of having the system repaired and ready to restart work while the machine subjected to the minor intervention is still under maintenance. In this undesired circumstance the consequence would be a throughput loss.

This work aims at evaluating the implementation of the just outlined opportunistic maintenance policy, demonstrating that setting it correctly can bring great benefits at acceptable or even null risk levels.

1.4 Thesis structure

- Chapter 1 provides a brief description of today manufacturing systems concerns in order to highlight their complexity and the need of operations optimization. This need is the motivation behind this thesis, and it is faced in the maintenance field, with an opportunistic perspective. Finally the objective which wants to be achieved is established.
- Chapter 2 supplies a literature review about manufacturing systems and maintenance in general, outlining the most important concepts to get in touch with the maintenance field, its influences and the main policies. Then the focus moves more specifically on the opportunistic area and various related topics.
- Chapter 3 deals with the development of the analytical model, starting from a description of the system and all the hypothesis and assumptions made explicit. An analysis of the lead time in the system considered is then carried out, in order to understand how to manage time intervals with the policy. After that the policy itself is modelled in Matlab, based on the lead time analysis previously conducted.
- Chapter 4 shows the experiments executed to have a validation of the model and check its convergence, through a comparison with simulation results. Numerical results from the software model are presented, explaining how the graphs generated can be exploited to set policy parameters, in order to achieve different types of optimization. Finally the effectiveness of the policy is demonstrated by applying it to a simulation model that indicates, anytime an opportunity comes up, the best minor maintenance tasks to carry out from the available ones. Results showing the production increments are provided.
- Chapter 5 presents, after a short introduction to interfaces and their main features, a possible interface, which could help a machine operator to work according to the policy.
- Chapter 6 provides the conclusions of this study and suggestions about future research.

Chapter 2

Literature Review

Here a brief review is provided about manufacturing systems and their features, their relationship with maintenance and finally a focus on opportunistic maintenance is made, which is the side of this large topic the thesis is more related to.

2.1 Manufacturing systems

Manufacturing means the making or producing of goods by manual labor or by machinery, through the transformation of inputs (resources, e.g. raw materials, manpower, equipment, information) in outputs (finished parts). It includes also all the intermediate processes involving the production of semi-finished parts.

Systems used in the production of goods and delivery of services constitute the vast majority of most industry's capital (Wang, 2002). This is a reason why the manufacturing field is considered a strong technology pull, with all the research and development activities related to it.

Manufacturing systems in today's world are highly complicated and interconnected, usually consist of machines and material handling systems, connected in a combination of serial and/or parallel lines, and computers, storage buffers, people and other items. With the market globalization, the turbulence of demand, the increasing product variety and the frequent introduction of innovations in processes and technologies lead to the continuous need for adjusting production targets (Takata, 2004) in order to meet customers' requests, while maintaining a certain level of efficiency and effectiveness. It's worth to remind that efficiency is the ability to accomplish something with the least waste of time and effort, and effectiveness is the capability of producing a desired result .The continuous pursuit of these objectives is essential to realize a sustainable and valuable production.

In this context, manufacturing companies are continuously facing the challenge of redesigning their manufacturing systems architecture and operational parameters to deliver the required production rates of high quality products with profitable operating conditions and limited use of resources (Colledani and Tollio, 2012).

In the last decades manufacturing systems have been deeply studied and investigated to understand their behavior and performances to effectively support their design and improvement. Simulation methods and analytical methods have been developed and are the most commonly adopted tools used to measure, quantify and evaluate the performance (for example throughput, work in progress and lead time) of a manufacturing system.

The widespread automation coupled with reorganization of manufacturing operations using just-in-time and lean management philosophies has heightened the significance of maintenance activities: a good level of reliability and availability is required to achieve the desired performances, and this makes maintenance play a fundamental role in any company strategy.

This is due to the fact that, beside the role of great importance from a manufacturing point of view, it has turned into a critical business function capable of influencing an organization income.

The development of this perspective can be demonstrated comparing what was stated in Jonsson (1997) with respect to Sharma et al. (2011). The first author states that in practice few manufacturing companies were creating maintenance strategies and linking them to their manufacturing and business goals, while the second and more recent one affirms that maintenance in today's manufacturing systems is becoming more important as companies start to adopt it as one of their profit generating elements.

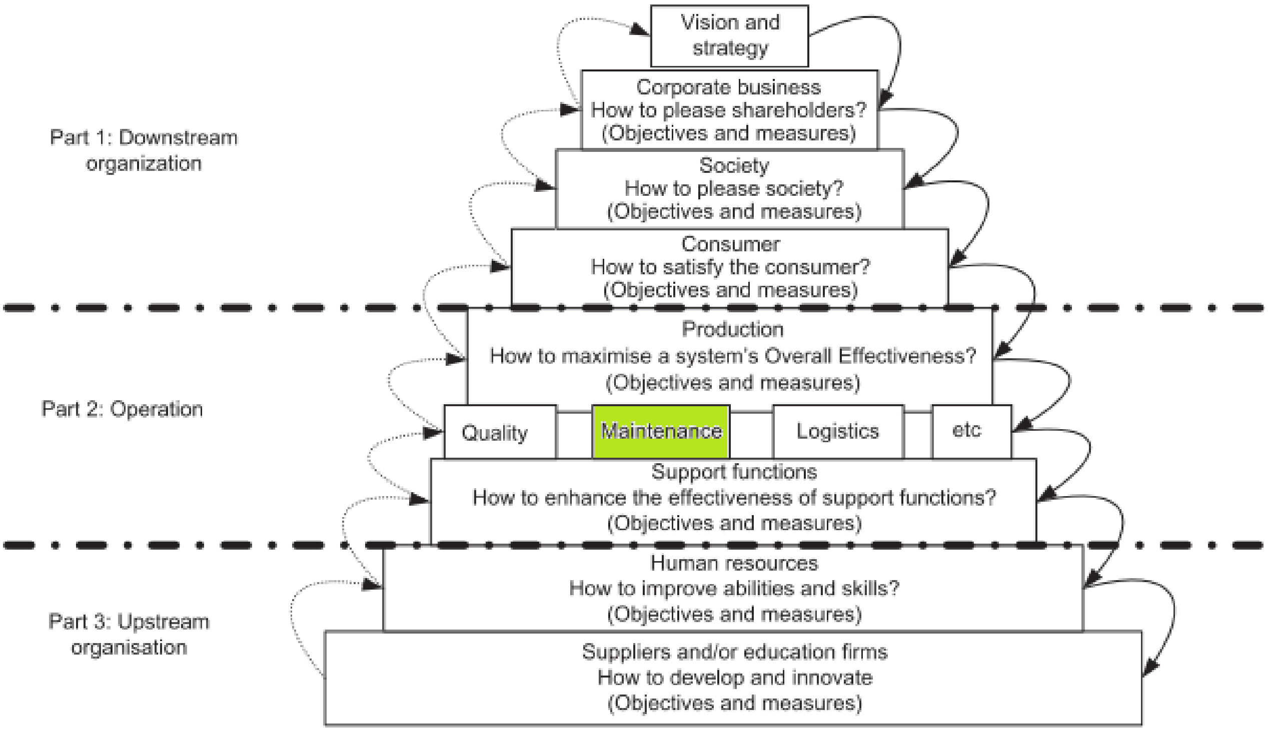


Figure 2.1: Maintenance position in a company hierarchy scheme (Alsyouf, 2006).

2.2 Role of Maintenance

In order to have a proper definition of maintenance, we can refer to the one by the British Standards Institute: maintenance is the combination of all the technical and associated administrative activities required to keep equipment, installations and other physical assets in the desired operating condition or to restore them to this condition.

Hence maintenance is executed in a company to assure that all the machines of the company are repaired, replaced and adjusted according to production requirements.

Other definitions can help to have a deeper understanding of the spirit of maintenance:

Kelly (1989) states that the objective of maintenance is to achieve the agreed output level and operating pattern at a minimum resource cost within the constraints of the system condition and safety.

Tsang et al. (1999) states that maintenance also includes the engineering decisions and associated actions that are necessary for the optimization of specified equipment capability, with capability meaning the ability to perform a specified function within a range of performance levels that may relate to capacity, rate, quality, safety and responsiveness.

It is possible to make a summary of the main objectives of maintenance:

- Ensure the manufacturing system functions, such as reliability, availability and final product quality.
- Make the manufacturing system survive during its designed lifecycle.
- Ensure safety and sustainability, from manufacturing system point of view and environmental point of view.
- Ensure a cost-effective maintenance and an efficient use of the available resources (raw materials and energy).

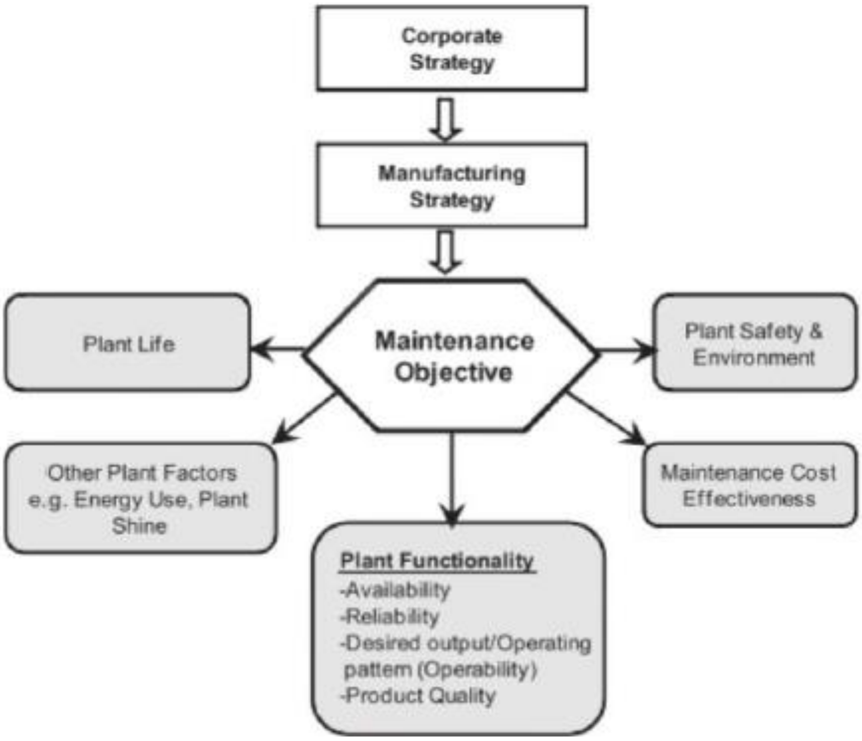


Figure 2.2: Summary of maintenance objectives (Muchiri et al. 2011).

In Murphy and Hill (2009) the researchers put the focus on three macro-areas: safety, reliability and performance, evaluating the importance of these maintenance aspects and stating that a company should focus on one or more of these areas according to the field where it operates.

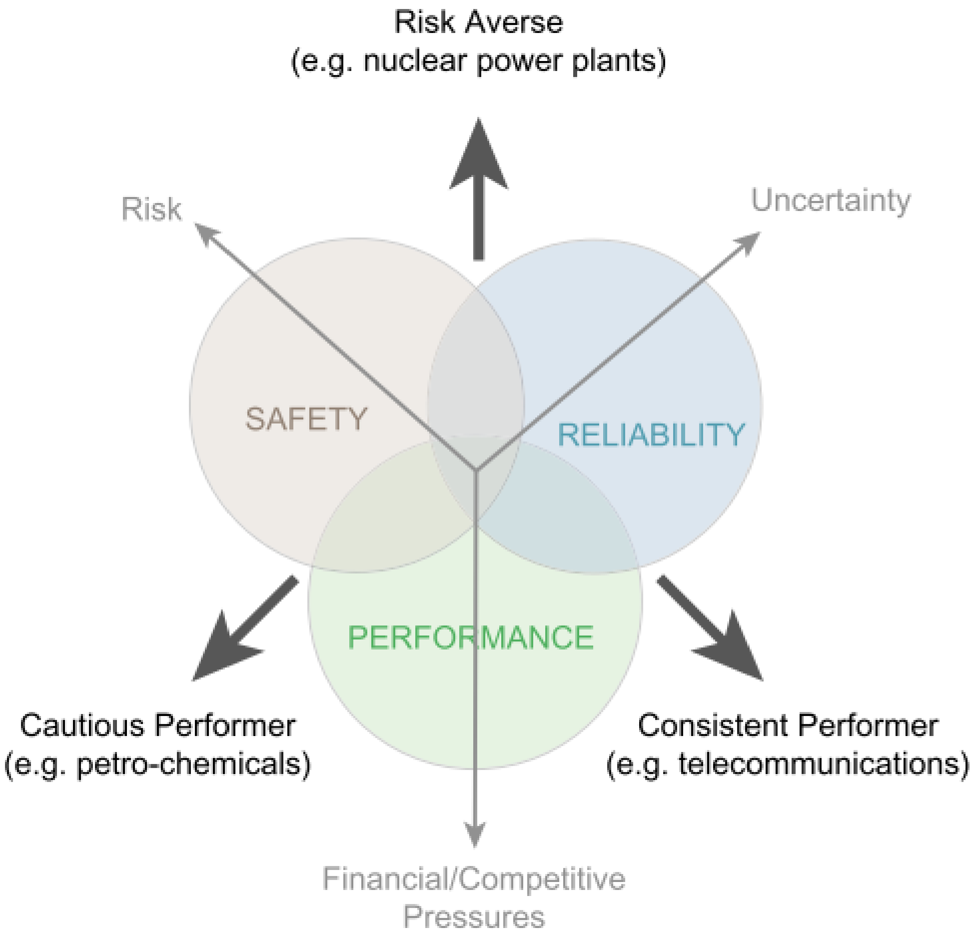


Figure 2.3: Maintenance operating areas (Murphy and Hill, 2009).

Wang (2002) states that maintenance should minimize system maintenance cost rate, maximize the system reliability and minimize system maintenance cost rate while the system reliability requirements are satisfied or maximize the system reliability while the requirements for the system maintenance cost are satisfied. To pursue these objectives is very important to choose the right policy and, in order to make the correct choice, many information must be taken into account, as the following Figure explain:

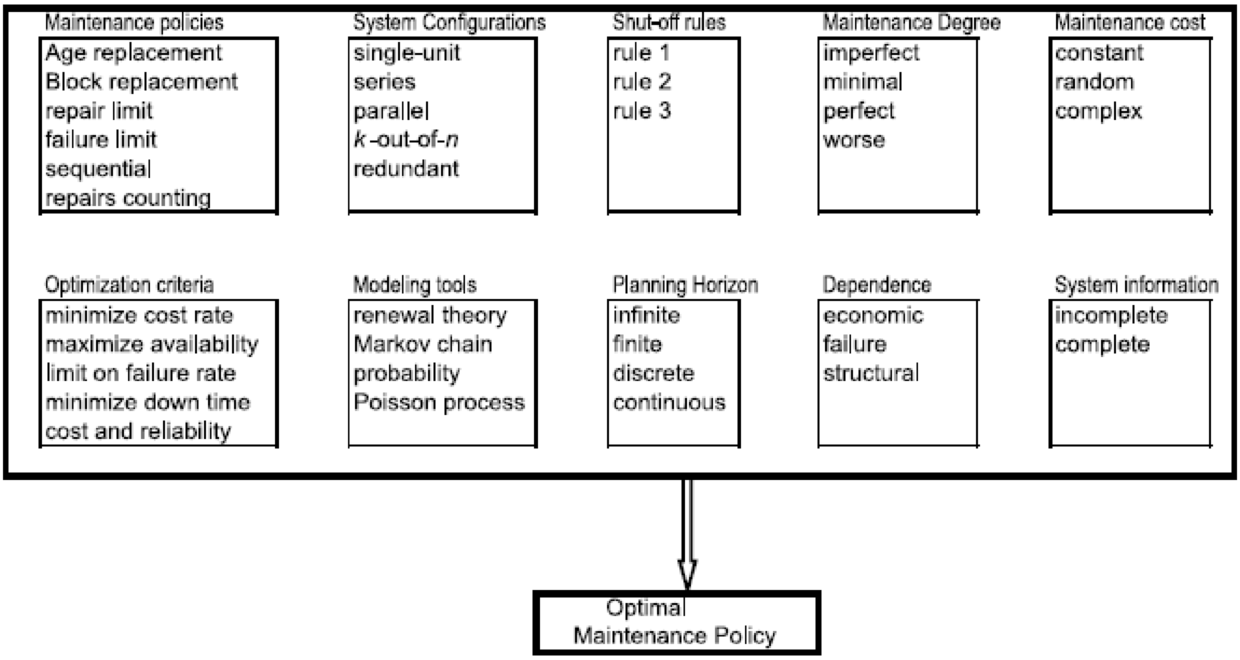


Figure 2.4: Maintenance policy influence factors (Wang, 2002).

2.2.1 Maintenance costs

For a long time maintenance was executed by workers themselves, with no defined parameters, so it wasn’t well organized and there was no haste to make failed equipment operational again. Then times changed and a deeper concerning about money and safety developed, and the need of keeping equipment operational gained the maximal priority. This is a consequence of the change of point of view in modern industry, from ‘maximum gain with minimum capital’ to ‘maximum added value from the minimum use of resources’. To make this possible maintenance started requiring a larger amount of resources and investments, so the economic aspect became fundamental.

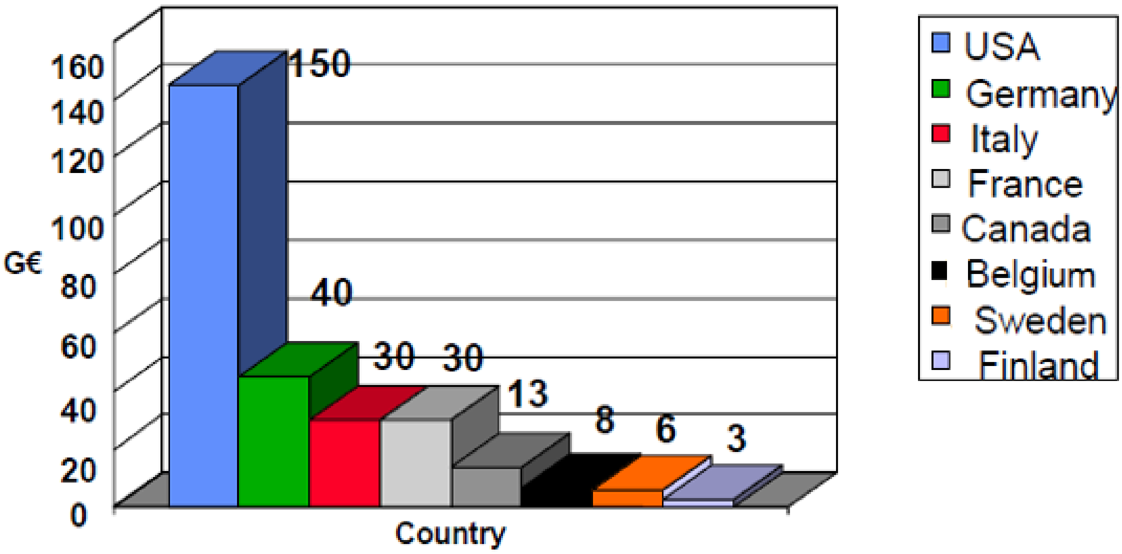


Figure 2.5: Billions per years spent in maintenance by some countries.

Another interesting data that gives an idea of the importance that maintenance has gained is that, in Italy, the total number of people involved in maintenance activities during their work is around 2 millions (more than 3% of the population).

Varying according to the type of field a company operates, Bevilacqua and Braglia (2000) affirmed that maintenance costs can reach 15-70% of production costs. Later Wireman (2003) showed that up to 33% of this maintenance cost is actually wasted or spent unnecessarily, so lot of improvement is generally available.

The following figure shows in a schematic way how a company can gain benefits and at the same time lower the cost of maintenance itself from a long-period point of view, by the implementation of a good performing maintenance.

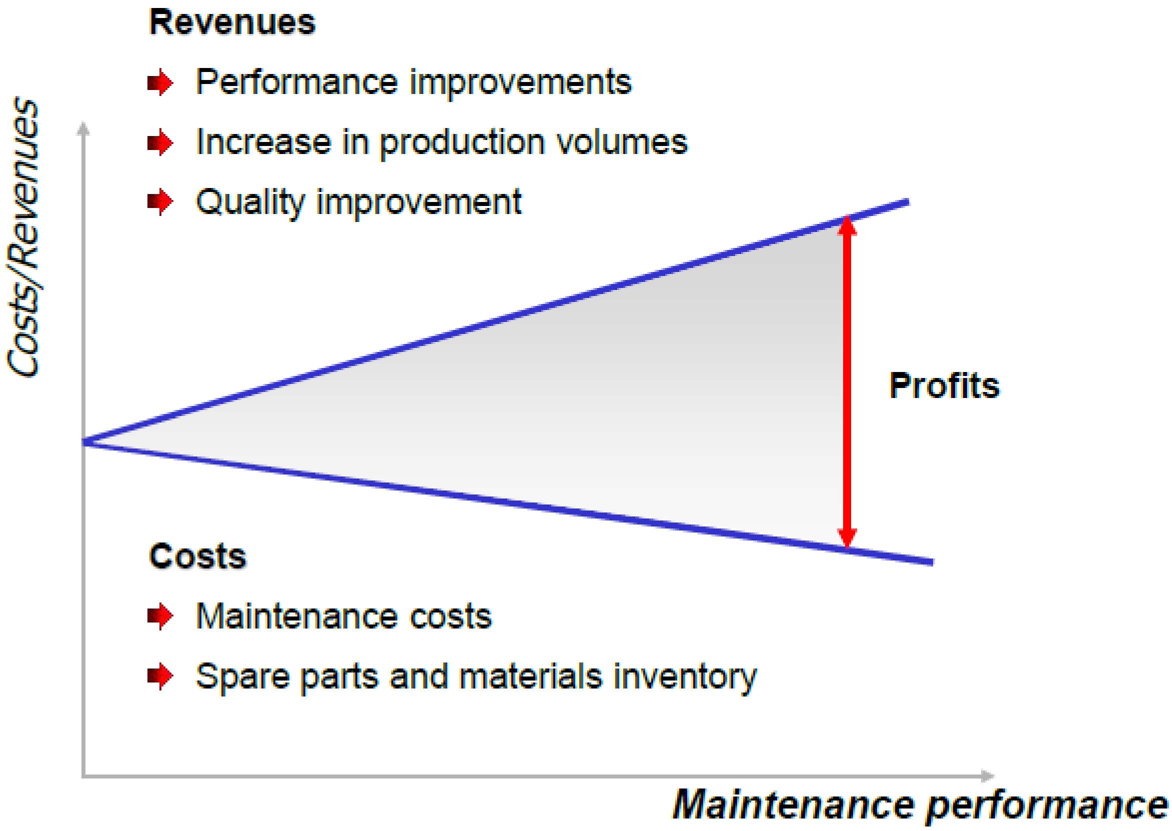


Figure 2.6: Behavior of costs and revenues improving maintenance.

Anyway it’s very common in companies that needs to cut costs to choose maintenance as one of the target department, and this is related to the fact that maintenance gives ‘hidden’ advantages (e.g. lower production/services loss) to a company while it’s a source of clear visible cost(mainly human work but also spare parts, consumables, etc).

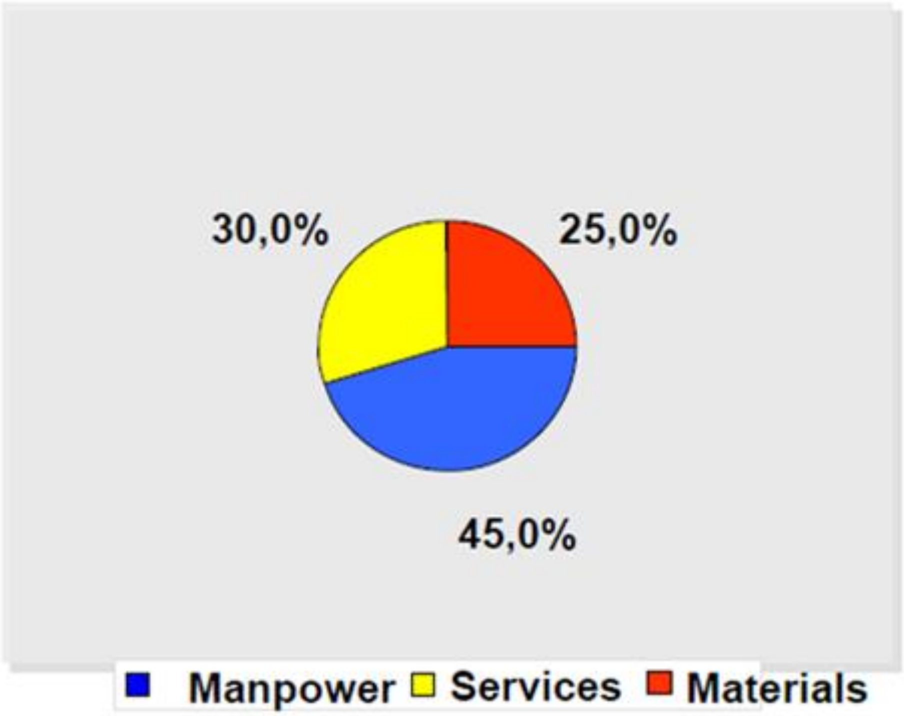


Figure 2.7: Average distribution of maintenance cost percentages in Europe.

More precisely, the costs of maintenance can be classified in the following way:

DIRECT VISIBLE COSTS

- Internal manpower: labour cost of internal maintenance personnel.
- External manpower: labour cost of external maintenance personnel.
- Materials: cost of component replacement and consumables.

INDIRECT VISIBLE COSTS

- Maintenance structure: cost of indirect personnel part of the maintenance service (e.g. maintenance engineering, spares management, etc.).
- Facilities: cost of technical equipment and utilities used by maintenance (e.g. welding equipment, testing equipment, etc.).
- Inventory: financial cost of spare parts stocked in the company inventory.
- Auxiliary services: cost of services used by maintenance (e.g. CMMS).

HIDDEN (INEFFICENCY) COSTS

- Service unavailability (production or service losses).
- Quality losses: internal costs (e.g. scrap, rework) and external costs (e.g. market withdrawal, penalties).
- Process inefficiency (e.g. electricity overconsumption).
- Safety losses (accidents, environmental damages).

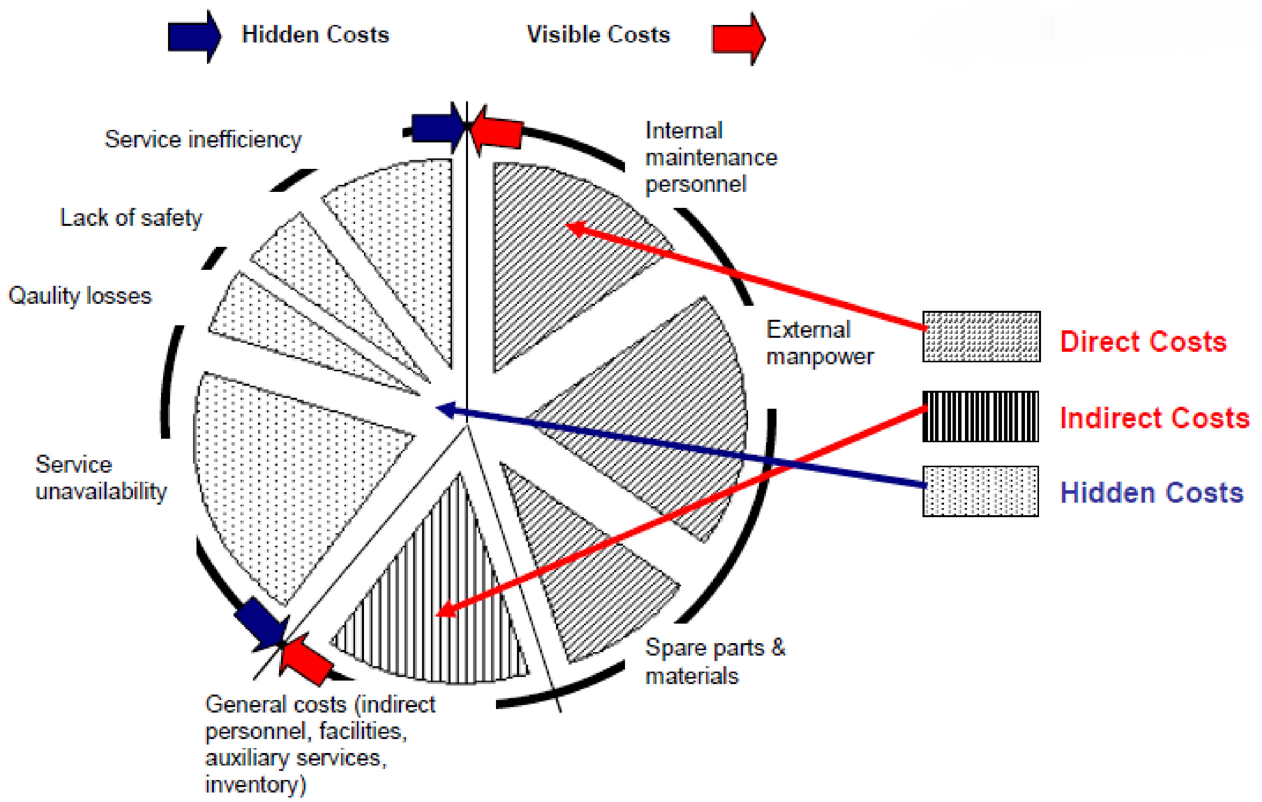


Figure 2.8: Detailed cost categories and distributions.

These costs can largely vary with respect the way maintenance is executed, the so called maintenance policies.

2.2.2 Maintenance policies

A maintenance policy is the criteria and strategies used in making maintenance. A policy has therefore two interpretations, both defined by UNI EN 13306:

- A maintenance policy is the type of maintenance intervention defined according to well known standards.
- A maintenance policy is the strategy or management method used in order to achieve the objective of the maintenance function.

Policies can be divided in two main categories:

- Corrective maintenance: maintenance interventions are performed after failure occurrence.
- Preventive maintenance: maintenance interventions are performed before failure occurrence.

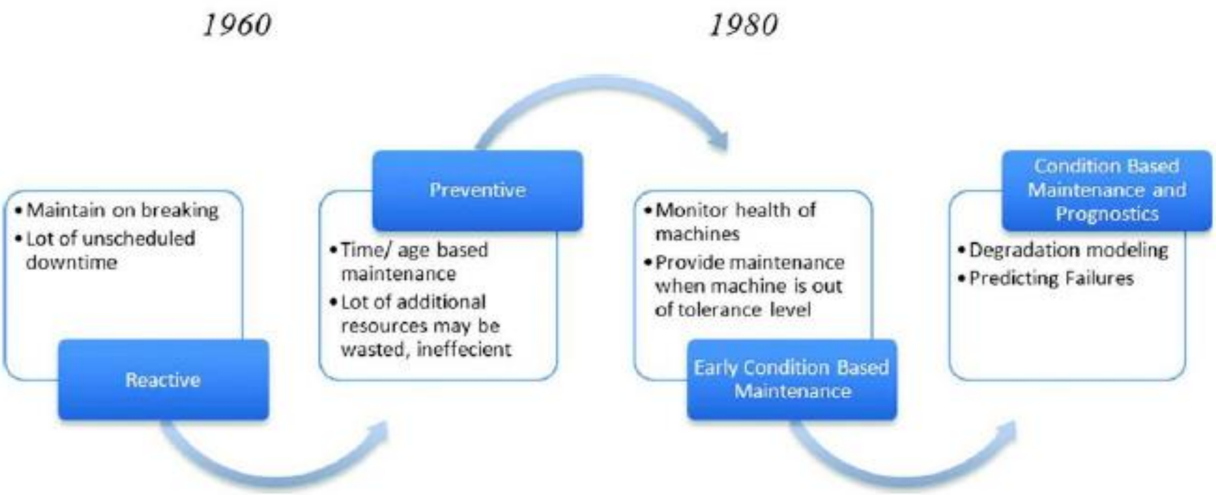


Figure 2.9: Evolution of maintenance policies (Ambani et al., 2009).

Corrective maintenance can be executed as deferred or immediate maintenance (EN 13306).

- Deferred Maintenance is the maintenance which is not immediately carried out after a fault detection but it is delayed in accordance with given maintenance rules.
- Immediate Maintenance instead is the maintenance which is carried out without delay after a fault has been detected to avoid unacceptable consequences.

Corrective maintenance is the most simple and traditional example of maintenance, while preventive maintenance is more innovative, and, usually, is preferred in real cases because, as stated in Jin et al. (2009), cost of corrective maintenance can be even three or four times higher than preventive maintenance.

Preventive maintenance can be further divided in some sub-categories:

- Cyclic maintenance (also time based maintenance): maintenance is carried at fixed time intervals (clock-based) or at a fixed age or usage of a component (age-based).

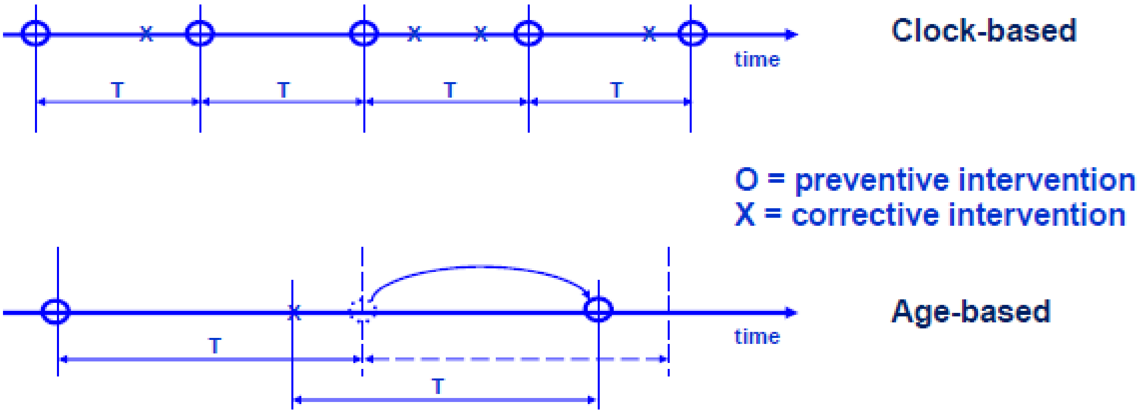


Figure 2.10: Cyclic (or time based) maintenance.

- Condition based maintenance: interventions are based on the condition of the component being maintained. This involves the monitoring (continuous or at fixed intervals) of one or more parameters characterizing the wear process (e.g. crack growth, temperature, vibrations, etc). The choice of the correct equipment for measuring parameters is fundamental in this kind of policy, as it should provide accurate data.

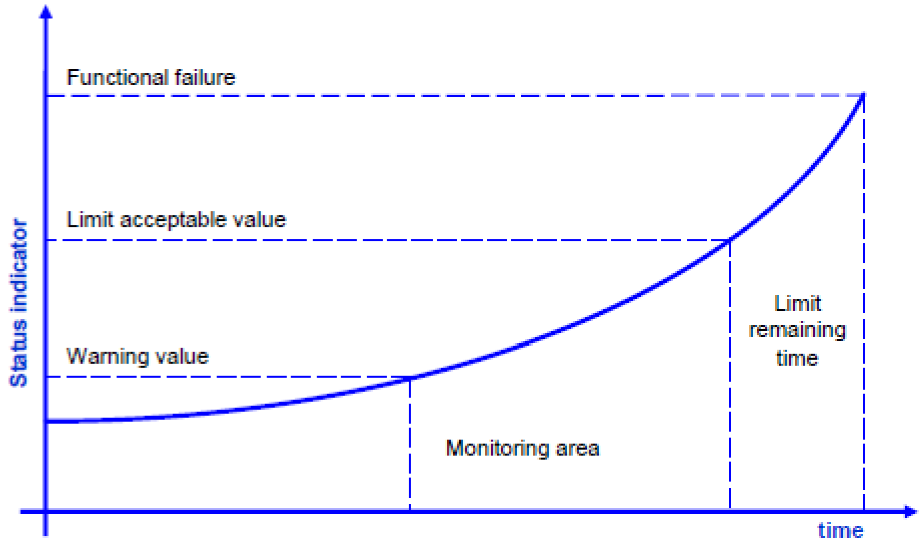


Figure 2.11: Condition based maintenance.

- Predictive maintenance: interventions are based on the evaluation of the trend of one or more parameters, which are linked to the wear process (usually through a mathematical model). It is somehow an evolution of condition based maintenance.

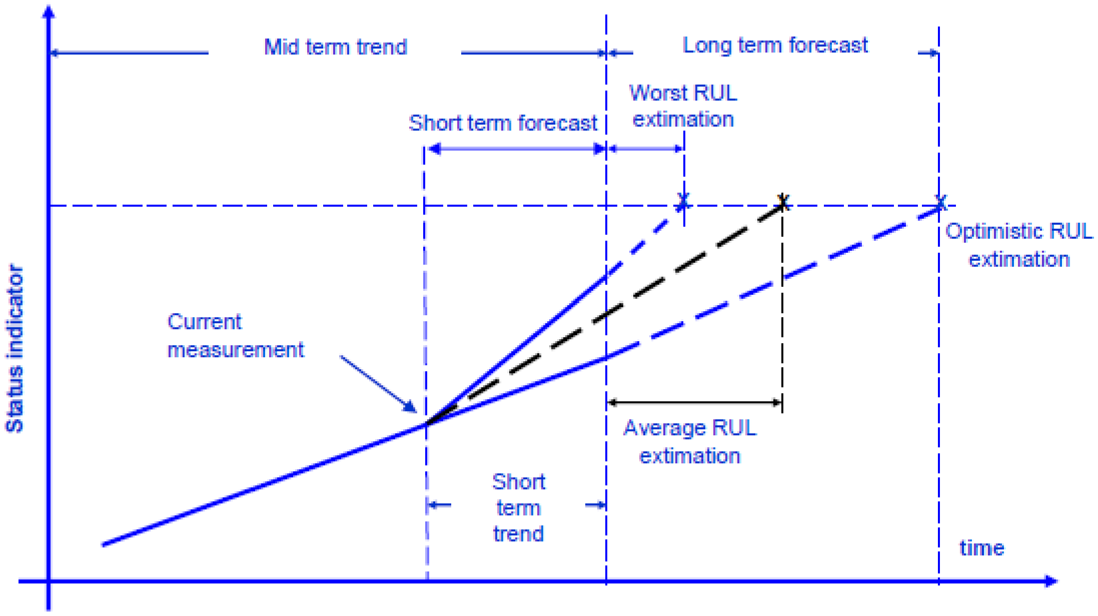


Figure 2.12: Predictive maintenance.

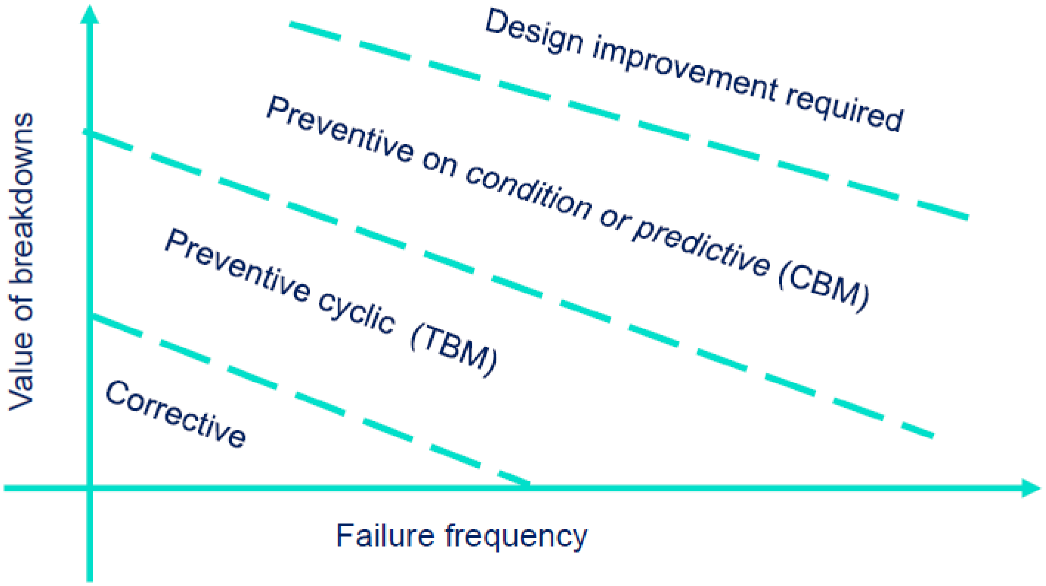


Figure 2.13: Scheme to choose between policies.

It is worth to mention also some maintenance philosophies often recalled in the literature, that contributed to the evolution of maintenance itself.

- Reliability centered maintenance is a traditional approach appeared in the 70s, initially directed mainly to the aircraft field. It is a process to ensure that systems continue to do what their users require in their present operating context, and enables the definition of a complete maintenance regimen. After the execution of a Failure, Mode, Effects and Criticality Analysis (FMECA), the appropriate maintenance tasks for the identified failure modes are determined and a maintenance strategy is developed.
- Risk based maintenance deals with the analysis of hazards and their risks and consequences. It focuses on the most dangerous items and is common in risky environments like nuclear power plants.
- Total productive maintenance is a set of management techniques developed around the 1970s in the Japanese manufacturing context, especially in the production system of the car manufacturer Toyota. It is based on the just-in-time philosophy, that aims at reducing production lead times and response times from suppliers and to customers, and total quality management, a management approach centered on quality, requiring the participation of all its members and aiming at long term success through customer satisfaction and benefits to all members of the organization and society (ISO 8402:1994). Total productive maintenance can be defined as a methodology to maintain and improve the integrity of production and quality systems through the machines, equipment, processes, and employees.

  In particular the maintenance executed by the machine operators is considered fundamental by this philosophy. It is named autonomous maintenance and is the one exploited in this thesis. This kind of operators' interventions will be later discussed in this work.

- Lean maintenance is the extension of lean manufacturing in the maintenance field, with the aim of eliminating all the non-value adding activities in order to achieve a waste minimization, in all its seven sub-categories (transportation, inventory, motion, waiting, over-processing, over-production, defects).

It must be mentioned also a common literature classification of maintenance based on the result of the actions performed:

- major (or perfect) maintenance (repair): maintenance brings back the failed system to an 'as good as new' condition.
- minimal maintenance (repair): the system is restored to the operational state it was just before the failure, the so called 'as bad as old' condition.
- imperfect maintenance (repair): maintenance restores the system to an operating state somewhere between 'as good as new' and 'as bad as old' conditions. Major and minor maintenance can be considered the two possible extreme cases of imperfect maintenance. This 'imperfect' concept was introduced by Pham & Wang (1996).
- Worse maintenance (repair): after the maintenance intervention, system failure rate increases, so system is restored to a worse condition but without the happening of a failure.
- Worst maintenance (repair): maintenance action that undeliberately makes the system fail.

2.2.3 Single-unit and multi-unit systems

All the policies described are designed for a single-unit system, where the term 'unit' refers to a machine or a piece of equipment. It's easy to understand that in real complex multi-unit manufacturing systems, these policies lose effectiveness and can not be optimal. This is due to the fact that, unless all the units are independent (and then all the units can be considered separately, but it's very improbable in real systems), one or more types of dependence exist between them.

- Failure dependence: failure distribution of different units are stochastically dependent (failure of one unit may affect one or more of the other functioning units, and times to failures of different units are then statistically dependent (Nakagawa and Murthy, 1993)).
- Economic dependence: executing maintenance on different units jointly costs less money and/or time than performing it separately.

Therefore, in a multi-unit system, the optimal maintenance action depends not only on the state of the unit under consideration, but also on the condition of all the dependent units.

Nowadays the interest is focused on multi-unit systems as they represent the real industrial context. Most of continuous operating systems, as power plants, aircrafts and chemical plants show an economic dependence. Unavailability costs are greater than maintenance costs so an opportunistic policy may become very profitable in these cases.

This last type of policy differs from the previous ones because is not cost effective if dealing with single-unit systems, while with multi-unit systems requires complex scheduling and planning activities but can be very advantageous. Indeed the objective of an opportunistic policy is to take advantage of components dependency to improve maintenance performance.

As it is the type of policy this thesis deals with, next part will be focused on it.

2.3 Opportunistic Maintenance

The first policies termed as ‘opportunistic’ appear for the first time in McCall and Radner and Jorgenson (1963). The concept of the ‘opportunistic’ maintenance policy is the dependency of the components and equipment in a system: maintenance has to be performed on a given part, at a given time, in a limited time frame (called MOW, maintenance opportunity window), depending on the state of the rest of the system. It has gained lots of attention in the last years, as the number of publications constantly increases.

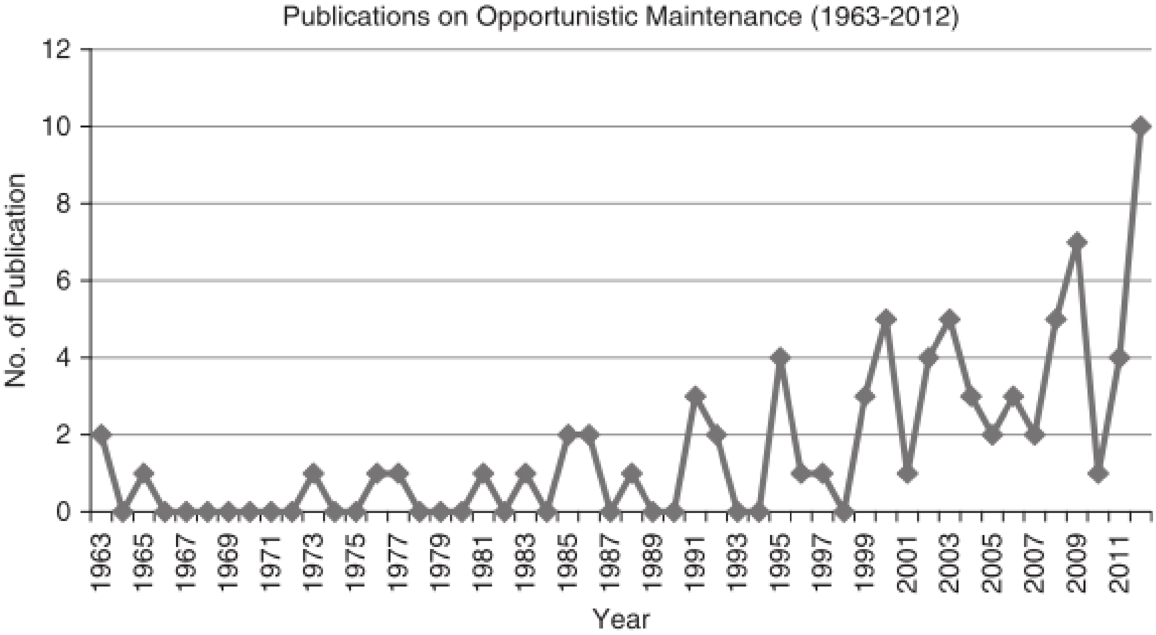


Figure 2.14: Number of publications related to opportunistic maintenance from 1963 to 2012 (Ab-Samat and Kamaruddin, 2014).

However, despite the increasing number of publications, it is very hard to find real cases application, while there is abundance of numerical analysis (numerical analysis aims at designing and analyzing techniques that can provide approximate but accurate solutions to hard problems). The main limiting factor to the application is related to the assumptions of this kind of policy, usually too strong for the real industrial context (e.g. unlimited maintenance resources), and the few case studies available are too specific to be generalized.

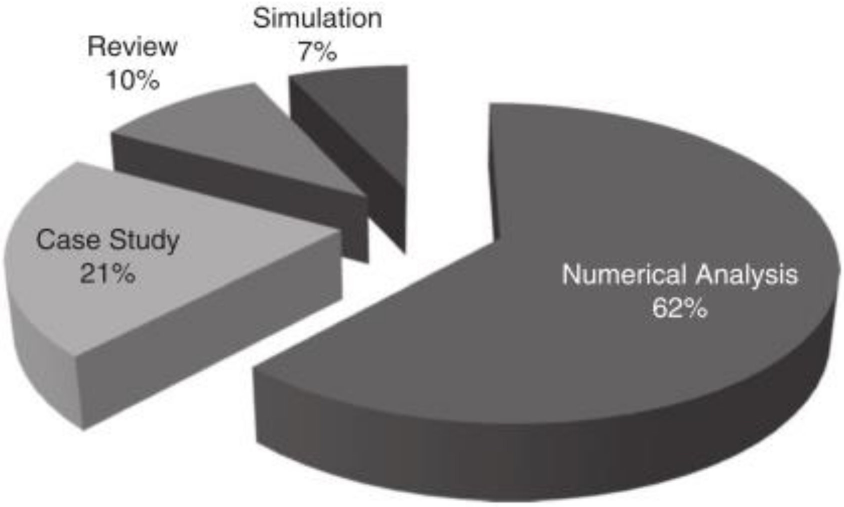


Figure 2.15: Percentage of publications on research approaches in opportunistic maintenance research (Ab-Samat and Kamaruddin, 2014).

The main feature of this policy is the execution of a maintenance action during an opportunity.

An opportunity can be defined as 'the moment at which the units to be maintained are less needed for their function than normally, that occurs occasionally and that is difficult to predict in advance' (Budai et al., 2006) or as 'any event at which a unit can be maintained preventively without incurring cost penalties for the shutdown of the unit' (Dekker and van Rijn, 2003).

Usually opportunity in reality are of two types: failures and hence repairs of other units or interruptions of production due to other external factors, as market interruptions or other activity that require units to be stopped (e.g. layout modifications, replacing of machines, etc).

The objective is then grouping maintenance actions together, usually associating predictive maintenance to a corrective action, so that to create cost effectiveness and improve system availability and reliability, through an increase of the number of failures avoided and a decrease of the number of stoppages or shutdowns for maintenance.

It was already proven by Koochaki et al. (2012) that, in a serial configuration, an opportunistic policy decrease maintenance cost and increase the production. They also made clear the relationship between condition based and opportunistic maintenance, because monitoring system conditions helps determining the opportunity windows for the opportunistic policy, offering additional solution space to the conventional planning and scheduling of maintenance activities, increasing system availability and decreasing maintenance costs.

Therefore opportunistic maintenance provides an opportunity to repair or replace components which are found to be defective or need replacement in the immediate future, during the maintenance of a sub-system or module (Saranga, 2004). This way the cost of future maintenance or replacement activities can be avoided (Pullen and Thomas, 1986).

2.3.1 The opportunity window

Maintenance opportunity windows (MOWs) were defined by Chang, Ni, Bandyopadhyay, Biller, and Xiao (2007) as the maximum time duration that allows maintenance on specific machines without bringing production loss to a system.

It's possible to distinguish between two types of MOWs:

- Passive MOW: it's due to the downtime of a machine that oblige the system to stop. It's an event-driven opportunity that takes advantage of starvation and blocking phenomena. The ability to forecast these phenomena makes possible to exploit the opportunity in a more effective way, because maintenance team can be ready to get prepared in advance and perform Maintenance tasks more effectively (Ni et al., 2015).
- Active MOW: it's the maximum time window during which one can actively shutdown one machine for preventive maintenance without violating the system production requirement by utilizing the inventories in the downstream buffers (Gu et al., 2015), so the knowledge of the behavior of the buffers is essential. It's also crucial to take into consideration the possibility of a failure happening during the execution of the maintenance task, in order to avoid the case of having not enough personnel to cope with it. The big advantage of this method is the chance to have more opportunities, not related just to machine downtimes.

2.3.2 Buffers role

Buffers require a special mention, because they have a great influence on MOWs, as it possible to realize from the previous active MOW description. Many times researchers studied buffers, trying to make them as lean as possible, to reduce inventory levels and consequently inventory costs, but larger buffers can provide more short-term maintenance opportunities through longer MOWs.

From a production rate point of view, buffers improve system performance, as it's well known their decoupling effect between unreliable machines, that helps making an unbalanced line less critical. Usually the production rate has an asymptotic behavior with respect to buffer capacity, so it is a common approach to look for the minimum level of buffer capacity (which means minimum effective investment in buffer capacity) that can provide the maximum throughput, achieving, in other words, a sort of trade-off between throughput and buffer capacity.

Not acquiring a too large and unnecessary buffer capacity is important even from a quality and lead time perspective. From a quality point of view, with smaller buffer it's easier to identify defects and limit their propagation. From a lead time point of view, smaller buffer correspond to a shorter lead time, as stated by the Little's law.

$$W = \frac{L}{\lambda}$$

W is the waiting time (lead time), directly proportional to the number of customers L (buffers capacity) and inversely proportional to the arrival rate λ.

A trade-off between throughput and buffer capacity is therefore very important, especially in companies dealing with deteriorating or perishable products, which can not sustain high lead times.

Moreover, most modern manufacturing system are made of a combination of serial and parallel structures, resulting in a great complexity, even if in many research works the system considered is simplified in a serial configuration.

2.3.3 Minor maintenance activities

As previously suggested in 2.2.2 in the TPM section, the idea behind this thesis is to exploit opportunities to make possible for machine operators to execute autonomously some relatively simple maintenance tasks. TPM has an high consideration of the contribution that every production operator can bring to productivity, because the operator himself can act as the an immediate 'sensor' of the behavior of his machine, and then perform a maintenance action or inform the maintenance crew.

These tasks will be called minor maintenance (MM) actions.

In order to make this possible it is required to provide practical and theoretical skills to operators about the equipment they are working with, and to motivate and sensitize them to continuously and effectively pay attention to all the signs and symptoms of anomalies, in order to prevent worse problems. A strict collaboration between maintenance and production teams is necessary to perform this kind of policy in an effective way.

Figure 2.16: Steps to develop an effective autonomous maintenance.

- Step 0 is about increasing the understanding of a machine components and functions, in order to define skills and knowledge required from an operator to work on such machine.
- Step 1 detects problems of a machine trough a complete inspection, usually combined with a cleaning activity in case of a non-new machine, in order to finally set some standards for the unit under investigation.
- Step 2 finds out all the possible external factors that can threaten the unit behavior and eliminates them. It is also about the elimination of inaccessible areas, aiming to make possible to reach any part of the unit that requires maintenance, in order to simplify the actions and reduce the time needed for execution.
- Step 3 develop provisional standards for each MM activity that will be done on the unit.

- Step 4 establish final standards and all the instructions of workers' training, which will include equipment parts and functions of interest, possible problems, corrective actions, correct methodology and criteria of execution.

Finally a list of common MM activities is here provided, inspired by the one-minute inspection method proposed by Fitch (2007) in the context of autonomous maintenance:

- Visual inspection of the condition of the lubricant (e.g. color, transparency, foams, emulsions, presence of undesired substances, signs of deterioration, etc).
- Check of the status of the lubricant system.
- Measurement of oil levels.
- Oil change.
- Check valves.
- Check of spills and leakages (e.g. from seals, fittings, gaskets, etc).
- Check of process parameters (e.g. pressure, flow, temperature, voltage, etc).
- Cleaning (dirt causes degradation and could make defects detection more difficult).
- Check and cleaning of filters.
- Check and cleaning of sensors.
- Control of vibration and noise levels (e.g. of couplings, bearings, fans, motors, levers, etc), by 'ear' or dedicated instruments.
- Check bolts tightening, especially when subjected to vibration.
- Switching of service lights (e.g. a light that indicates when a machine is working, if not already integrated in the machine).
- Check tension of transmission belts.
- Check for wear and corrosion.

2.3.4 Priority rules

Maintenance operations greatly influence production performances in manufacturing systems. Usually maintenance decisions are made over a long term point of view, based on available data analyzed in statistical way. The methods used for taking long term decisions are not applicable on a short term perspective, which is the perspective of opportunistic maintenance. Therefore the analysis should use as input data not historical and statistical data, but real-time information collected in the manufacturing system. A short term analysis is needed to react dynamically to sudden changes in the systems status, in order to exploit maintenance resources efficiently and reduce improper or unnecessary activities. Therefore prioritization among available tasks is crucial.

The existing research on maintenance tasks prioritization has three major limitations:

- Focus is usually put only on long term problems while short-term dynamics are ignored.
- The relationship between production and maintenance tasks is not so clear.
- Decisions are often made by heuristic rules.

In real cases the maintenance priority assignment methods are often heuristic or based on common sense and the experience of the decision maker. These rules generally are not the best way to choose between tasks and could result in avoidable downtimes, failures and consequent production loss. Saaty (1990) developed an analytical hierarchy process to determine priority tasks, where the decision is based on the summation of weighted scores, assigned to each task. An analytical hierarchy process is used also in Wang et al. (2007), with a modification to take into account the uncertain judgement of decision maker. Yang et al. (2007) developed methodologies to get optimal maintenance tasks priority according to the dynamic layout of production systems, work-in-process allocations and the online production situation, in order to reach a higher productivity. However this method requires simulation, so it's not effective when there is need for a quick reaction, and was not proven to be able to order actions in an optimal sequence. Li and Ni (2009) modelled a method for priority assignment based on the introduction of an impact factor, obtained through data driven bottleneck detection and maintenance opportunity window. A prioritization of the maintenance actions on bottleneck machines made possible an higher production level. Ni and Jin (2012) further developed this last decision tool introducing the issue of the management of maintenance crew available.

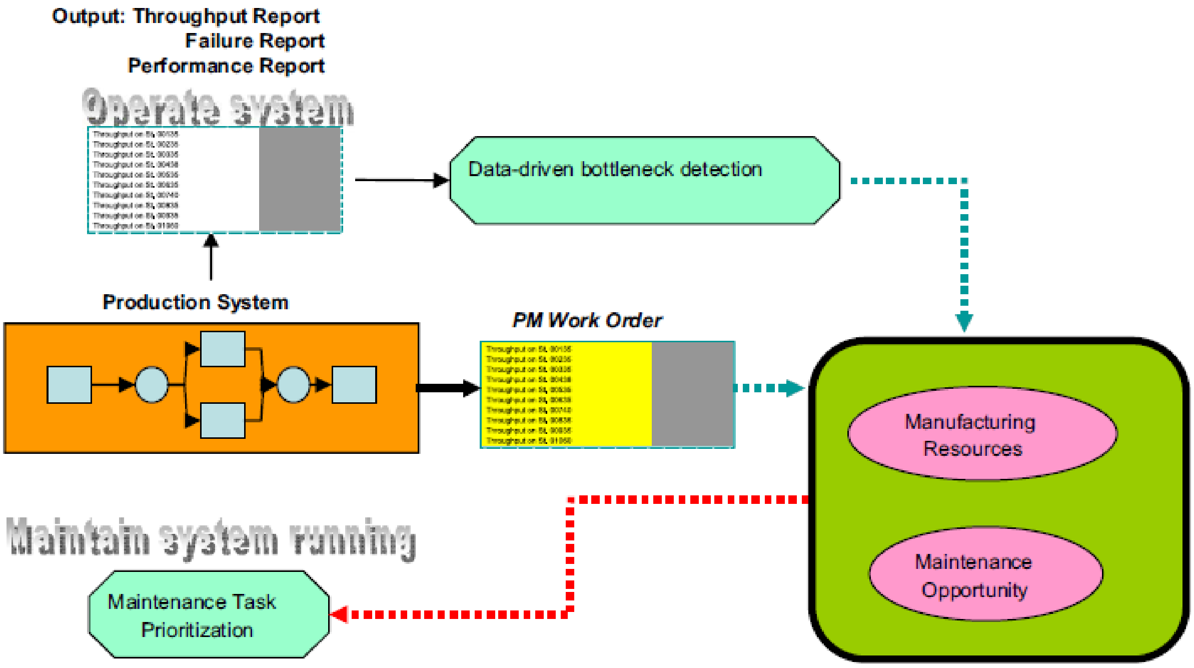


Figure 2.17: Short-term decision support system for maintenance task prioritization (Li and Ni, 2009).

Here is a now summary of the most commonly utilized rules:

- Longest processing time first, in order to maximize the exploitation of the opportunity and reducing the idle times.
- Shortest processing time first, in order to execute more than one task in the same window, doing maintenance on as much units as possible.
- First come first serve, meaning that the action performed farthest in the past will have the highest priority.
- Static heuristic, where priority is assigned according to the importance of the intervention. Some factors to be considered to evaluate the importance could be the relevance of an action, the possible consequences of a missed execution, the impact on the production rate, the needs of the maintenance crew.

Chapter 3

Model

3.1 General system description and hypothesis

Here a description of the modeled system is provided, explaining machines and buffer behaviors and features.

The system is a two-stage production line composed by machines M_1 and M_2, separated by an intermediate buffer with finite capacity B. M_1 is the upstream machine and M_2 the downstream machine. Material flows from outside the system to M_1, then to B, then to M_2 and finally leaves the system.

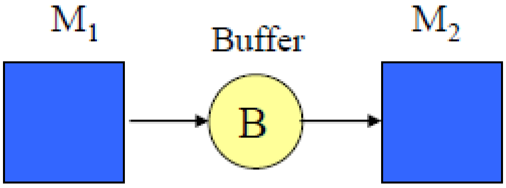


Figure 3.1: Two-stage production line.

In general a machine is characterized by two values: failure rate, that states the frequency with which a machine fails, and repair rate, that states the frequency with which a machine gets repaired. In this study the first machine is considered totally reliable (modelled with a very low failure rate and a very high repair rate, that correspond to an efficiency in isolation $e_1 > 0.99$) but has to undergo some minor maintenance (MM) activities of a duration assumed known and deterministic. At the moment only one MM activity will be considered. The second machine is instead an unreliable machine subjected to sequential failures and repairs, based on the values of its failure and repair rates.

In order to better understand the following description of the model, it’s worth to remind some definitions and make some assumptions explicit:

- Starvation is the condition in which a machine does not have parts available to be processed.
- Blocking is the condition in which a machine can’t process any other part because there is no space available in the downstream buffer to store an additional processed part.
- It’s assumed that there are always material available at system input and storage space available at system output, so the first machine is never starved and the second machine is never blocked.
- Blocking Before Service convention is considered, so machines can start processing a part only if there is an available storage place in the following buffer.
- Processing times of machines are deterministic and equal for each machine of the line. They are scaled to unity.

- A failure mode is a characterization of the way a machine fails. We consider only operational dependent failures, meaning that they can occur only if a machine is operational and it is processing a part. Time dependent failures are not considered.
- A machine fails or gets repaired at the beginning of the time unit, buffer content is changed accordingly at the end of the time unit.
- Failure and repair rates are derived from Times To Failure (TTF) and Times To Repair (TTR), assumed geometrically distributed.
- Maintenance is modelled as 'perfect maintenance', so a maintenance action brings back the system to an 'as good as new' condition since we assume a system not affected by degradation.
- Real time data are available.

In this model M_1 can be in three status (UP, DOWN and MAINTENANCE) and M_2 in two status (UP and DOWN).

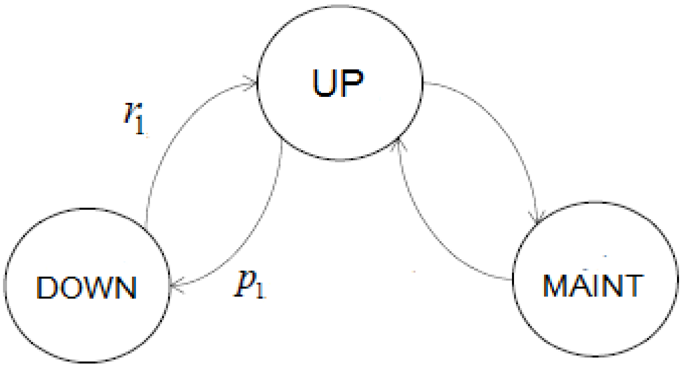


Figure 3.2: Possible states of M_1.

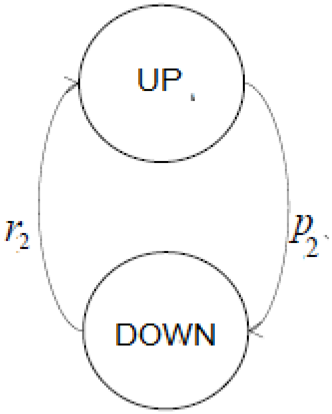


Figure 3.3: Possible states of M_2.

However, as M_1 is modelled as totally reliable, its DOWN state will have a probability very close to zero. Considering the previous assumptions, it's also possible to note that only M_2 can be affected by starvation and only M_1 can be affected by blocking.

3.2 Opportunistic policy

As the system is subjected to maintenance, it's required to define which kind of maintenance is executed on the system. When a machine fails, a corrective maintenance action will be executed on such machine. In this case, because of the reliability of M_1, only M_2 can undergo corrective maintenance interventions. It's possible to take advantage of these intervention to execute, in an clearly opportunistic way, MM actions on the first machine. The execution of the MM activities will be evaluated also in relationship to the buffer content, so it will be possible to stop M_1 for MM tasks even if M_2 will be still working. The condition is having a sufficient number of parts in the intermediate buffer to be processed by M_2, because these parts must require a total processing time that can cover the duration of the MM action. This policy corresponds to accept an higher risk of lowering the production rate and increasing the starvation probability of the system.

The aim is to find out the starvation risk (or starvation probability) and throughput (TH) of the system subjected to MM activities carried out during the production time, that will give a measure of the consequence of the implementation of the method. In other words the target is to find out if the application of this policy gives benefits (for example in terms of non-production hours dedicated to MM tasks saved) at an acceptable level of risk, looking for the right mix of parameters which makes it possible (buffer capacity, buffer level at which MM activities are activated).

The situations compared are the ones in next two figures.

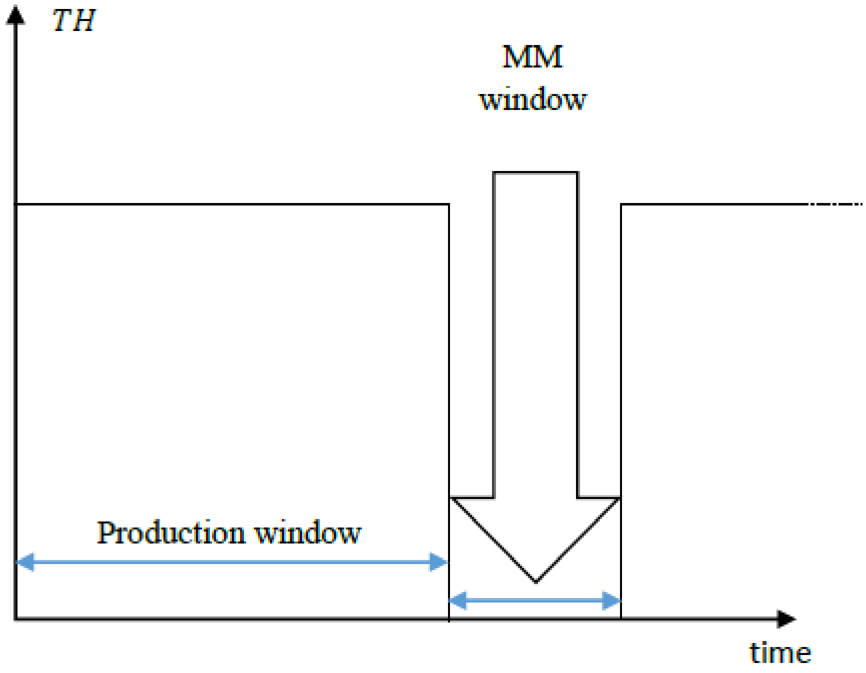


Figure 3.4: Baseline scheduling situation.

In the baseline situation, production time and MM tasks time are well separated and defined, with maintenance time corresponding for example to an interval between shifts, nights or weekends. TH is therefore influenced only by the system reliability.

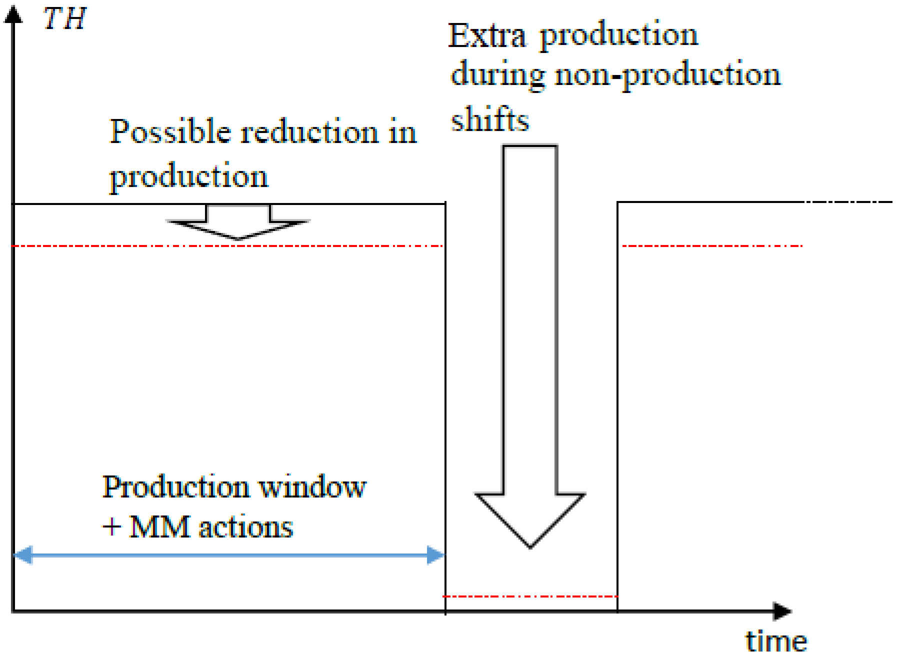


Figure 3.5: Policy scheduling situation.

With the opportunistic policy TH can be lowered by the risk related to MM actions. The time assigned in the baseline situation to the MM window (Figure 3.4) becomes available, and can be exploited for extra production, as in Figure 3.5, backlog production or can be even just considered as working hours, and therefore money, saved without performing any extra activity.

3.3 The method

It's now clear that the time for MM actions is provided by the parts already available in the buffer and the non-total reliability of the second machine. In the situation proposed, the risk is strictly related to the distribution of the lead time (LT) of the parts in the buffer (probability that the lead time is equal to a certain number of time units), which represents the time available for the execution of the MM task, and must be compared to the deterministic duration of the MM activity itself. So it's under evaluation the possible risk and consequence related to the fact that the opportunity window is shorter than the MM action, resulting in the starvation of M_2.

3.3.1 Lead time analysis

Before coming to the main method, the analysis starts from the computation of the LT distribution following the approach proposed by Colledani et al. (2014).

A Markov chain (or process) is a kind of probabilistic dynamic system (which is a kind of stochastic process) in which the future behavior depends on the present only, not on the past (Markov memorylessness property).

An absorbing Discrete Time Markov Chain (DTMC) can be used to characterize the lead time of a buffered two-machine line subject only to corrective maintenance, where the states are defined by the buffer level and the states of M_2.

An absorbing Markov chain is a Markov chain in which every state can reach an absorbing state. An absorbing state is a state that, once entered, cannot be left. In this case the absorbing state correspond to (0,U).

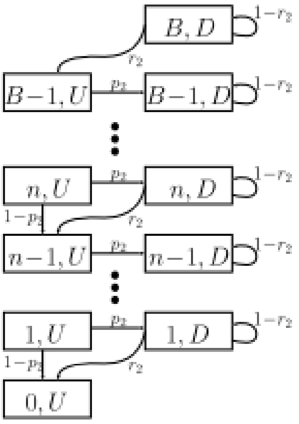


Figure 3.6: Absorbing Markov chain.

The two steps of the method consist in the calculation first of the time to absorption for each state of the DTMC and then of the initial state probabilities. Once these quantities are available, LT can be finally calculated. It can be noticed that the time to absorption probabilities depend just on the buffer capacity (B) and the performance of the second machine, while the initial state probabilities depend also on the first machine performance. Some LT distribution cases are here provided.

Parameter	***Value***
B	10
p_2	0.01
r_2	0.1

Table 3.1: Parameters of case 1.

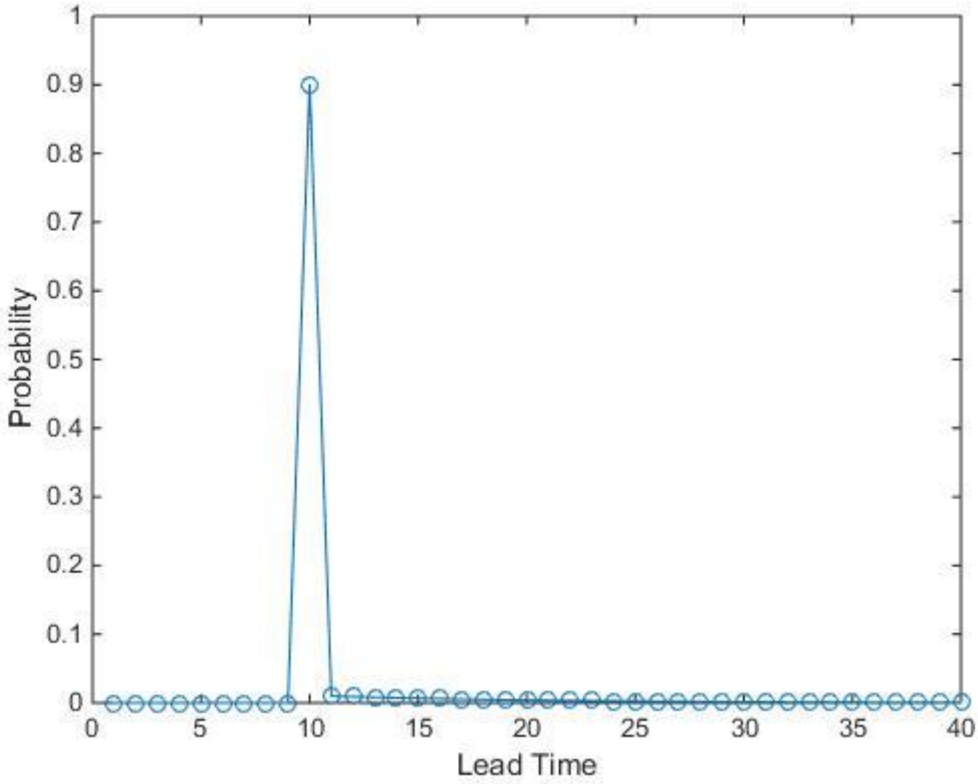


Figure 3.7: Lead time distribution, case 1.

Parameter	*Value*
B	10
p_2	0.05
r_2	0.1

Table 3.2: Parameters of case 2.

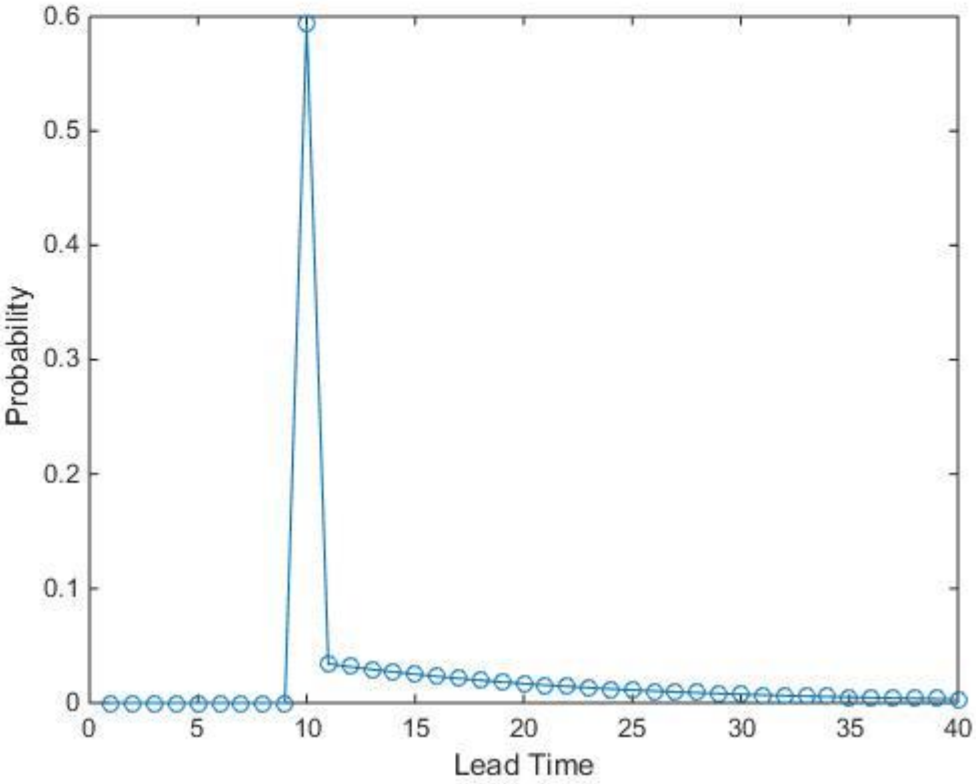


Figure 3.8: Lead time distribution, case 2.

Parameter	***Value***
B	10
p_2	0.01
r_2	0.2

Table 3.3: Parameters of case 3.

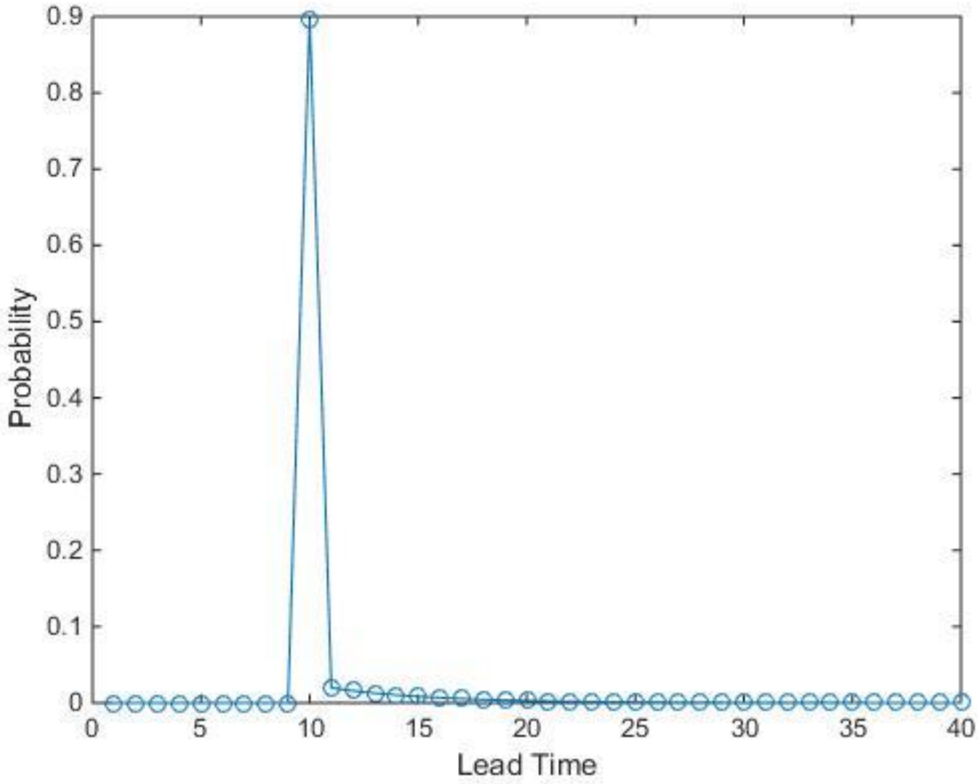


Figure 3.9: Lead time distribution, case 3.

Parameter	***Value***
B	10
p_2	0.05
r_2	0.2

Table 3.4: Parameters of case 4.

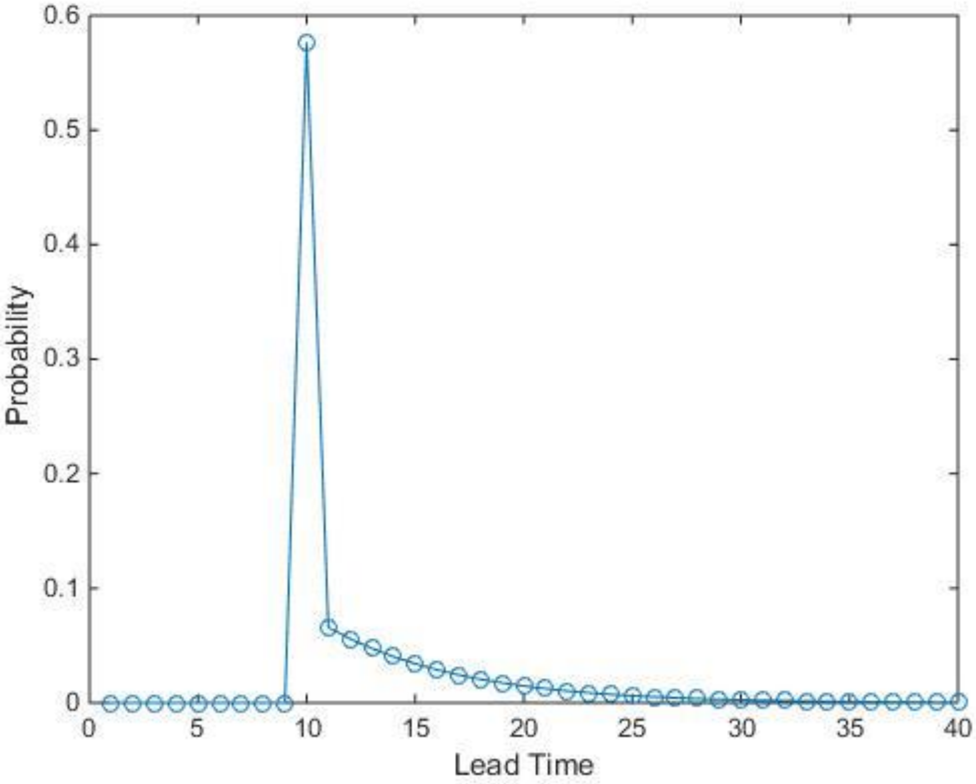


Figure 3.10: Lead time distribution, case 4.

A feature of this method used for the computation of the LT distribution is that it relies on two different LT distribution, namely p and q: p is defined starting with M_2 up (green) and q starting with M_2 down (red). Examples of these distributions are here provided, referred to the four previous LT distributions.

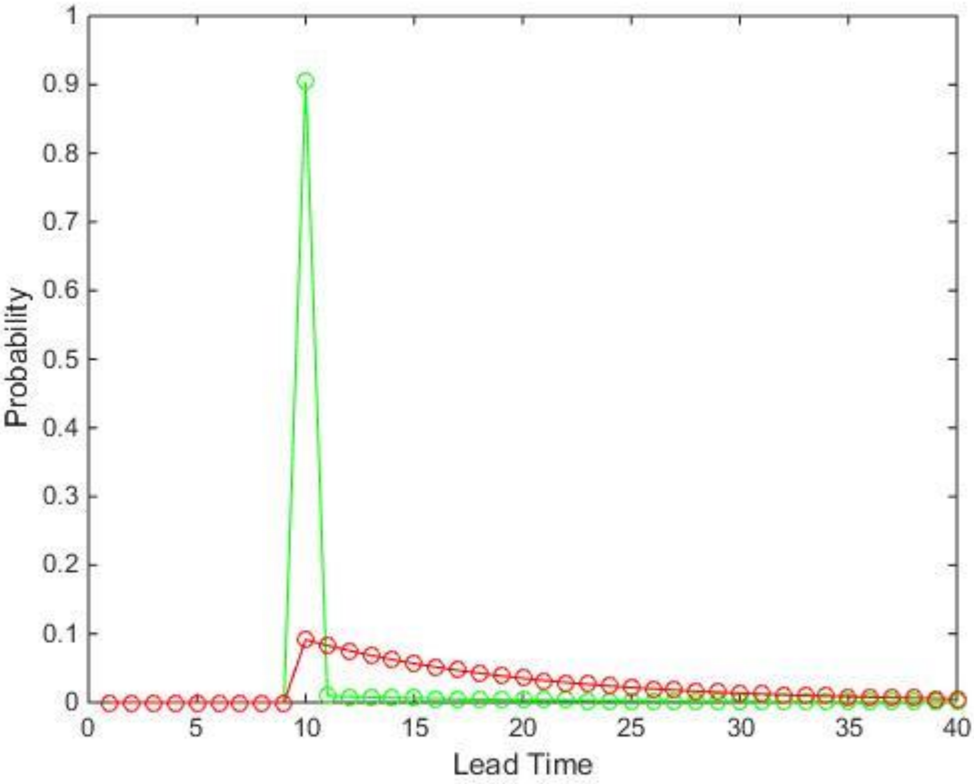


Figure 3.11: p and q distribution, case 1.

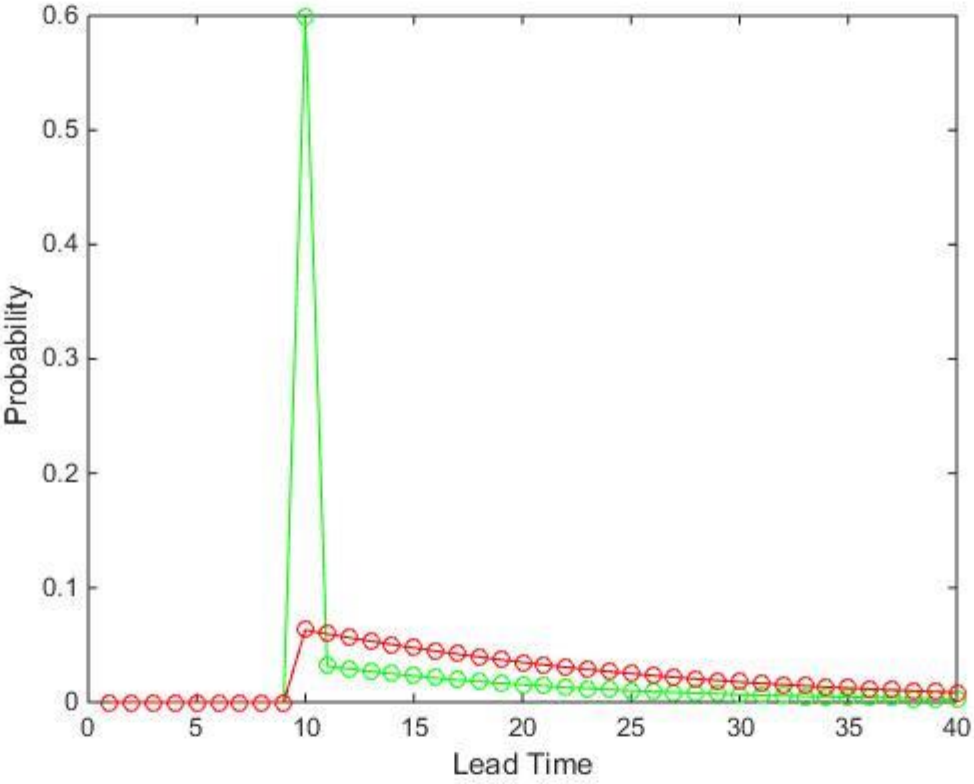


Figure 3.12: p and q distribution, case 2.

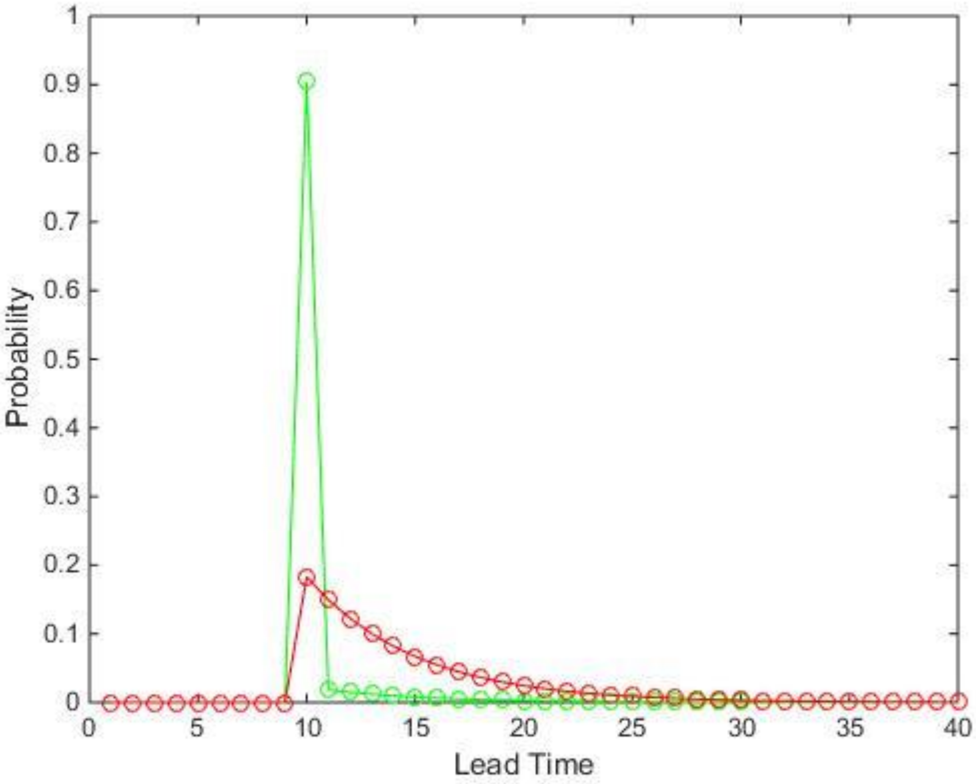


Figure 3.13: p and q distribution, case 3.

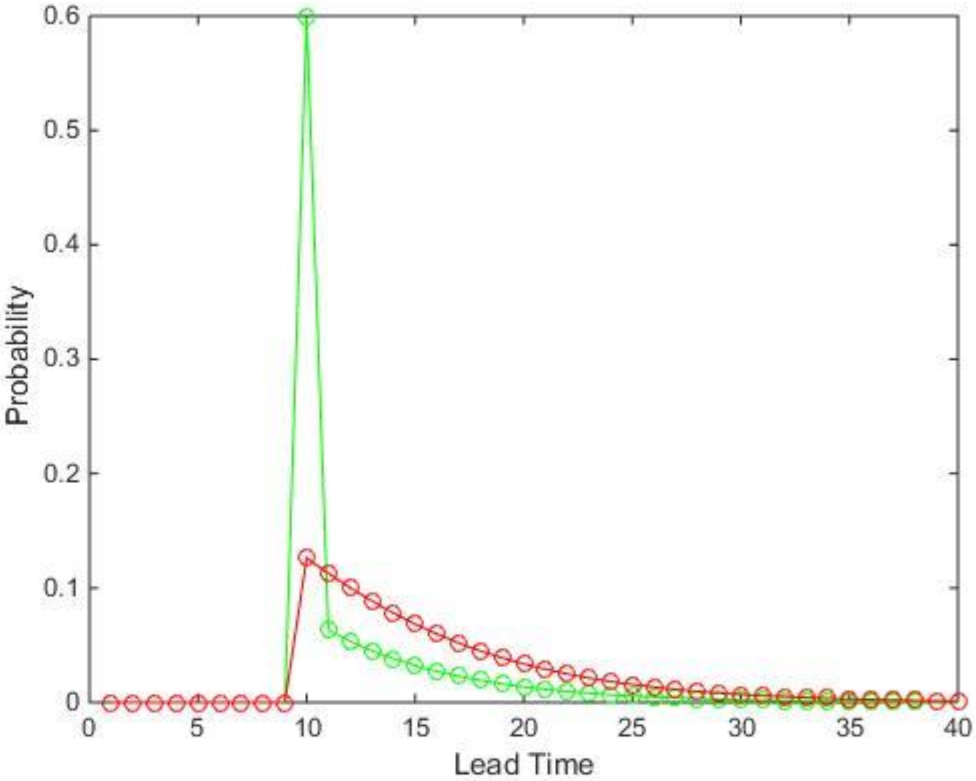


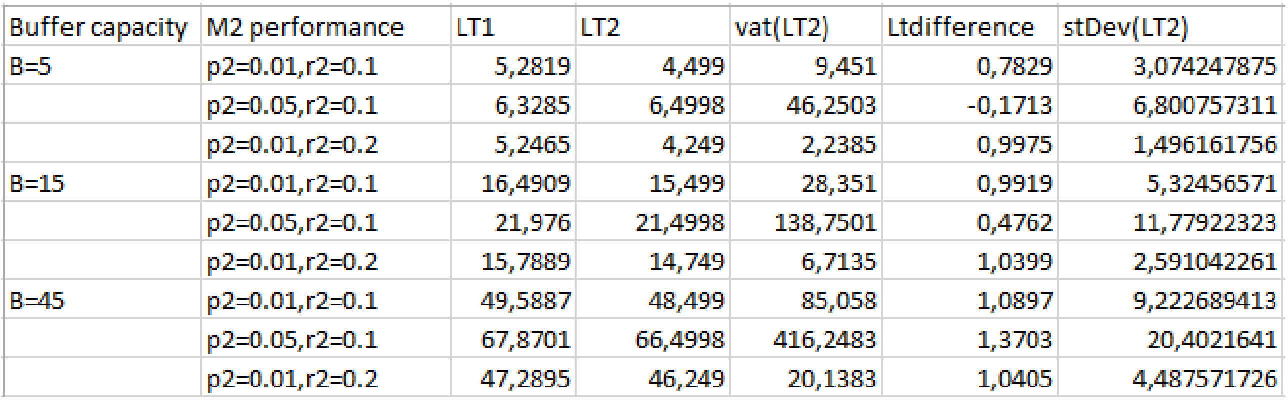
Figure 3.14: p and q distribution, case 4.

It’s easy to observe that, considering machines with normal performance, with p the LT is always more probable to be shorter with respect to q, even increasing p_2, r_2 or both the rates together, while keeping the buffer constant, as in figures 3.10, 3.11, 3.12. It can be also noticed that increasing p_2 the p distribution goes towards the q one, in particular in the tail zone, and increasing r_2 the first values of q goes towards the initial peak corresponding to the first non-zero value of p.

The p and q distribution will be fundamental in the modelling of the policy, together with the throughput of the system (by now there still isn’t any policy applied), which will be later compared with the TH of the system subjected to the maintenance policy.

About the calculation of the lead time, a check was made between the results of this method and the result obtained with the method proposed in the book Finite Markov Chains (Kemeny and Snell), where the lead time is calculated together with its own variance and standard deviation.

LT1 refers to the method used in this work, LT2 to the book method. LT1 was calculated summing each possible LT value multiplied by its own probability. The tests were made with the following combinations of parameters: p_2=0.01, r_2 2=0.1 / p_2=0.05, r_2=0.1 / p_2=0.01, r_2=0.2 each repeated 3 times for the buffer capacities B=5, B=15, B=45.



Buffer capacity	M2 performance	LT1	LT2	vat(LT2)	Ltdifference	stDev(LT2)
B=5	p2=0.01,r2=0.1	5,2819	4,499	9,451	0,7829	3,074247875
	p2=0.05,r2=0.1	6,3285	6,4998	46,2503	-0,1713	6,800757311
	p2=0.01,r2=0.2	5,2465	4,249	2,2385	0,9975	1,496161756
B=15	p2=0.01,r2=0.1	16,4909	15,499	28,351	0,9919	5,32456571
	p2=0.05,r2=0.1	21,976	21,4998	138,7501	0,4762	11,77922323
	p2=0.01,r2=0.2	15,7889	14,749	6,7135	1,0399	2,591042261
B=45	p2=0.01,r2=0.1	49,5887	48,499	85,058	1,0897	9,222689413
	p2=0.05,r2=0.1	67,8701	66,4998	416,2483	1,3703	20,4021641
	p2=0.01,r2=0.2	47,2895	46,249	20,1383	1,0405	4,487571726

Table 3.5: Results from the two methods.

The punctual value of the LT results always very close (LT difference always smaller than 1.4 time units), and the value obtained with the first method always falls in the variance interval of the book method. This demonstrate the correctness of the method used in this work.

3.3.2 Opportunistic policy model

Now a description of the core software is provided. The software, developed in Matlab, requires some input data by the user: failure and repair rate of the two machines, buffer capacity, buffer level for the activation of the policy with M_2 up (n_1), buffer level for the activation of the policy with M_2 down (n_0) and the deterministic duration of the MM activity (tmm). Obviously n_0 and n_1 can’t exceed the buffer capacity, and n_1 should not be lower than n_0, because, starting at the same buffer level and with M_2 working, the additional time spent in the maintenance of M_2 will not be available, at least at the beginning, and it’s not sure that M_2 will fail during the MM action.

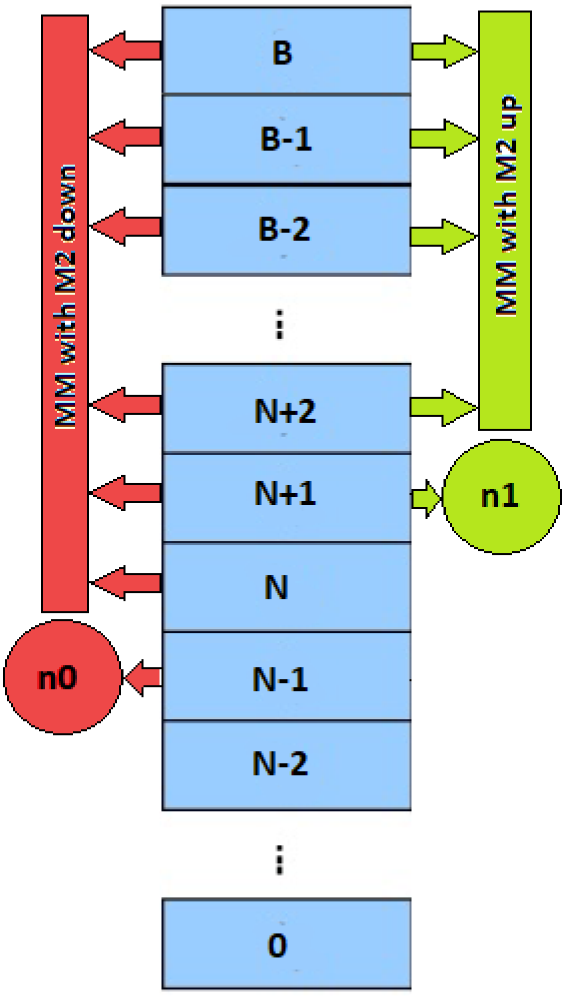


Figure 3.15: Behavior of the policy at activation levels level n_0 and n_1.

First the software builds the probability matrix P of the system without considering the policy. A state is defined by three quantities, the states of the two machines and the number of parts in the buffer. There are four possible state for each buffer level (UP-UP, UP-DOWN, DOWN-UP, DOWN-DOWN). The related Markov chain is the one in next figure.

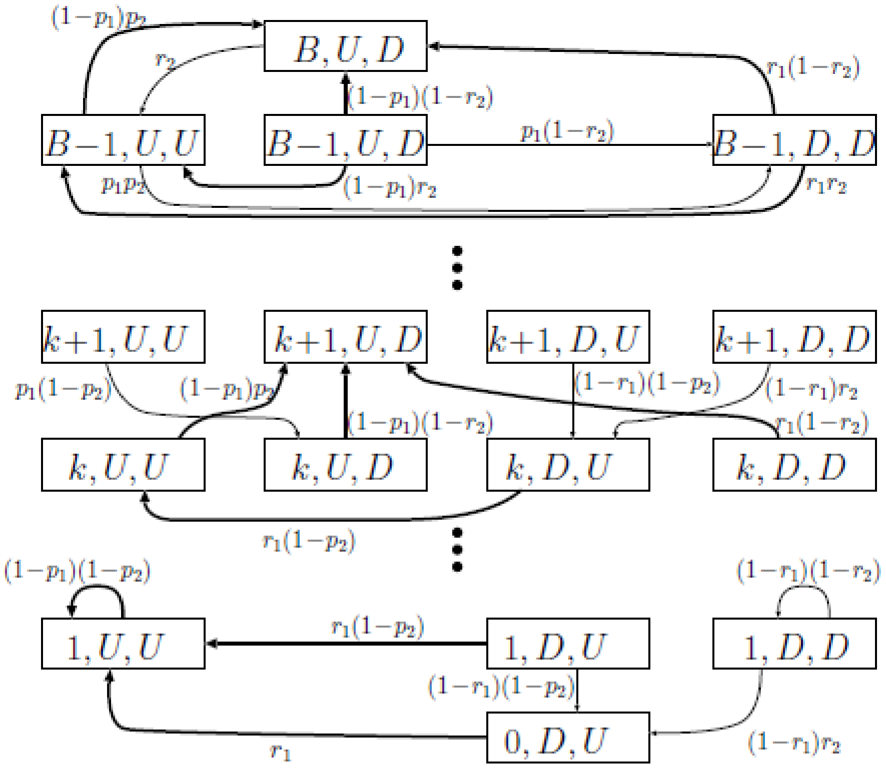


Figure 3.16: Initial Markov chain.

After being created, matrix P will be modified in order to take into account the greater probability, with respect to the base case, to have production losses and increased starvation probability due to the policy. This is done adding some new states, which will be referred to as ‘starved’ states, to the original ones, in order to consider the eventuality of running out of buffer content during an MM action. Therefore at levels equal or above n_0 (with M2 down) and n_1 (with M2 up) there will be two possibilities: move to a starved state or move to a non-starved state with a certain buffer level, according to the p and q distributions calculated for the buffer level under evaluation.

All the steps from the original to the final version of P are largely explained in Appendix A.

Finally P gets the following shape:

$$\mathbf{P} = \begin{bmatrix} \mathbf{A} & \mathbf{B} \\ \mathbf{C} & \mathbf{D} \end{bmatrix}$$

Figure 3.17: Final shape of the probability matrix P.

P will be composed of four parts:

- A is made of the transition probabilities between the original states of matrix P, but with their values modified according to the policy. Therefore it has the same

size of the original P, but the values in the rows where opportunistic maintenance is activated are different form the original matrix.
- B holds the transition probabilities from original states to the new starved states generated by the policy implementation.
- C contains the transition probabilities from the new starved states to the original ones.
- D holds the transition probabilities between the new starved states.

So the final matrix P will be larger than the original one, due to the new starved states that expand the original size through the three matrices B, C, D. All the features of matrices A, B, C and D are explained more in detail in Appendix A.

Chapter 4

Results

4.1 Model convergence

Some of the many cases tested are here provided, in terms of TH and Starvation Probability vs Iterations, where the number of iterations is set to 10000. From the results it will be possible to observe that sometimes convergence can be reached with many less iterations (even less than 1000 in some cases, hence the iteration axis in not always 10000 units long because graphs are cut in order to focus on their most interesting part), but with 10000 the computation speed is anyway very high.

B, $n_{1,}$, n_0, tmm are varied. Different types of failure rates and repair rates for M_2 are considered in order to model machines more or less reliable, according to Table 4.1. Failure rate is referred to two cases, one corresponding to a machine affected by frequent failures and one by rare failures. Also repair rate has two cases, low or high according to the easiness of getting the machine repaired.

	Rare	**Frequent**
Failure rate p_2	**0,001**	**0,01**

	Low	**High**
Repair rate r_2	**0,1**	**0,2**

Table 4.1: Standard values considered for failure and repair rates.

The examples were also compared to a simulation, developed in Matlab, which tested the policy over a period (Tsim) 10000 time units long. Simulation was run 20 times (r) for each example, averaging then replicates results to obtain TH and starvation probability which, if equal to the ones of the Markov chain model, prove the correctness of the method implemented. Through simulation is provided also the number of times that maintenance is activated (TMA) over the simulation period, averaged again over the 20 replicates.

- Case 1

Parameter	***Value***
B	5
p_2	0.01
r_2	0.1
n_1	5
n_0	4
tmm	3
Iterations	10000
Tsim	10000
r	20

Table 4.2: Parameters of case 1.

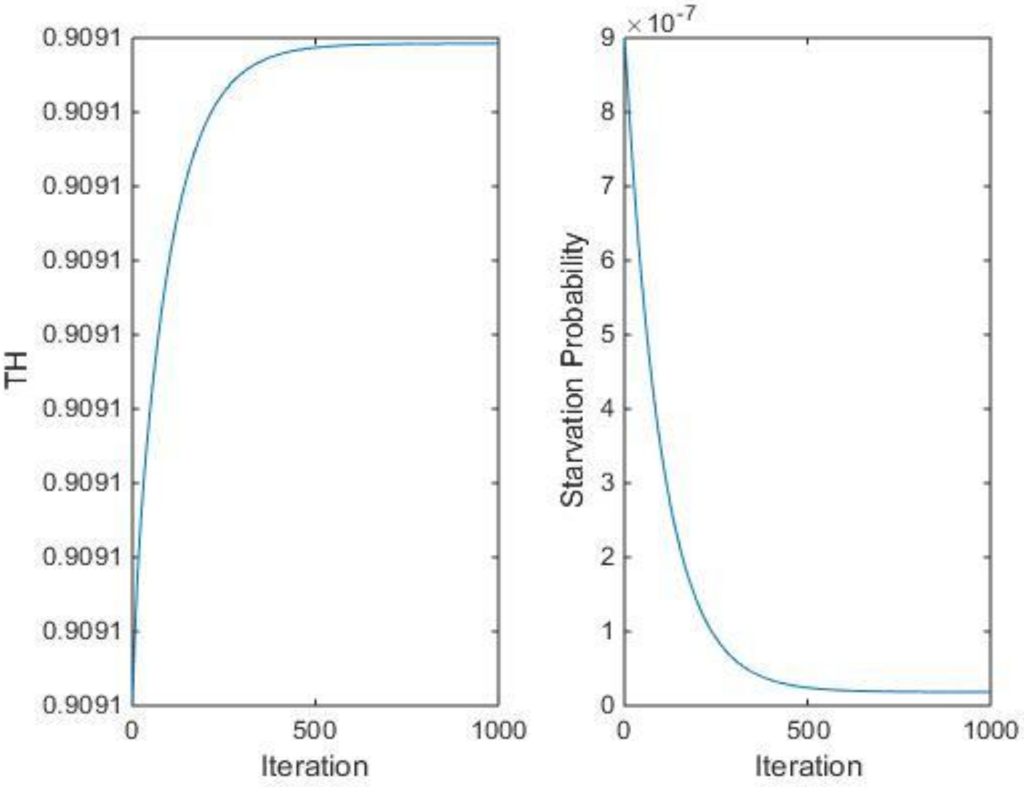


Figure 4.1: Case 1 performances convergence graphs.

	TH	**Starvation Probability**	**TH lost**	**TMA**
Analytical method	**0.9091**	**1.8E-08**	**-1.67E-04**	**-**
Simulation method	**0.9092**	**0**	**-**	**689**

Table 4.3: Comparison of case 1 results.

- Case 2

Parameter	***Value***
B	5
p_2	0.01
r_2	0.1
n_1	3
n_0	2
tmm	5
Iterations	10000
Tsim	10000
r	20

Table 4.4: Parameters of case 2.

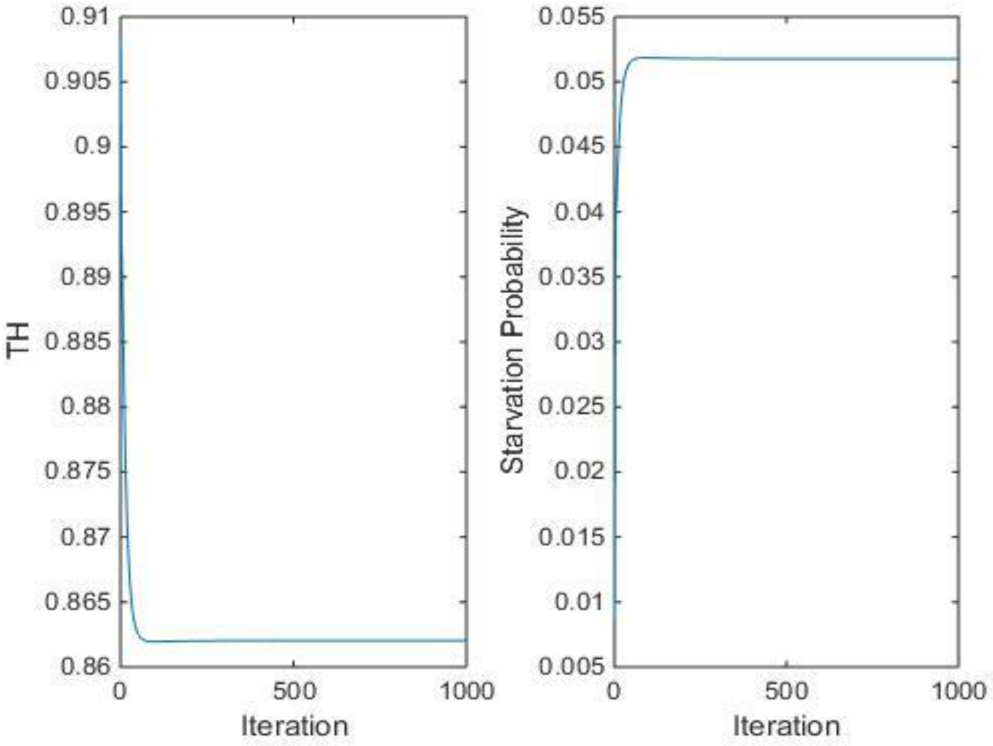


Figure 4.2: Case 2 performances convergence graphs.

	TH	**Starvation Probability**	**TH lost**	**TMA**
Analytical method	**0.8620**	**0.0518**	**-0.0471**	**-**
Simulation method	**0.8643**	**0.0515**	**-**	**922**

Table 4.5: Comparison of case 2 results.

- Case 3

Parameter	***Value***
B	5
p_2	0.01
r_2	0.1
n_1	3
n_0	2
Tmm	8
Iterations	10000
Tsim	10000
R	20

Table 4.6: Parameters of case 3.

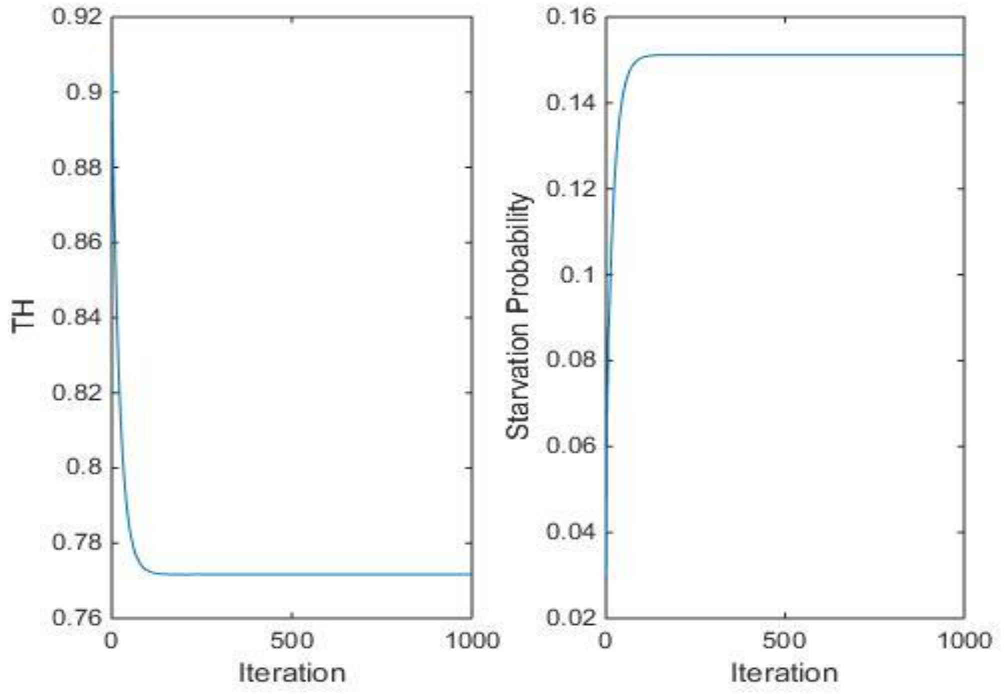


Figure 4.3: Case 3 performances convergence graphs.

	TH	**Starvation Probability**	**TH lost**	**TMA**
Analytical method	**0.7717**	**0.1511**	**-0.1374**	**-**
Simulation method	**0.7683**	**0.1537**	**-**	**827**

Table 4.7: Comparison of case 3 results.

- Case 4

Parameter	***Value***
B	5
p_2	0.01
r_2	0.1
n_1	5
n_0	5
Tmm	8
Iterations	10000
Tsim	10000
R	20

Table 4.8: Parameters of case 4.

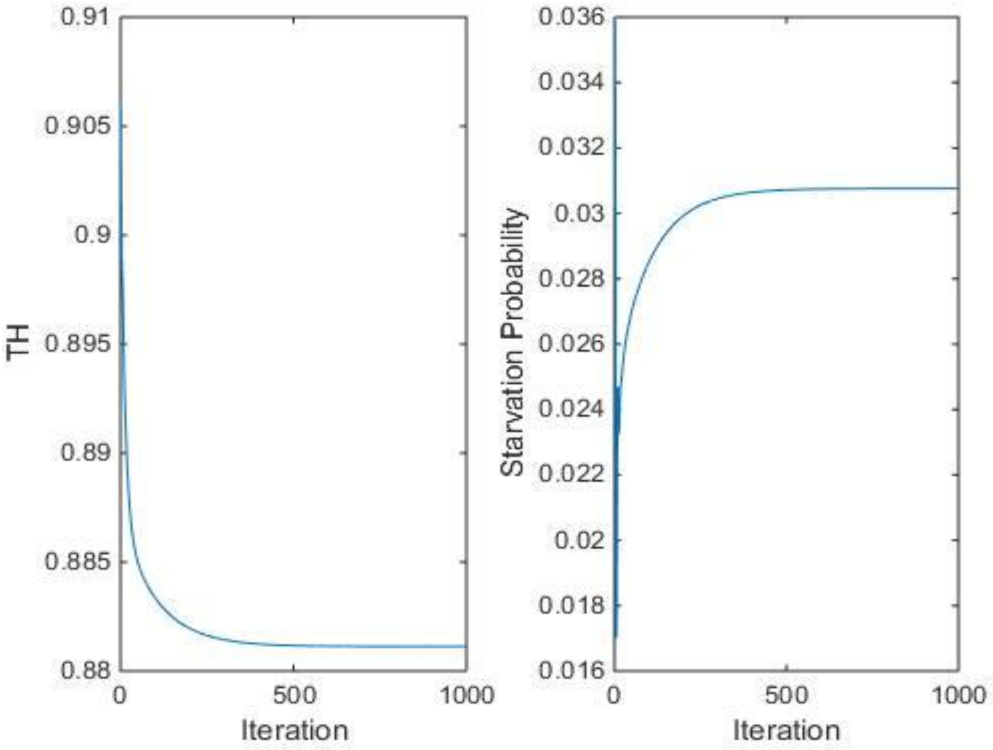


Figure 4.4: Case 4 performances convergence graphs.

	TH	**Starvation Probability**	**TH lost**	**TMA**
Analytical method	**0.8811**	**0.0308**	**-0.0433**	**-**
Simulation method	**0.8815**	**0.0304**	**-**	**346**

Table 4.9: Comparison of case 4 results.

- Case 5

Parameter	***Value***
B	5
p_2	0.01
r_2	0.1
n_1	3
n_0	4
Tmm	4
Iterations	10000
Tsim	10000
R	20

Table 4.10: Parameters of case 5.

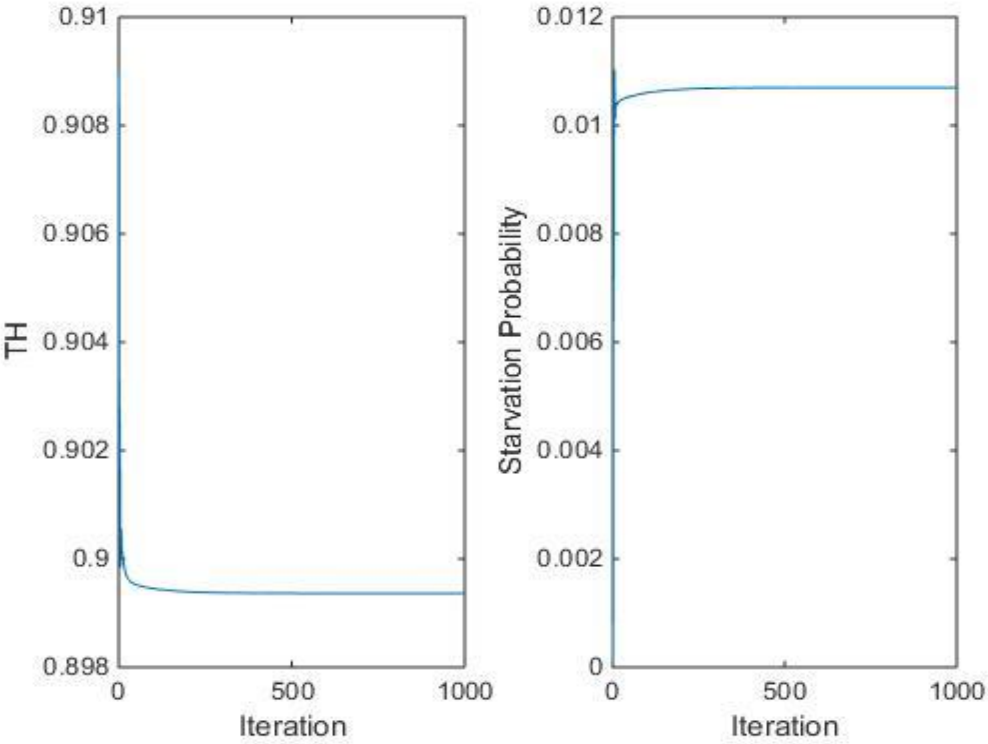


Figure 4.5: Case 5 performances convergence graphs.

	TH	**Starvation Probability**	**TH lost**	**TMA**
Analytical method	**0.8994**	**0.0107**	**-0.0097**	**-**
Simulation method	**0.8999**	**0.0105**	**-**	**574**

Table 4.11: Comparison of case 5 results.

- Case 6

Parameter	***Value***
B	6
p_2	0.001
r_2	0.1
n_1	5
n_0	2
Tmm	3
Iterations	10000
Tsim	10000
R	20

Table 4.12: Parameters of case 6.

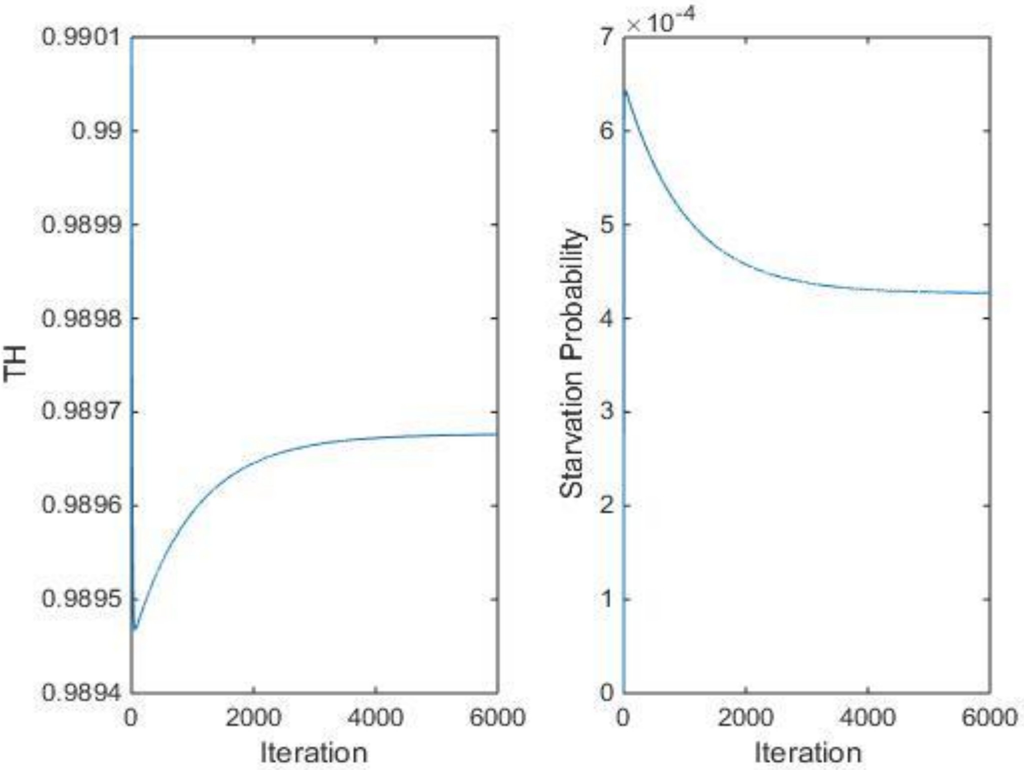


Figure 4.6: Case 6 performances convergence graphs.

	TH	**Starvation Probability**	**TH lost**	**TMA**
Analytical method	**0.9897**	**4.2E-04**	**-4.2E-04**	**-**
Simulation method	**0.9878**	**4.5E-04**	**-**	**137**

Table 4.13: Comparison of case 6 results.

- Case 7

Parameter	***Value***
B	20
p_2	0.001
r_2	0.2
n_1	10
n_0	6
Tmm	8
Iterations	10000
Tsim	10000
R	20

Table 4.14: Parameters of case 7.

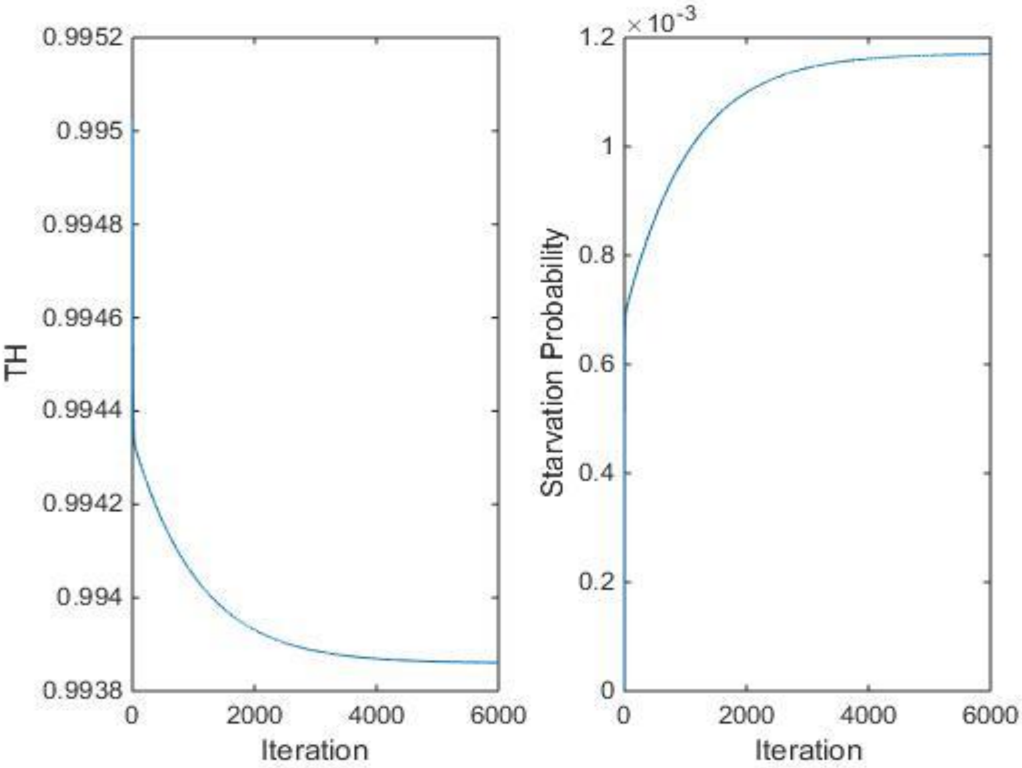


Figure 4.7: Case 7 performances convergence graphs.

	TH	**Starvation Probability**	**TH lost**	**TMA**
Analytical method	**0.9939**	**0.0012**	**-0.0012**	**-**
Simulation method	**0.9936**	**0.0012**	**-**	**16**

Table 4.15: Comparison of case 7 results.

- Case 8

Parameter	***Value***
B	20
p_2	0.01
r_2	0.2
n_1	10
n_0	6
tmm	8
Iterations	10000
Tsim	10000
R	20

Table 4.16: Parameters of case 8.

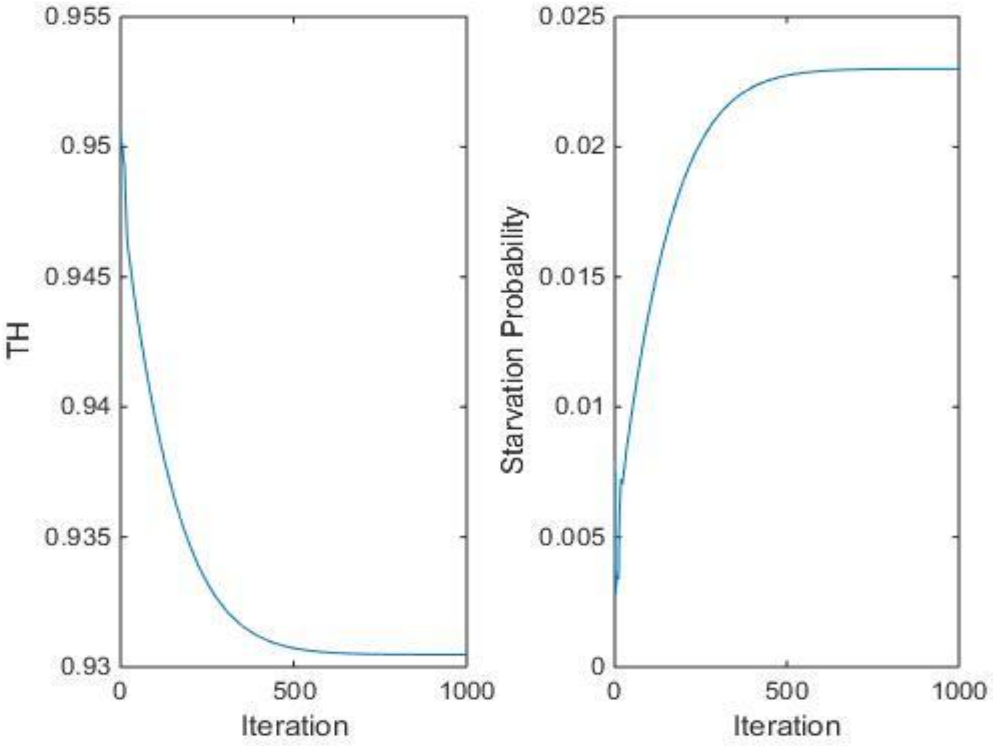


Figure 4.8: Case 8 performances convergence graphs.

	TH	**Starvation Probability**	**TH lost**	**TMA**
Analytical method	**0.9305**	**0.0230**	**-0.0219**	**-**
Simulation method	**0.9314**	**0.0226**	**-**	**44**

Table 4.17: Comparison of case 8 results.

- Case 9

Parameter	***Value***
B	40
p_2	0.01
r_2	0.1
n_1	30
n_0	20
Tmm	25
Iterations	10000
Tsim	10000
R	20

Table 4.18: Parameters of case 9.

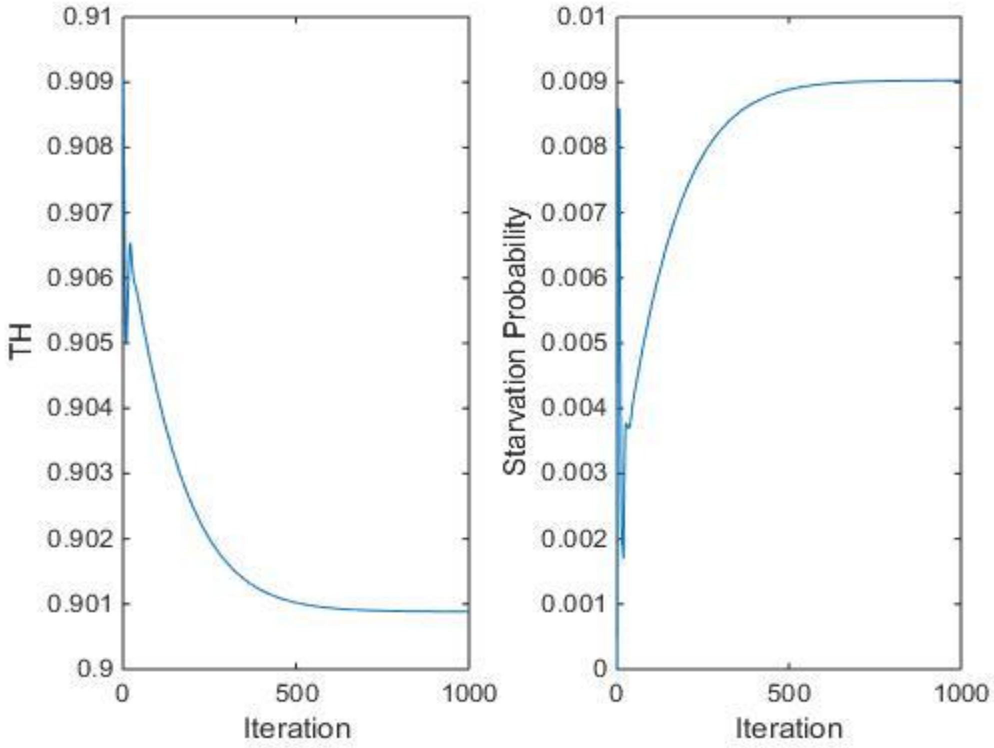


Figure 4.9: Case 9 performances convergence graphs.

	TH	**Starvation Probability**	**TH lost**	**TMA**
Analytical method	**0.9009**	**0.0090**	**-0.0082**	**-**
Simulation method	**0.9013**	**0.0093**	**-**	**66**

Table 4.19: Comparison of case 9 results.

- Case 10

Parameter	*Value*
B	42
p_2	0.001
r_2	0.2
n_1	40
n_0	30
tmm	35
Iterations	10000
Tsim	10000
R	20

Table 4.20: Parameters of case 10.

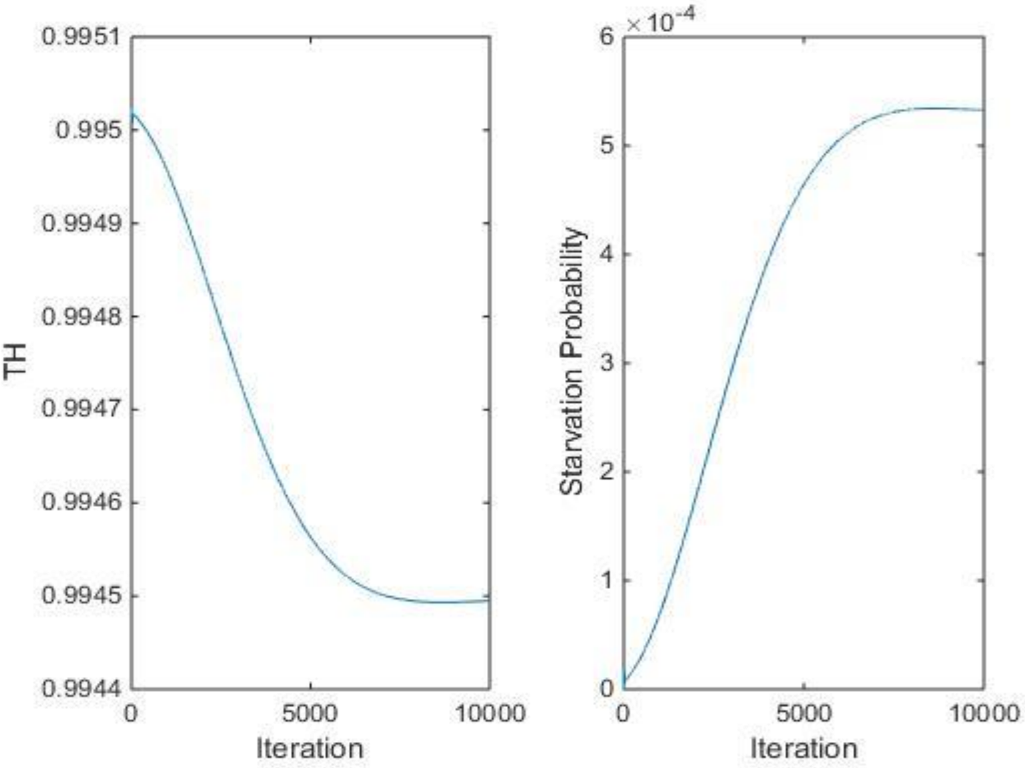


Figure 4.10: Case 10 performances convergence graphs.

	TH	**Starvation Probability**	**TH lost**	**TMA**
Analytical method	**0.9945**	**5.3E-04**	**-5.3E04**	**-**
Simulation method	**0.9946**	**3.8E-04**	**-**	**2**

Table 4.21: Comparison of case 10 results.

The main thing that is possible to observe is that, with 10000 or even less iterations, convergence is always reached, even if through different paths. The two outputs this study is dealing with, TH and starvation probability, seems to change with the parameters in a logical way, regardless of the failure and repair rates which seems to modify just the number of iterations needed to get to convergence.

- Increasing only n_1 they both improve.
- Increasing only n_0 they both improve.
- Increasing only tmm they both get worse.
- With a tmm smaller than the time required to process n_0 parts the performance are almost not affected by the maintenance policy (TH lost and starvation probability close to zero).
- With a tmm bigger than the time required to process n_0 and n_1 parts the performance can be heavily affected by the maintenance policy (high TH lost and starvation).

Next parts will give a better explanation of these observations.

The second important result is that, in each case tested, analytical and simulation performances differ for less than the 1%. This validates the model and states that it gives correct results, so it makes sense to proceed with this study using the Markov model developed as a solid base.

Moreover the TMA indicator shows how the various parameters influence the frequency of activation.

- Increasing n_0 TMA decreases.
- Increasing n_1 TMA decreases, even if its influence is lower than n_1.
- Increasing tmm TMA decreases.
- Increasing B TMA increases.

4.2 Analysis of the results

Relevant results in terms of TH and starvation probability behaviors obtained with the policy are here presented and discussed. Various buffer capacities B, MM activity durations tmm and activation levels n_0 and n_1 were considered. The previous classes of high/low failure and repair rates are again considered for the second machine, in order to generalize as much as possible the results obtained.
Behaviors have been studied both varying one at a time or more than one at a time all the six parameters (p_2, r_2, B, n_1, n_0, tmm) provided as input.
The base situation considered is the one in Table 4.22 and any variation will be clearly indicated in each example.

Parameter	***Value***
B	15
p_2	0.01
r_2	0.1
n_1	14
n_0	12
tmm	13
Iterations	10000

Table 4.22: Base parameters.

4.2.1 Variable repair rate

Variable r_2, from 0.05 to 0.5 with a step of 0.05.

Parameter	***Value***
B	15
p_2	0.01
r_2	variable
n_1	14
n_0	12
tmm	13
Iterations	10000

Table 4.23: Parameters of variable repair rate case.

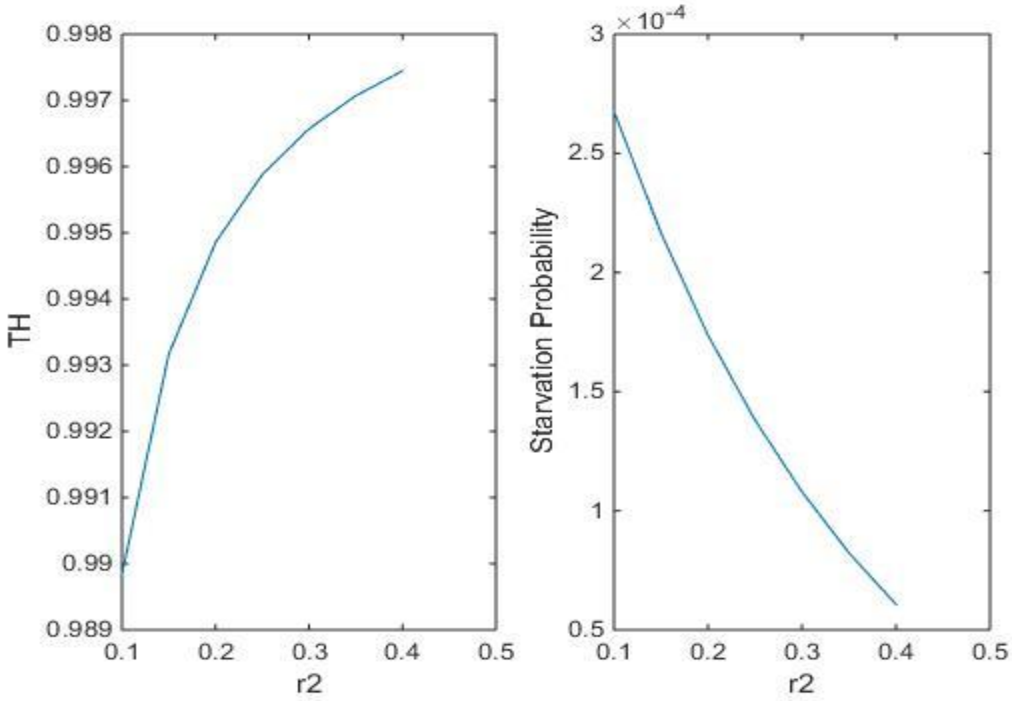


Figure 4.11: Variable repair rate performances.

Both throughput and starvation probability follow a predictable path, the first increasing and the second decreasing with a growing repair rate. Similar slopes were obtained also considering M_2 less subjected to fails (p_2=0.001).

4.2.2 Variable buffer capacity

Variable B, from 5 to 25 with a step of 1. At each iteration (that means increasing the previous buffer capacity of one unit) n_0 is set two units lower than buffer capacity B (n_0=B-2) and n_1 one unit lower than B (n_1=B-1). tmm is kept constant at 13.

Parameter	***Value***
B	variable
p_2	0.01
r_2	0.1
n_1	B-1
n_0	B-2
tmm	13
Iterations	10000

Table 4.24: Parameters of variable buffer capacity case.

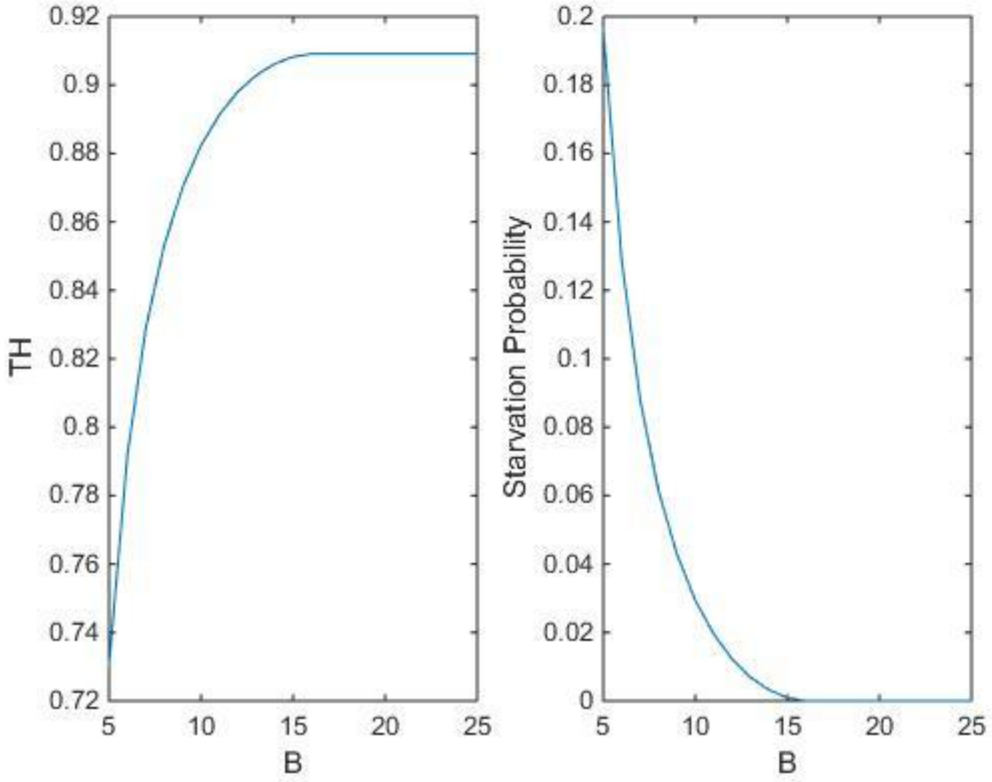


Figure 4.12: Variable buffer capacity performances.

As expected the performance improve with the buffer capacity until a stable level, with the throughput increasing and the starvation probability decreasing. Similar slopes were obtained also considering all the possible combinations of M_2 performances in terms of failure and repair rates.

4.2.3 Variable activation level n_1

Variable n_1, from 3 to 15 with a step of 1.

Parameter	***Value***
B	15
p_2	0.01
r_2	0.1
n_1	variable
n_0	12
tmm	13
Iterations	10000

Table 4.25: Parameters of variable n_1 case.

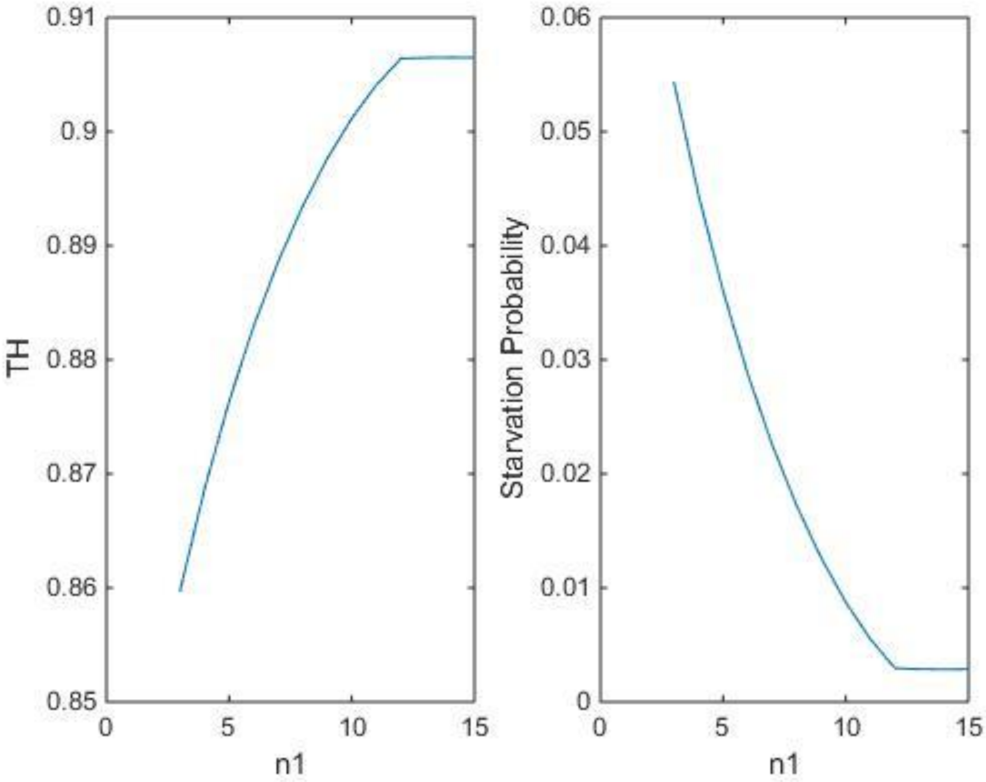


Figure 4.13: Variable n_1 performances.

With a growing n_1, TH increases and starvation probability decreases. The path change at n_1=12 and the gain in term of performances increases more slowly and with a lower slope, almost flat. This should be due to the fact that 12 is also the activation level n_0 and at the same time it’s already very close to the buffer content needed to cover the tmm, that is 13, without even the need of a stoppage.

Therefore the gain achievable from this point on is much lower with respect to lower levels of n_1, where going one unit towards 13 makes a greater difference than increasing of one unit from 13 onwards. From a different perspective, the loss in performances achieved stopping the machine at a level that can not cover the duration of the intervention will be for sure greater than a level where maintenance task is already covered with high probability, and has a low range of variation.

Similar behaviors have been noticed with all the possible combinations of M_2 performances.

4.2.4 Variable activation level n_0

Variable n_0, from 3 to 15 with a step of 1.

Parameter	***Value***
B	15
p_2	0.01
r_2	0.1
n_1	14
n_0	variable
tmm	13
Iterations	10000

Table 4.26: Parameters of variable n_0 case.

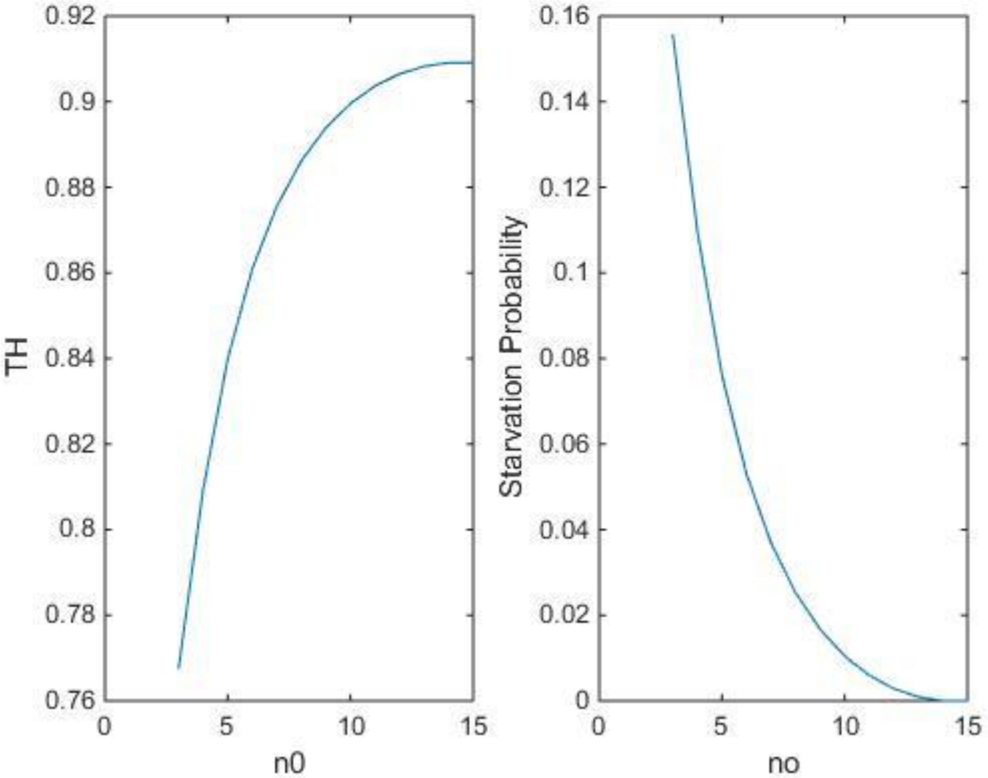


Figure 4.14: Variable n_0 performances.

Increasing n_0, TH increases and starvation probability decreases, as the two previous cases of B and n_1. It’s worth to be noticed that in this case there is no slope change around the level n_1.

Again, similar graph paths have been noticed with all the possible combinations of M_2 performances.

Considering these last two cases it's possible to affirm that n_0 affects much more than n_1 the performances, as the behavior of the graph with variable n_1 changes clearly at level n_0 while the graph with variable n_0 is not affected at level n_1. The following two cases prove this last sentence.

4.2.5 Variable activation levels n_0 and n_1

- In this first case n_1 is varied between 10 and 15 for every level of n_0 between 7 and 15 (lines of increasing n_1 going upwards in TH and downwards in starvation probability).

Parameter	***Value***
B	15
p_2	0.01
r_2	0.1
n_1	variable (lines)
n_0	variable (x axis)
tmm	13
Iterations	10000

Table 4.27: Parameters of variable activation levels, first case.

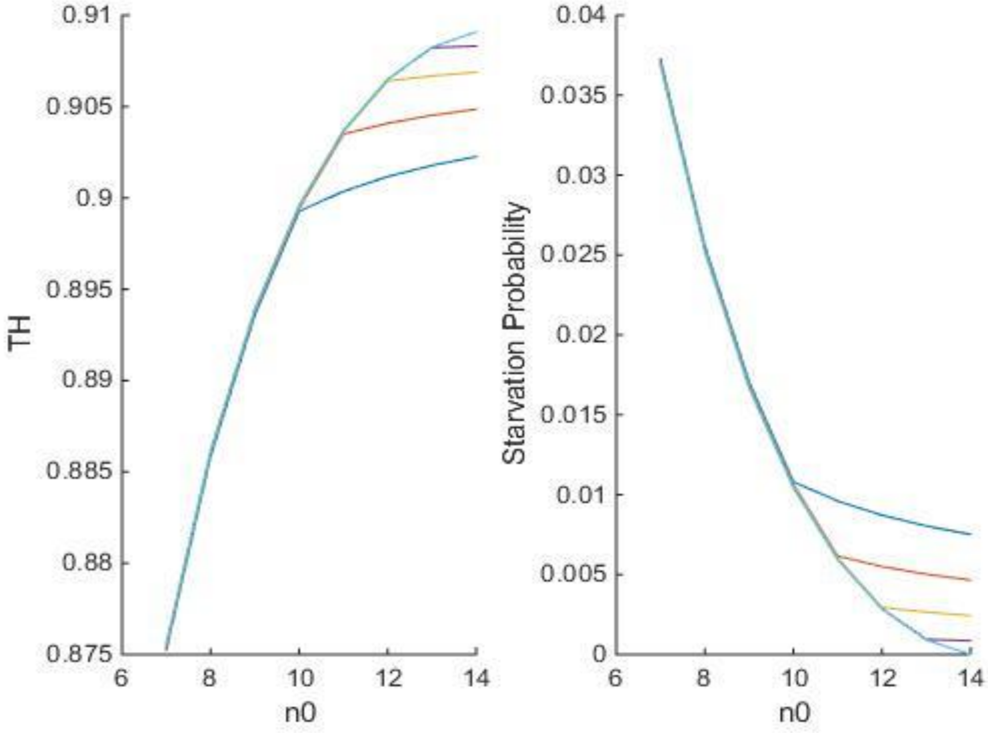


Figure 4.15: Variable activation levels performances, first case.

- In this second case n_0 is varied between 7 and 12 for every level of n_1 between 5 and 15 (lines of increasing n_0 going upwards in TH and downwards in starvation probability).

Parameter	***Value***
B	15
p_2	0.01
r_2	0.1
n_1	variable (x axis)
n_0	variable (lines)
tmm	13
Iterations	10000

Table 4.28: Parameters of variable activation levels case, second case.

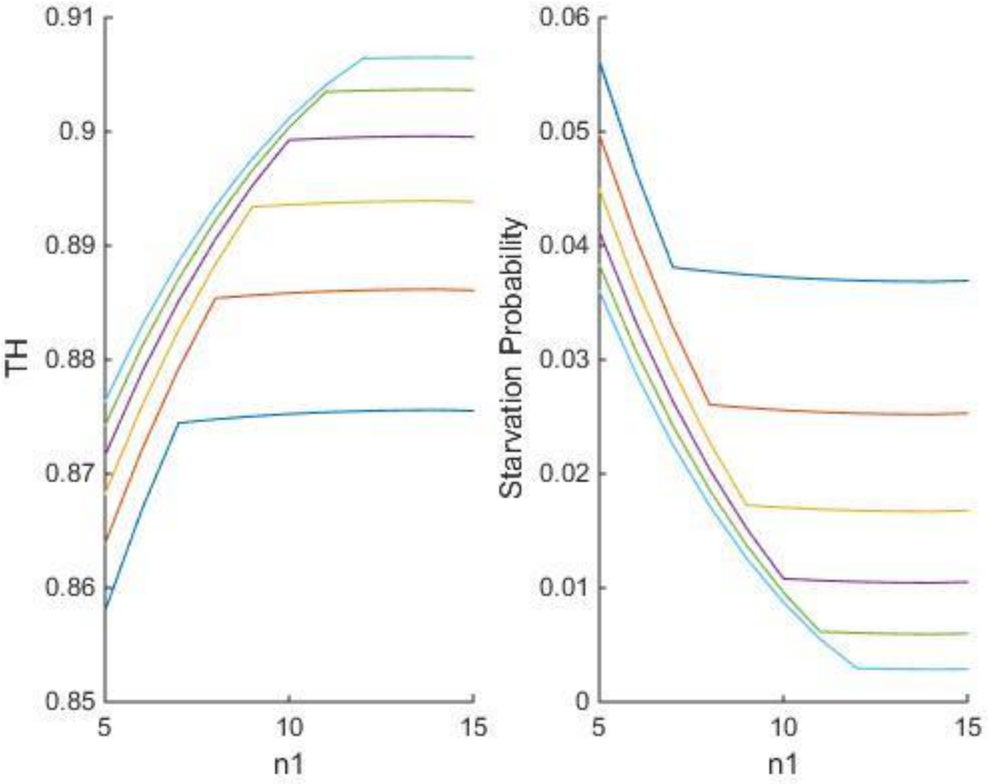


Figure 4.16: Variable activation levels performances, second case.

The greater influence of n_0 with respect to n_1 is confirmed, because different levels of n_1 (Figure 4.15) makes TH and starvation vary less than 1% while different levels of n_0 (Figure 4.16) allows variations greater than 3%.

4.2.6 Variable maintenance intervention duration

Variable tmm, from 3 to 25 with a step of 1.

Parameter	***Value***
B	15
p_2	0.01
r_2	0.1
n_1	14
n_0	12
tmm	variable
Iterations	10000

Table 4.29: Parameters of variable MM task duration case.

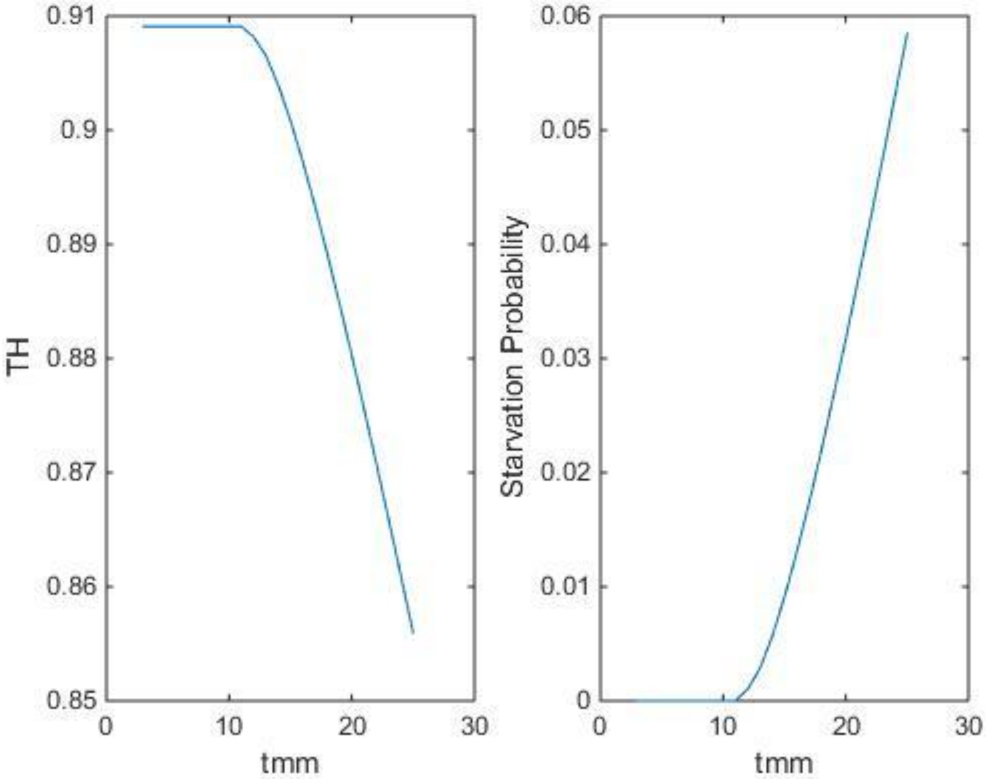


Figure 4.17: Variable MM task duration performances.

Increasing the duration of the minor maintenance intervention both TH and starvation probability are heavily affected: TH decreases and starvation probability increases. Different combinations of M_2 performances give always the same behaviors.

4.2.7 Variable buffer capacity with constant n_0/n_1 ratio

- Variable B, from 3 to 42 with a step of 3, keeping constant at each iteration the ratio n_0/n_1 (n_0=B/3 and n_1=2/3*B so n_1=2*n_0) and considering, always at each iteration, a tmm of duration equal to time needed to empty a buffer with n_0 units available (tmm=n_0=B/3).
  The target is to verify if a constant activation levels ratio at different buffer levels results in constant performances.

Parameter	***Value***
B	variable
p_2	0.01
r_2	0.1
n_1	2*B/3
n_0	B/3
tmm	B/3
Iterations	10000

Table 4.30: Parameters of variable B and constant n_0/n_1 ratio case, first case.

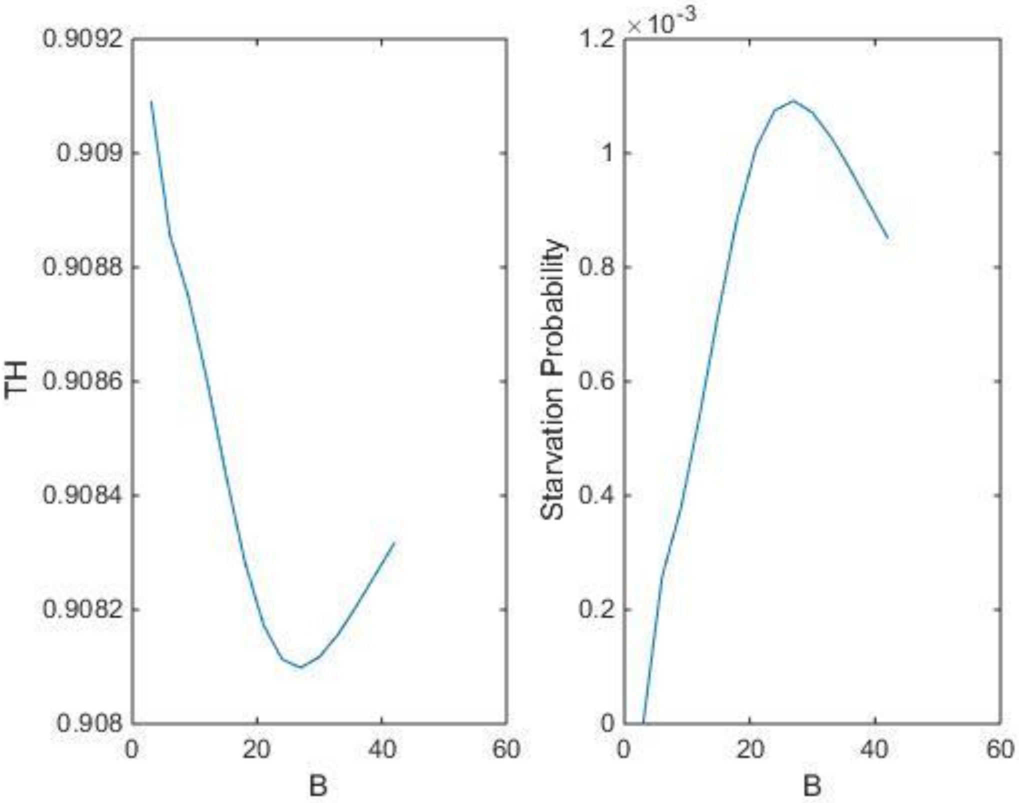


Figure 4.18: Variable B and constant n_0/n_1 ratio performances, first case.

A peak can be noticed in both the graphs, anyway the interval of variation of TH and starvation probability are very small (0.1% for TH and even smaller for starvation probability), so it’s possible to affirm that the constant ratio n_0/n_1 makes TH and starvation probability almost constant even though the variable B.

The peak would indicate the buffer capacity to avoid with this ratio, but the range is so small that it is not an interesting fact.

- Variable B, from 3 to 42 with a step of 3, keeping constant at each iteration the ratio n_0/n_1 (n_0=B/3 and n_1=2/3*B so n_1=2*n_0) and considering a tmm of duration equal to time needed to empty a buffer with n_1 units available. Therefore this experiment is similar to the previous one but with a tmm that is the double at each iteration.

Parameter	***Value***
B	variable
p_2	0.01
r_2	0.1
n_1	2*B/3
n_0	B/3
tmm	2*B/3
Iterations	10000

Table 4.31: Parameters of variable B and constant n_0/n_1 ratio case, second case.

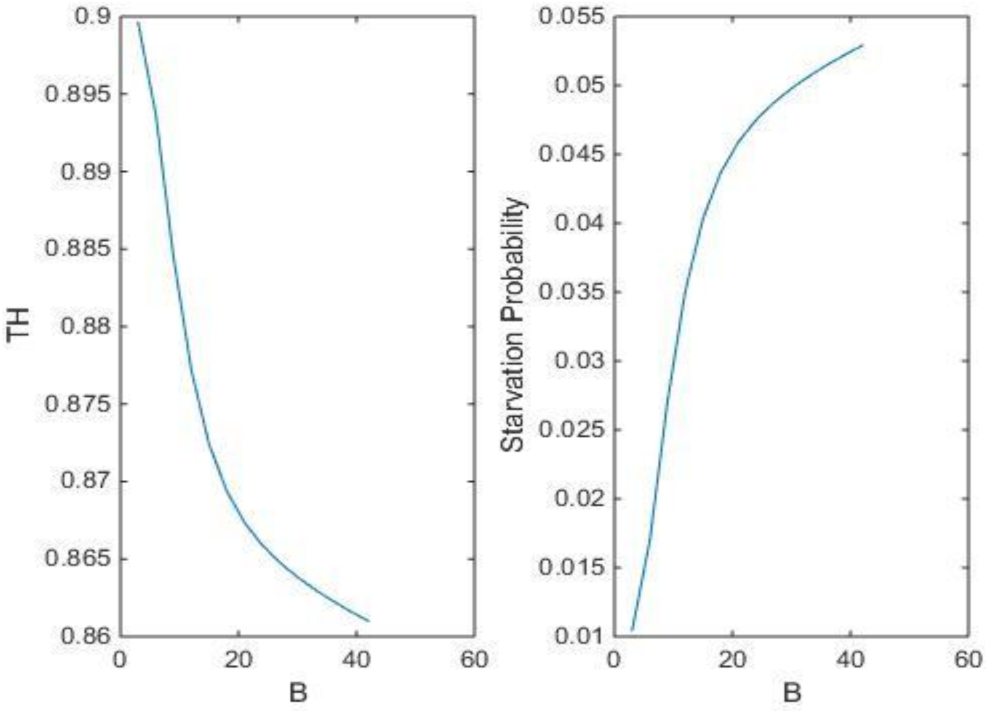


Figure 4.19: Variable B and constant n_0/n_1 ratio performances, second case.

Considering these different and higher values for tmm there is no peak and TH and starvation probability are more affected by the increasing buffer capacity B, leading to worse values (4% of TH lost and even more starvation probability gained).

- Variable B, from 6 to 42 with a step of 6, keeping constant at each iteration the ratio n_0/n_1 (n_0=B/3 and n_1=2/3*B so n_1=2*n_0) and considering a tmm of duration equal to time needed to empty a buffer with a medium level between n_0 and n_1 of units available (tmm=(n_0+n_1)/2=B/2). This is therefore an experiment with a mean tmm between the two previous ones.

Parameter	***Value***
B	variable
p_2	0.01
r_2	0.1
n_1	2*B/3
n_0	B/3
tmm	B/2
Iterations	10000

Table 4.32: Parameters of variable B and constant n_0/n_1 ratio case, third case.

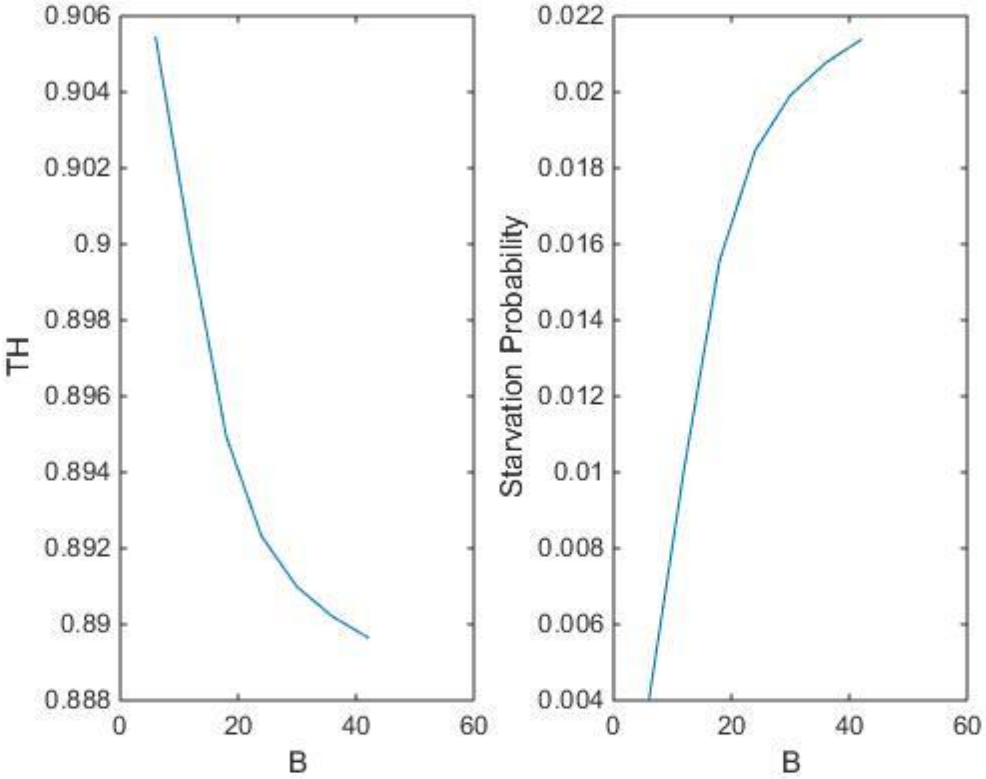


Figure 4.20: Variable B and constant n_0/n_1 ratio performances, third case.

The slope is very similar to the second case, but the range of values is much different, less of 2% of variation both for TH and starvation probability. The result is as expected a mean between the results of the two previous experiments, but anyway the range is still a bit too large to talk about constancy of performances as in the first one.

These last three experiments highlights two results: first that a shorter tmm leads to a smaller variation in performances, second that, to have performances almost close to a constant value while keeping constant the ration n_0/n_1 and varying buffer capacity B, the MM task duration should be at least higher than the time needed to process half of the buffer capacity.

4.2.8 Variable activation level n_0 and maintenance intervention duration

- Variable n_0 from 5 to 14 with tmm varied between 5 and 20 at each level of n_0 (tmm increasing downward in TH and upward in starvation probability).

Parameter	***Value***
B	15
p_2	0.01
r_2	0.1
n_1	14
n_0	variable (x axis)
tmm	variable (lines)
Iterations	10000

Table 4.33: Parameters of variable n_0 and MM task duration case.

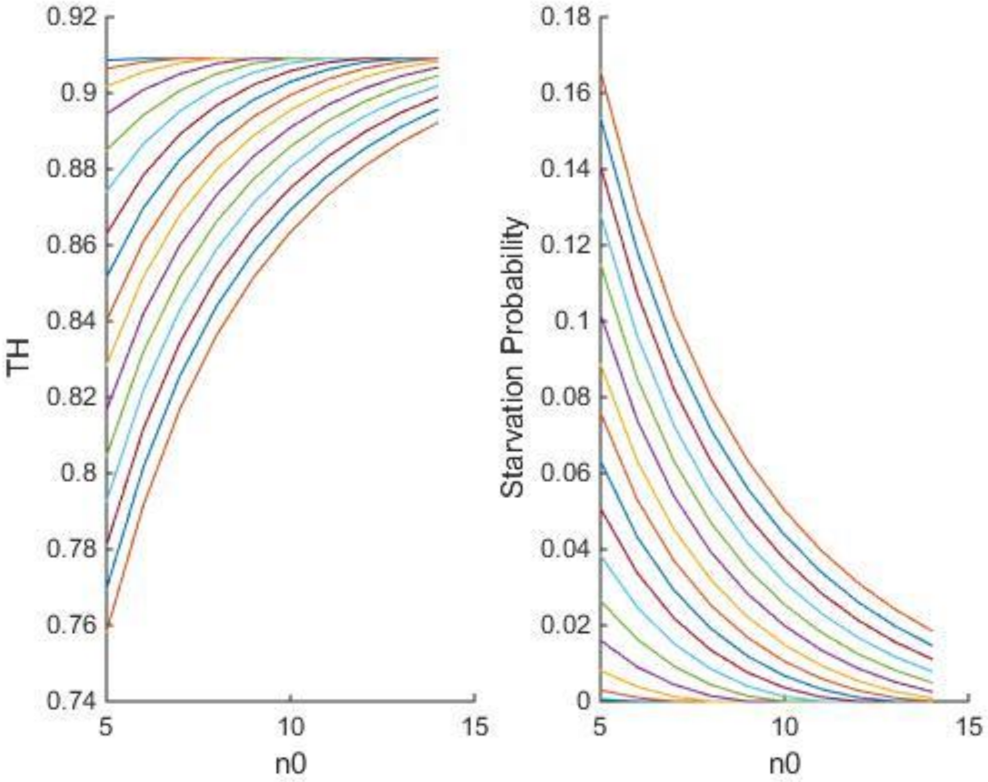


Figure 4.21: Variable n_0 and MM task duration performances.

This last graph and its specular, with tmm and n_0 inverted on the axis, can be very important, because can be optimization tools from different perspective: for example they can help choosing the minimum activation level n_0 in function of a certain tmm, in order not to cross a certain risk level. A low level n_0 may be desirable because it means that maintenance can be activated more frequently. It can also be used to select the maximum tmm executable with a certain n_0 previously established, again in order not to cross a certain risk level. This topic will be now studied more deeply.

4.3 Parameters optimization

Now that the behavior of the performances indicators is more clear and the influence of the variable input parameters has been analyzed, the question is how to optimize the setting of the manufacturing system policy in order to reach some concrete targets. From now on, n_1 will be always set with a value intermediate between n_0 and B. As anticipated, the focus will be just on n_0, because of its influence, much greater than n_1, as demonstrated in 4.2.5. A description of targets and how the software developed can help the decision maker in achieving objectives is provided.

4.3.1 Maximization of intervention duration

Maximization of MM action duration sustainable by the system without exceeding some performances thresholds (of TH, starvation probability or both).

This target is interesting when an opportunistic maintenance activity that has to be implemented lasts a relative high amount of time units, or when a sequence of tasks, with a total relevant duration, must be executed in the same opportunity window. This request of a large tmm push the decision maker towards high activation levels, knowing that this way also the frequency of activation will be lower. So also the frequency of need of these activity should be evaluated in order to verify if this configuration works properly.

An example is here provided, where a minimum TH is set.

Parameter	***Value***
B	20
p_2	0.01
r_2	0.1
n_1	18
n_0	variable
tmm	variable
THlimit	0.88
Iterations	10000

Table 4.34: Parameters of intervention duration maximization, first case.

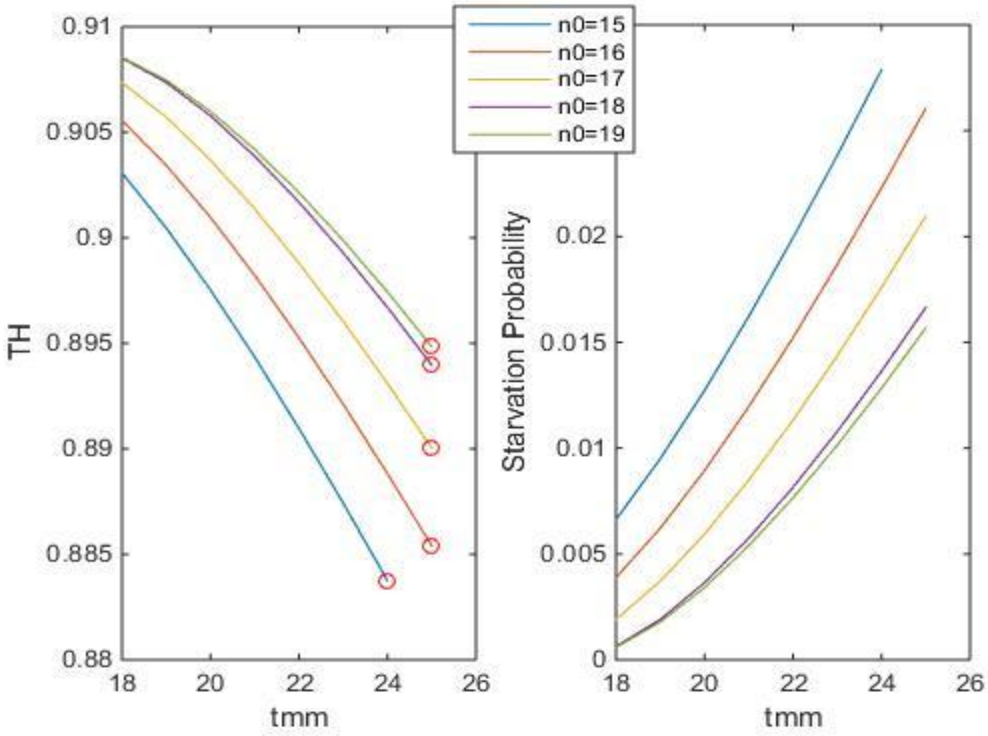


Figure 4.22: Intervention duration maximization graph, first case.

The plot shows for each activation level n_0, from 15 to 19, the maximum duration of a tmm task, in the range from 18 to 25, achievable without going below a set limit TH, in this case of 0.88. The software automatically cut the line of each n_0 at the maximum tmm duration with an acceptable value of TH, represented by the point marked with a red circle. This means that each level n_0, at the next tmm duration, would have overcome the limit set for TH.

It is visible how higher levels of n_0 allow higher TH at the same tmm duration of 25, while the lowest level can't even reach the maximum duration without going over the minimum TH, so it indicates 24 as maximum duration for that activation level (n_0=15).

Looking at this graph the decision maker can select between different alternatives: he can choose between the two lowest activation levels if TH is just needed to be higher than the threshold, or instead decide between the highest n_0 in order to gain up to 1% in TH, even if losing in interventions frequency as the policy will be activated less often. That's the reason why the best decision must take into account also the aspects of an intervention and not only its duration.

Parameter	*Value*
B	20
p_2	0.01
r_2	0.1
n_1	20
n_0	variable
tmm	variable
THlimit	0.90
Iterations	10000

Table 4.35: Parameters of intervention duration maximization, second case.

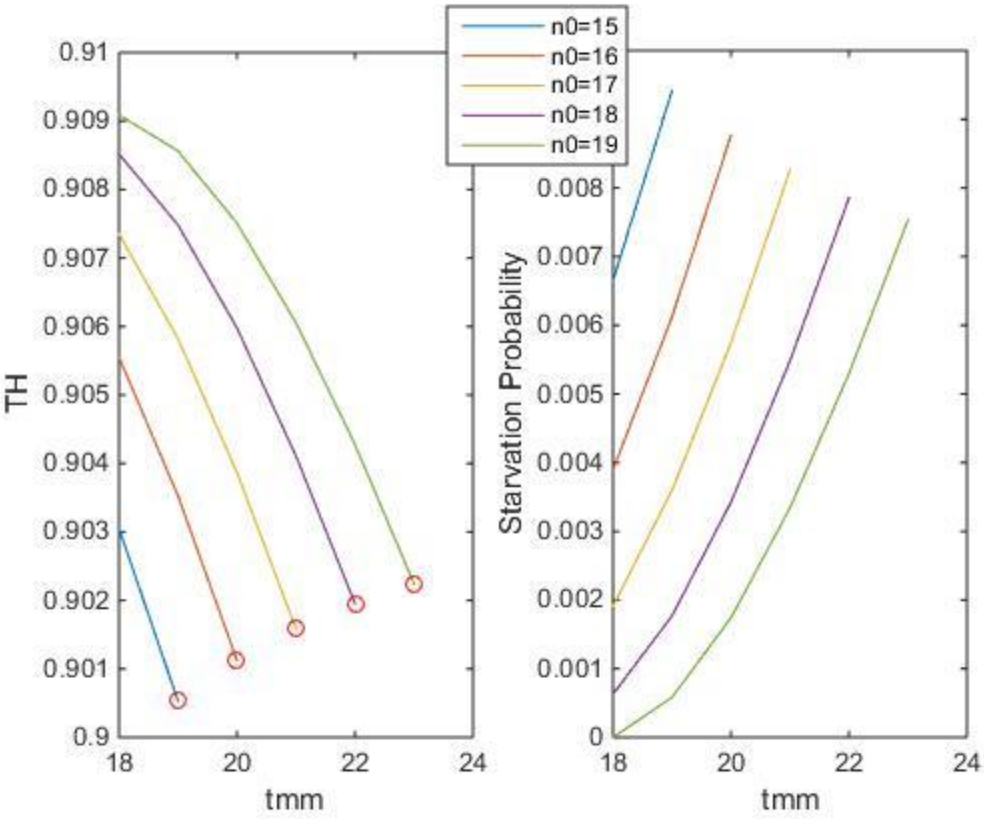


Figure 4.23: Intervention duration maximization graph, second case.

In this second example n_1 is increased to B, so maintenance is activated just by n_0 (when M_2 is down). TH threshold is set to 0.90. Activation levels n_0 are the same as before, but tmm is let varying from 18 to 30. This example shows how in this case there is almost no TH gain at different levels, and how the maximum tmm achievable without crossing the limit TH is 23. Hence it’s possible to notice that, up to the limit of 23, longer MM tasks affects the TH almost equally, so they are highly recommended.

Parameter	***Value***
B	20
p_2	0.01
r_2	0.1
n_1	20
n_0	variable
tmm	variable
THlimit	0.90
SPlimit	0.008
Iterations	10000

Table 4.36: Parameters of intervention duration maximization, third case.

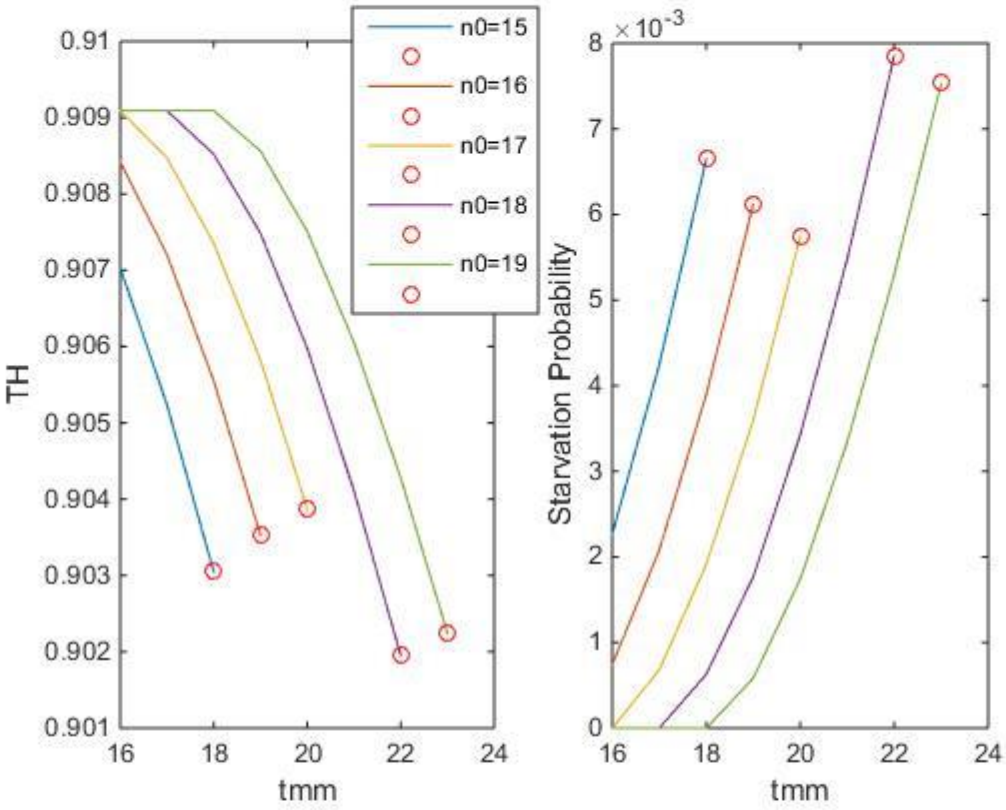


Figure 4.24: Intervention duration maximization graph, third case.

This third example keeps the same parameters of the previous one, but adds, beside the TH limit, also a limit for starvation probability of 0.008. The consequence is that the lowest three level of n_0 allows now a tmm one unit shorter than the previous example, because they were exceeding the new threshold set for starvation probability, as can be seen comparing Figures 4.23 and 4.24. In other words with a double limit it’s possible to improve the control of the performances of the system, even if usually they are strictly correlated and just a single threshold could be enough.

4.3.2 Maximization of intervention activation

Maximization of the number of MM actions executed without exceeding some performances thresholds (of TH, starvation probability or both). This correspond to a lower activation level.

This target correspond to find out the minimum activation level n_0 that makes possible to overcome a performance threshold limit, in order to execute MM activities as often as possible. Clearly, the shorter the duration of the task or sequence of tasks under evaluation, the lower the level n_0 achievable and consequently the time between MM execution.

Here the risk is to choose a too low level n_0, but ,due to its nature, the software immediately returns a warning if the first n_0 to be evaluated does not guarantee a TH over the limit value. Therefore the user knows that must focus his research on higher activation levels, while the software moves automatically to the following n_0 to be evaluated. At the end a parameter indicates also the total number of n_0 initially rejected and the first acceptable level.

In this example n_0 will be tested from 8 to 13 and tmm from 12 to 18.

Parameter	***Value***
B	15
p_2	0.01
r_2	0.1
n_1	15
n_0	variable
Tmm	variable
THlimit	0.90
Iterations	10000

Table 4.37: Parameters of intervention activations maximization case.

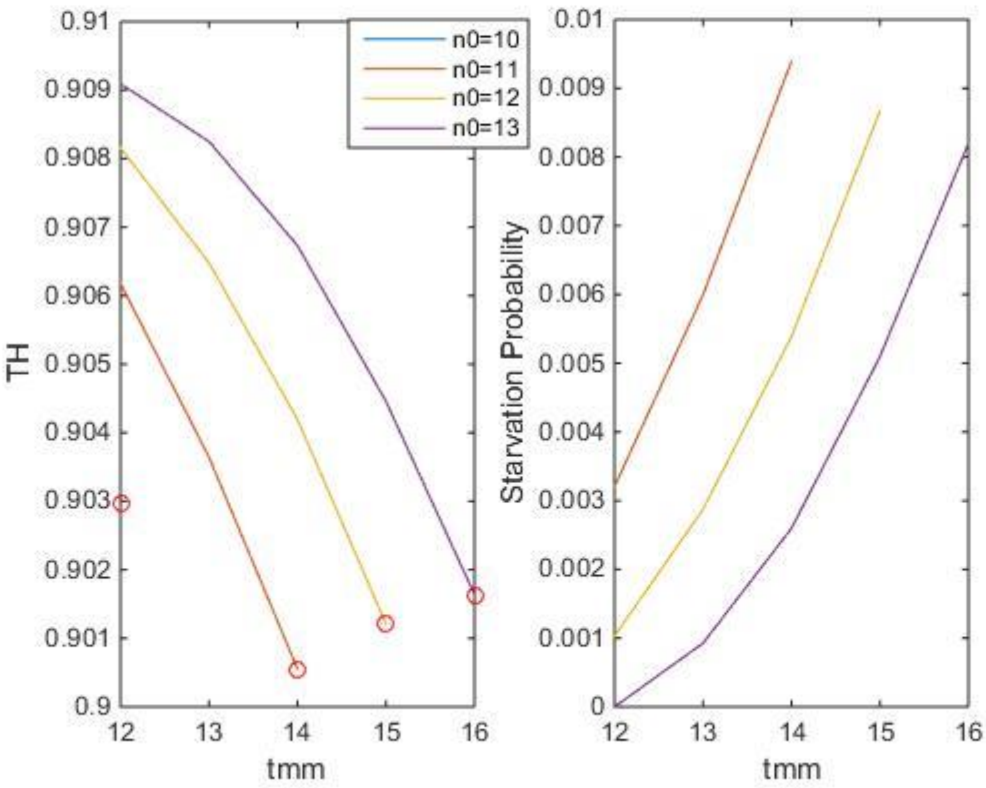


Figure 4.25: Intervention activation maximization graph.

As it can be noticed, the plot shows only n_0 levels from 10 to 13, because the first two levels, equals to 8 and 9, can't even cover the duration of the shorter MM task under evaluation, that lasts 12 time units, so they are cut off and not showed in Figure 4.25. Therefore, if the purpose is to look for the minimum n_0 which can guarantee the shortest tmm, equal to 12, to be activated as frequently as possible, the decision maker would pick the first solution proposed n_0=10. Instead, if a recurring maintenance activation is not so needed he can choose higher levels profitably, as the TH variation with respect to the smaller n_0 is minimal.

4.3.3 Maximization of system performance

Maximization of performances (TH, starvation probability or both), while guaranteeing a certain tmm duration.

Maximization of throughput is the most common target of a manufacturing system. When an opportunistic policy like the one developed in this work is under implementation, is crucial to set parameters correctly. It can happen that the parameters setting is made in function of a minimum tmm that must be guaranteed. So to achieve this target is just needed to look at graphs and pick the activation level that guarantee the higher TH and the minimum tmm.

In the next example n_0 is varied between 14 and 19 and tmm between 18 and 23.

Parameter	***Value***
B	20
p_2	0.01
r_2	0.1
n_1	18
n_0	variable
Tmm	variable
Iterations	10000

Table 4.38: Parameters of performance maximization case.

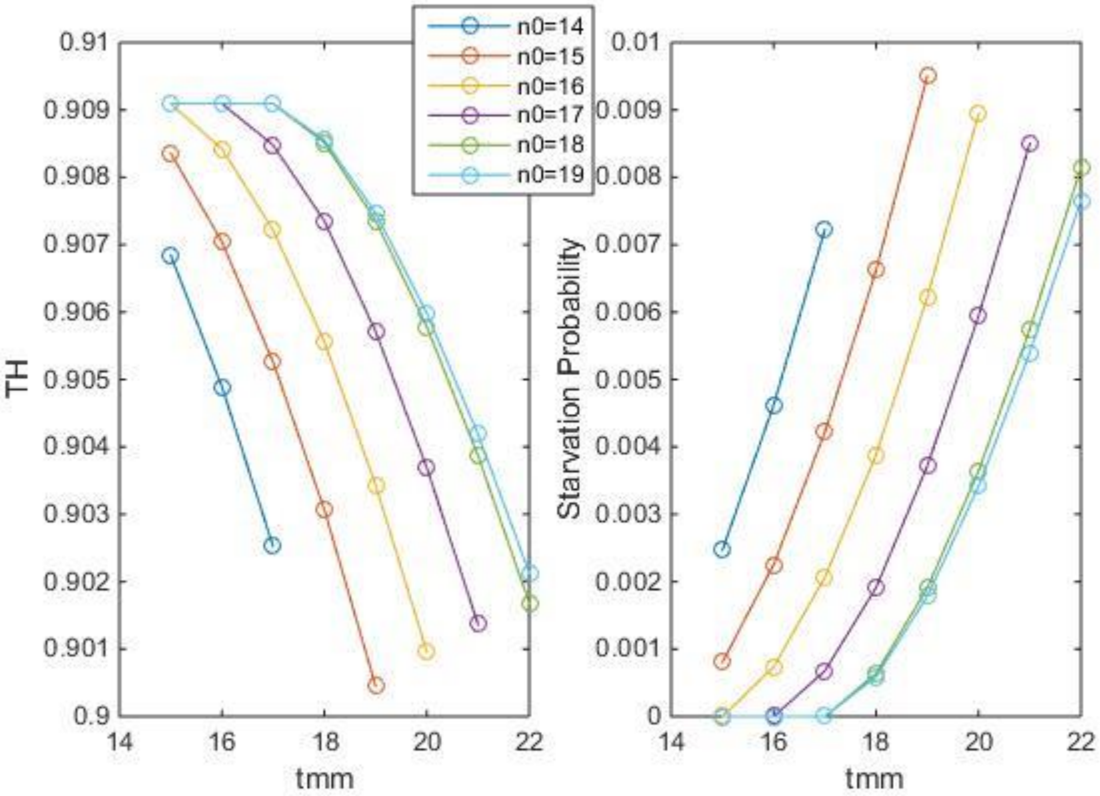


Figure 4.26: Performance maximization graph.

Results are filtered in order to delete values of TH lower than 0.90. Values of maximum tmm, equal to 23, are not even showed because TH goes under 0.90 with any activation level. If a not too long tmm is required, the highest four n_0 levels can guarantee the same performances, so the user can choose between them with the respect to the frequency of activation needed. For the highest two levels this holds for all the tmm values, so, from a purely production performance point of view, choosing one or the other produce exactly the same results. Instead it's possible to notice the great performance difference at medium tmm, where, for example at 19, there can be almost 1% of TH difference or even some levels not showed, as the first one. Therefore it's clear what must be avoided. It's visible also how, from a starvation point of view, the options suggested to the user are the same, as can been expected due to the correlation between TH and starvation probability.

4.4 Multiple minor maintenance actions availability

In the previous part a model to understand the effects of an opportunistic policy was described. The model took into account just one MM action or a sequence not specified of actions that, concretely, is just like considering an artificial action during as the summation of them. As the actions considered have a deterministic duration, also their summation is deterministic. In reality there are usually many actions available for the machine operator, as shows the list presented in 2.3.3, and the choice of which one to execute can be crucial. It will be showed now how the model can advise the decision maker about which action between a certain number of available is the best one to be executed and how this give benefits to performances.

At the beginning just two actions will be considered to simplify the understanding, then more actions will be introduced.

The idea behind this extension takes into account two factors: the difference between starvation probabilities, anytime an activation level is reached, and priority rules.

The effects of the actions will be evaluated in terms of risk of going to one of the starved states presented in 3.2.2 each time an activation level is reached. If the difference between the immediate starvation risks of the two actions is comparable (smaller than a certain value chosen by the decision maker) a choice based on a priority rule is made.

The possible scenarios are two:

- A small difference is calculated and it means that the execution of the first or the second action does not make a great difference from a system performances point of view. Hence a priority rule will help choosing the preferable one between the available.
- The difference is larger than a chosen threshold, so the selection will go to the safer action, without the need of the help of a priority rule.

As described in section 2.3.4 there are many kinds of priority rules available. In this case the decision is to give more priority to the longest MM action, the action that requires more time to be executed, as the longest processing time first rule states. This choice makes sense also from the point of view of this research, because executing longer maintenance tasks during production time allows to save more extra hours of maintenance work.

Here an example of behavior of the performances varying the MM actions duration while keeping fixed the gap between the first and the second (e.g. a gap of 5 time units in the example) is presented. It is useful to understand which is the basic idea behind the simulation cases, showed after this part.

The green line represents the shorter action and the red line the longer one.

A reasonable threshold for considering two MM activities comparable in term of risk is, for example, a difference lower than 1% in TH and starvation probability.

The first MM action ranges from 6 to 42 time units. The second MM action is, each step, 5 time units longer than the first MM action. On the x axis there is the tmm of the first action, so summing five units it's possible to obtain the duration corresponding to the second action.

Parameter	***Value***
B	15
p_2	0.01
r_2	0.1
n_1	14
n_0	12
tmm1	variable
tmm2	tmm1+5

Table 4.39: Example parameters.

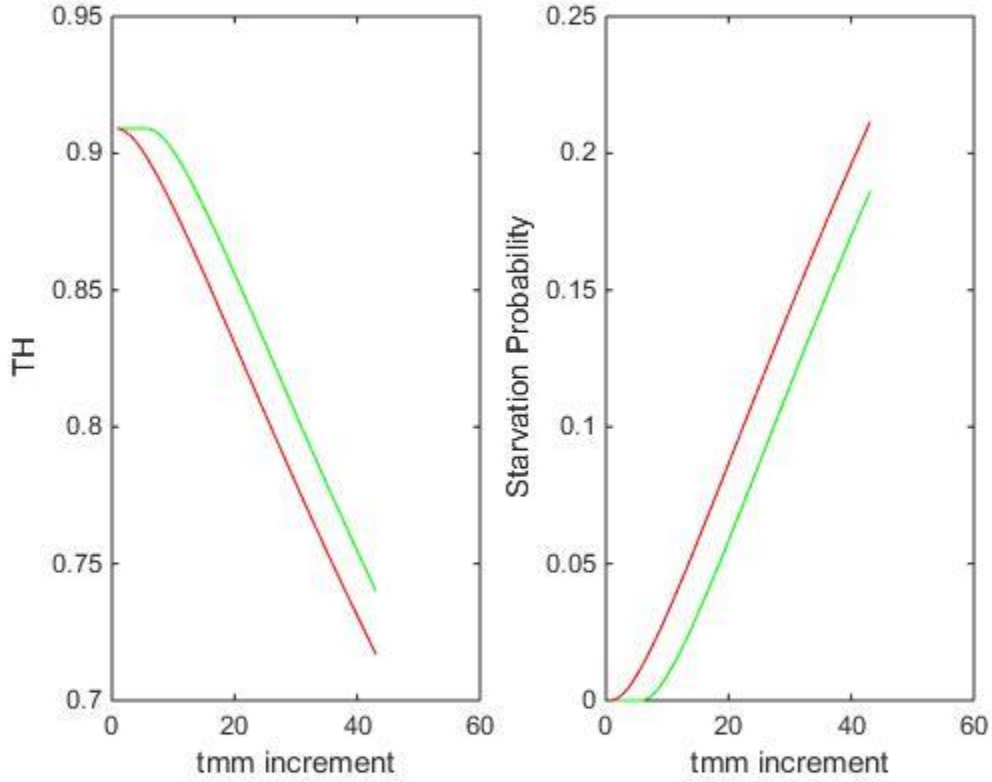


Figure 4.27: Performances with two different MM tasks.

As one could expect, the red graph is the same as the green one but translated. The longer MM task leads faster to worse performance, both in throughput and starvation probability

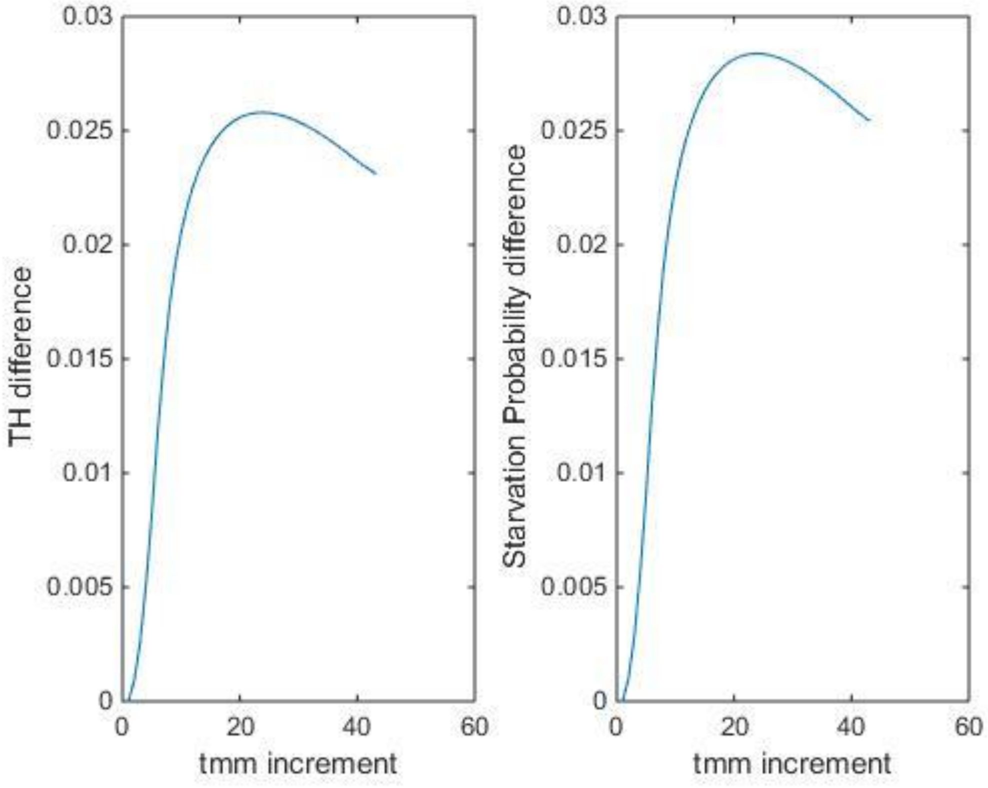


Figure 4.28: Performances differences with two different MM tasks.

Figure 4.28 shows the difference between the green and red lines, giving a measure of the difference of consequences related to the different actions. While the MM durations increase, the difference increases, then changes slope and finally decreases, because the high tmm values bring to closer and closer values of TH and starvation probability. For example, exaggerating, if a system can generally sustain MM duration around 15 time units, starting a maintenance activity lasting 60 or 65 time units is almost the same thing from a performance perspective. In other words this highlights that comparing long MM activities, even if different, makes no sense on buffers that requires times much smaller than the MM activities to be emptied.

With the parameters considered, the difference is probably too high to have doubts about the possibility to execute the longer MM action, because, except for the first levels of tmm, it affects the system performance too heavily (more than 1%).

4.5 Simulation cases

To evaluate the policy, a simulation was developed in Matlab, which compares two cases: maintenance action selection random or based on the policy of this work.

The first case represents a situation where activation levels are set but the operator choose randomly an action between the available ones, without having any criterion on which basing his selection.

In the second case instead the policy is applied, and when an activation level is reached a comparison between the available options is made in terms of starvation risk. As previously said, if the risk difference between the two options is below a set threshold, the operator will carry out the longest action.

Some examples are now presented in order to show how a correct risk threshold (RT) selection can give benefits and provide value to a company.

In each case the random selection simulation was run first, in order to obtain base values for TH (THb) and starvation probability (SPb), depicted in magenta in next figures. Their value is constant in next figures because it is not affected by the risk threshold.

4.5.1 Case 1: 2 MM actions, high failure rate and low repair rate

The opportunistic policy simulation was run varying the risk threshold from 0.01 to 0.4 with a step of 0.01. The performances obtained with each threshold are reported in blue in the graphs, with also a 4th grade polynomial approximation in light blue.

Parameter	***Value***
B	14
p_2	0.01
r_2	0.1
n_1	11
n_0	9
tmm1	14
tmm2	10
RT	variable
THb	0.8951
SPb	0.0163

Table 4.40: Parameters of case 1.

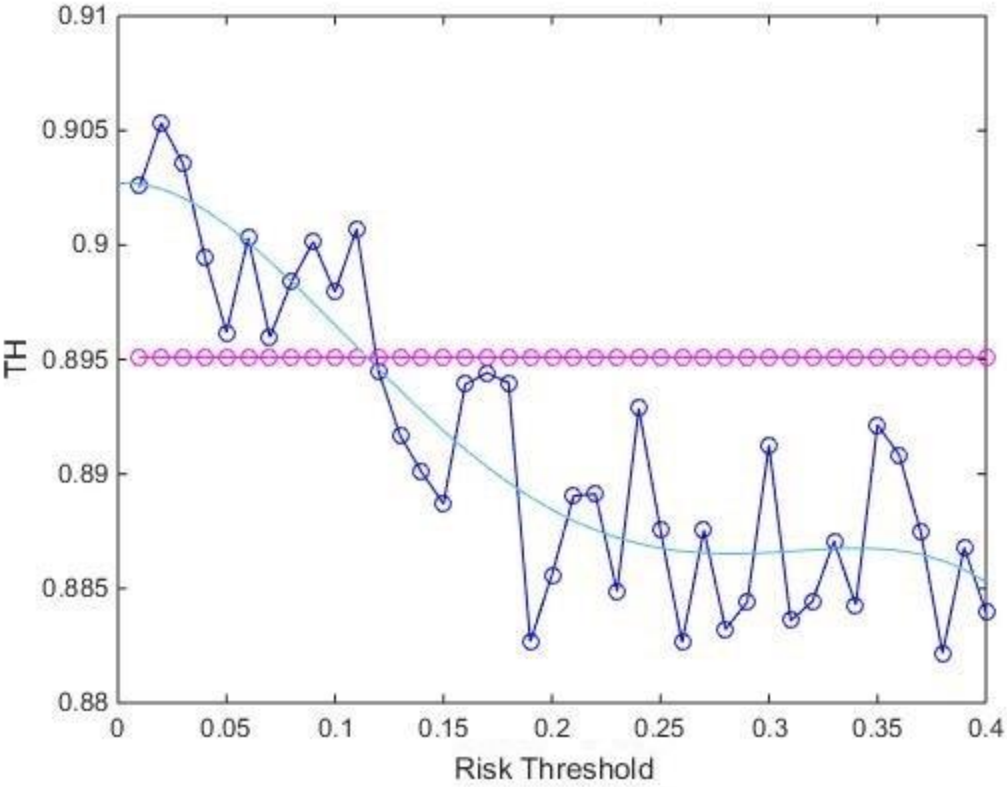


Figure 4.29: TH with variable RT, case 1.

TH decreases as RT increases, but the figure shows that up to RT=1.1 the performance of the manufacturing system are better than executing MM tasks randomly. A TH gain up to 1% around the lowest RTs is available, with respect to random selection.

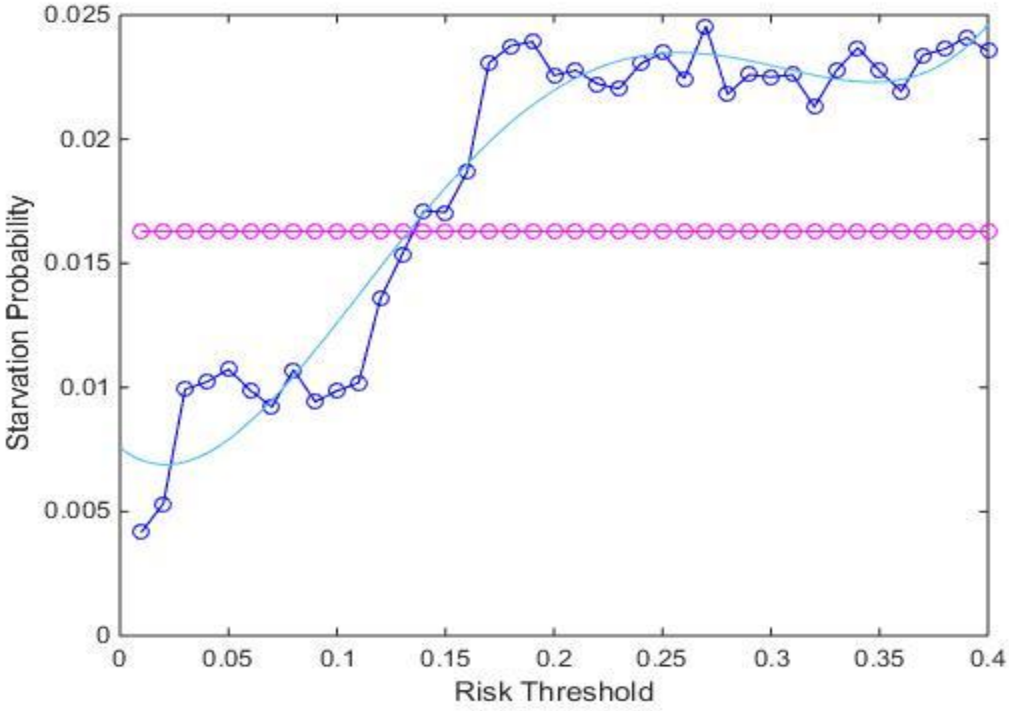


Figure 4.30: Starvation probability with variable RT, case 1.

Starvation probability increases as the RT increases, but up to RT=1.13 the risk is below the risk achieved with a random selection. In particular, close the lowest RTs, it’s possible to observe also a starvation risk more than 1% lower with respect to random selection.

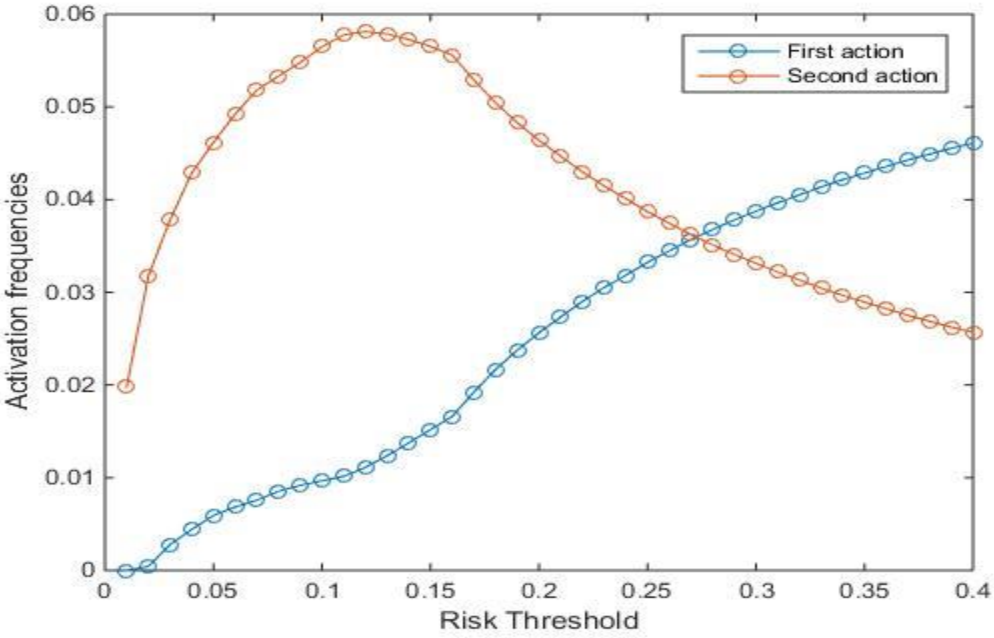


Figure 4.31: MM actions activation frequencies with variable RT, case 1.

Figure 4.31 shows with which frequency the selection goes to the first or the second action at different RTs. As the first action is longer and therefore more risky than the second one, initially its frequency grows more slowly than the second one. Then at a certain RT, around 0.12, the slopes change, because the acceptable risk difference becomes so large that the choice will fall more and more often to the first action. Indeed the frequency of the second action, after a peak, starts decreasing and the first one grows faster.

Finally we can state that, if the interest is just toward starvation probability, it’s possible to set a RT equal to 1.3. If the interest is otherwise also toward TH, it would be better to set a safer RT equal to 1.1. Anyway, in both cases, according to activation frequencies, some tasks will be executed during production times in a smart way, with all the related benefits, while TH and starvation will be kept at a good level.

4.5.2 Case 2: 2 MM actions, very high failure rate and low repair rate

Risk threshold varies now from 0.01 to 0.4 with a step of 0.01. With respect to Case 1 failure probability is now higher, in order to simulate a less reliable machine.

Parameter	***Value***
B	20
p_2	0.02
r_2	0.1
n_1	18
n_0	12
tmm1	16
tmm2	14
RT	variable
THb	0.8170
SPb	0.0164

Table 4.41: Parameters of case 2.

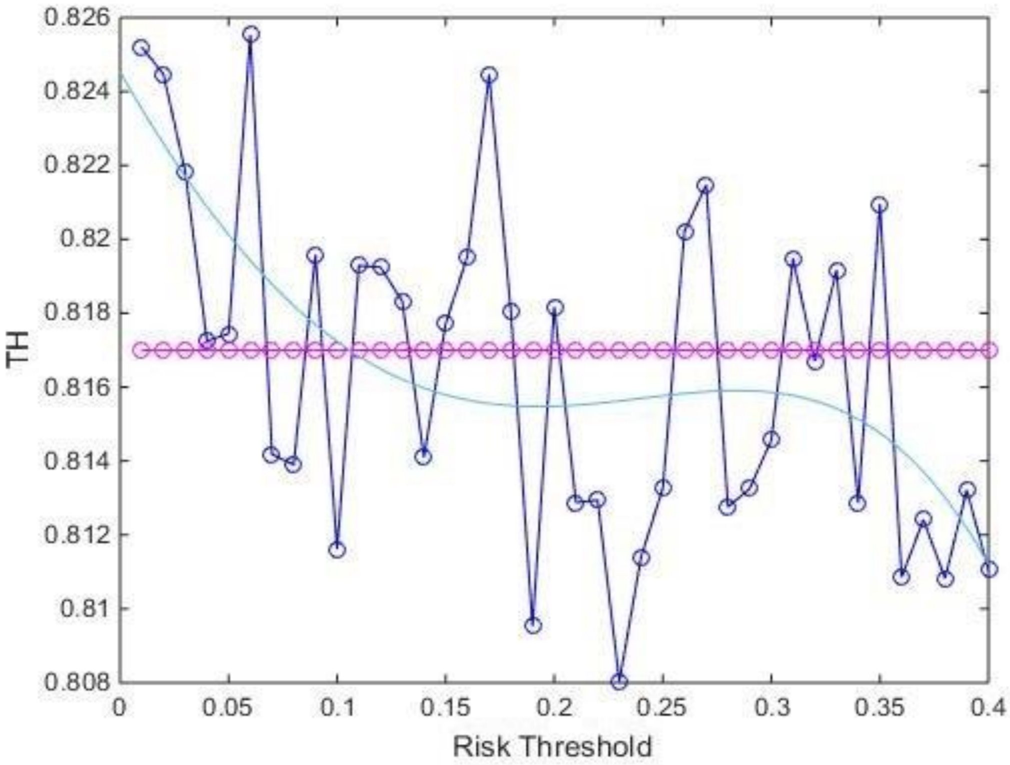


Figure 4.32: TH with variable RT, case 2.

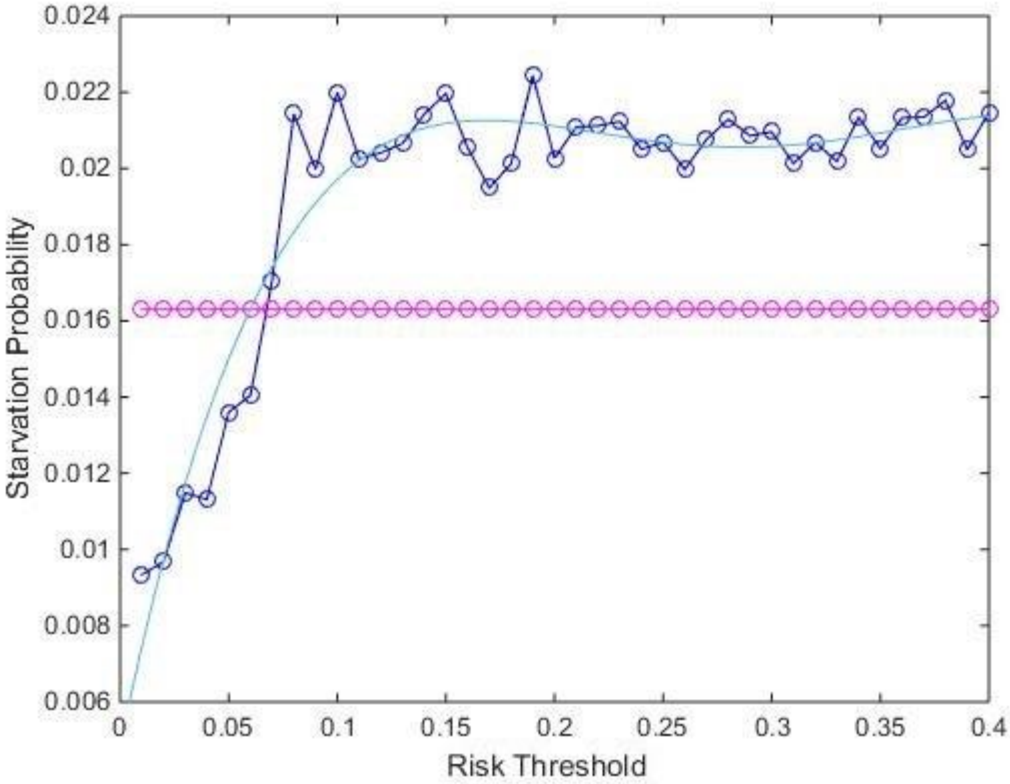


Figure 4.33: Starvation probability with variable RT, case 2.

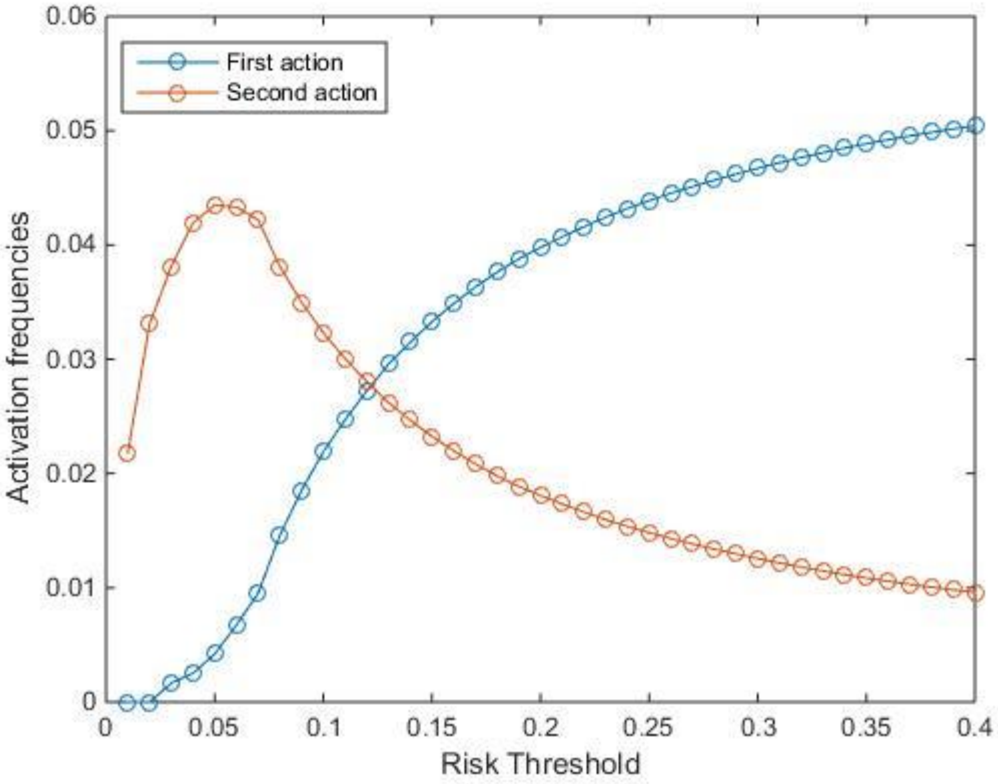


Figure 4.34: MM actions activation frequencies with variable RT, case 2.

Apart from punctual values, the paths are very similar to the previous case, even if the TH values are closer to the random selection simulation. Anyway also here it’s possible to find a threshold value which is better to not overcome in order to guarantee good performance while executing some MM action.

4.5.3 Case 3: 2 MM actions, high failure rate and high repair rate

Simulation was run varying the risk threshold from 0.01 to 0.4 with a step of 0.01. With respect to previous cases, now a higher repair rate is considered, in order to see what happens when the second machine can get repaired faster.

Parameter	***Value***
B	10
p_2	0.01
r_2	0.2
n_1	10
n_0	7
tmm1	10
tmm2	8
RT	variable
THb	0.9417
SPb	0.0100

Table 4.42: Parameters of case 3.

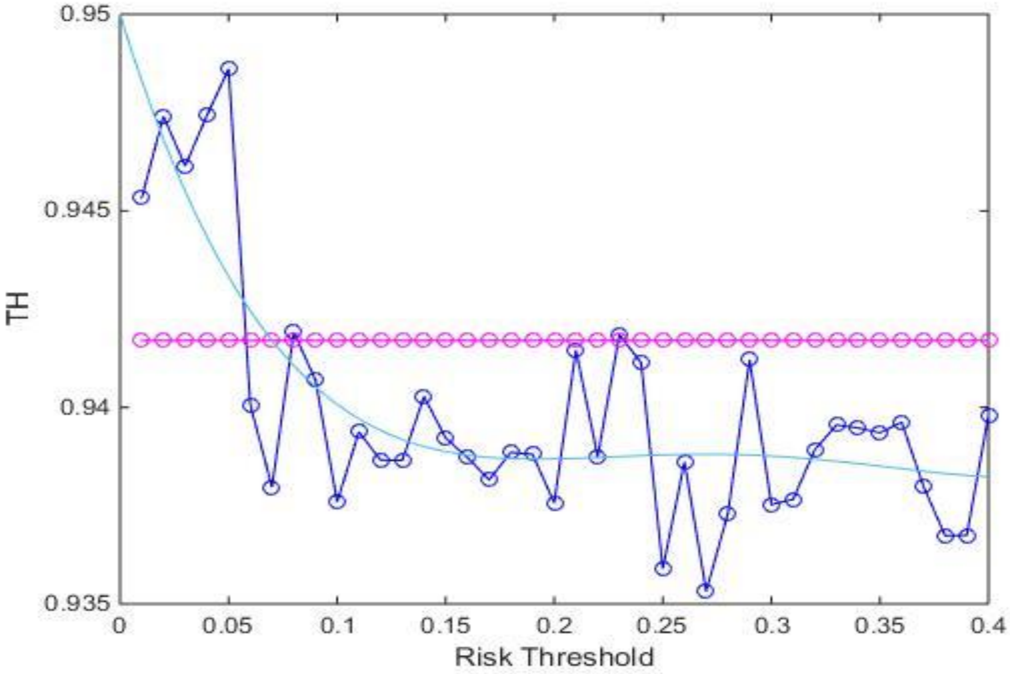


Figure 4.35: TH with variable RT, case 3.

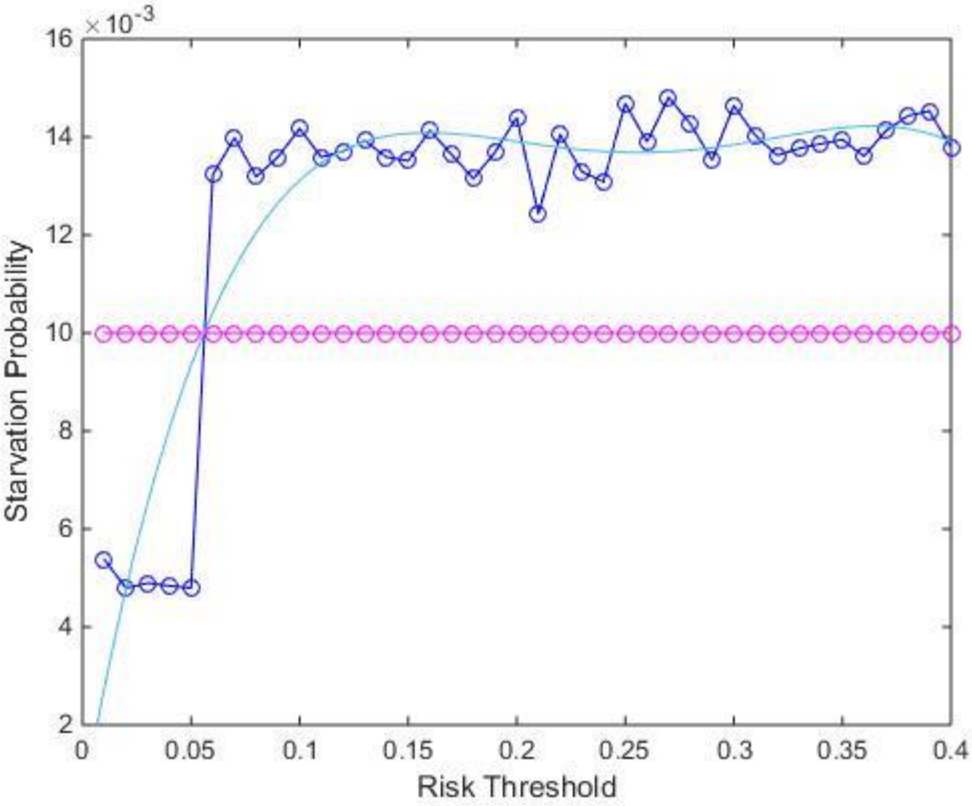


Figure 4.36: Starvation probability with variable RT, case 3.

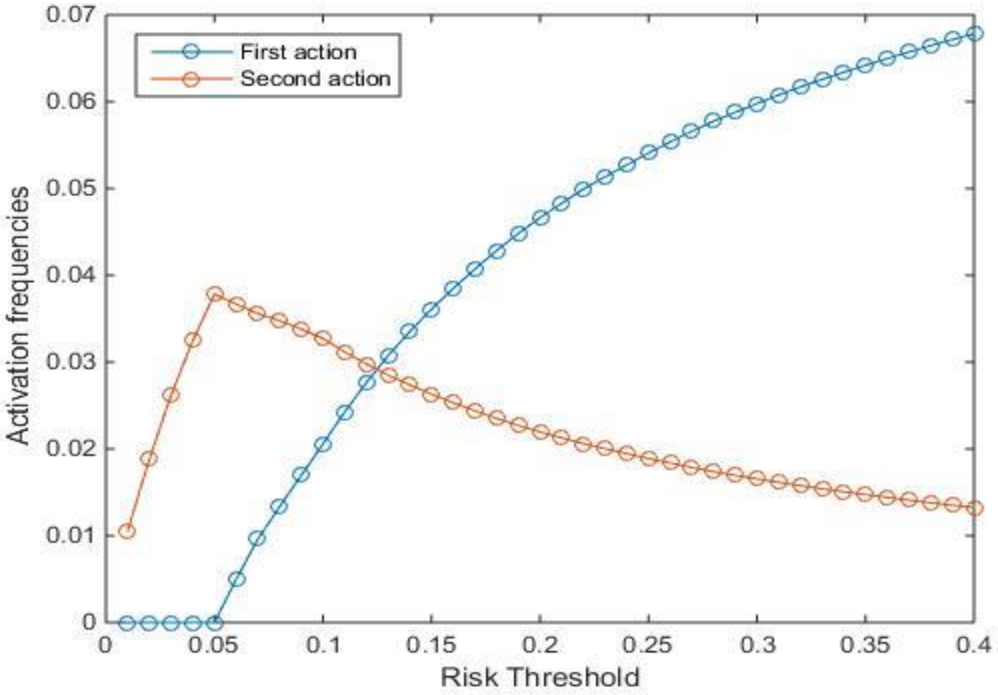


Figure 4.37: MM actions activation frequencies with variable RT, case 3.

Generally the behaviors are similar to the previous ones but with a more clear threshold, as moving from a RT equal to 0.05 to 0.06 changes completely the performance achievable. Indeed between those two RT values a large step is observable, where TH drops of 1% and the policy becomes worse than a random selection. It corresponds also to the point where the longest action begins to be activated, meaning that it is too risky with the parameters of this system.

4.5.4 Case 4: 2 MM actions, low failure rate and low repair rate

In this simulation the risk threshold ranges from 0.01 to 0.4 with a step of 0.01. Now the failure rate is low and the MM tasks duration are set to high values.

Parameter	***Value***
B	15
p_2	0.001
r_2	0.1
n_1	15
n_0	14
tmm1	18
tmm2	15
RT	variable
THb	0.9893
SPb	0.0007

Table 4.43: Parameters of case 4.

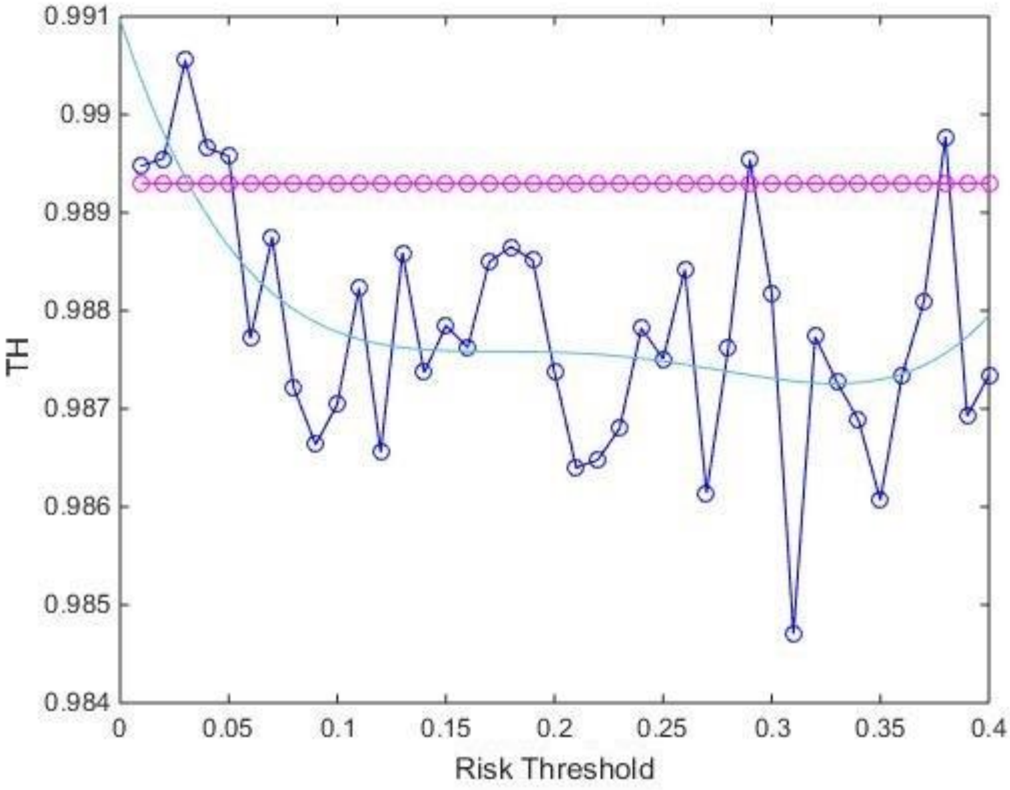


Figure 4.38: TH with variable RT, case 4.

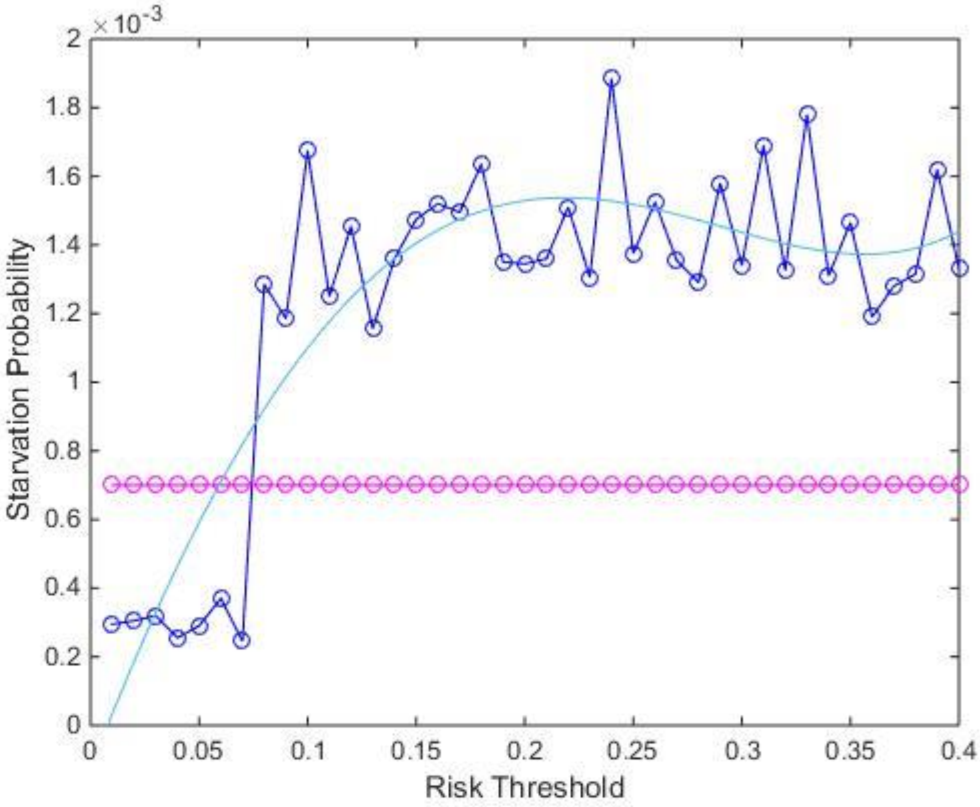


Figure 4.39: Starvation probability with variable RT, case 4.

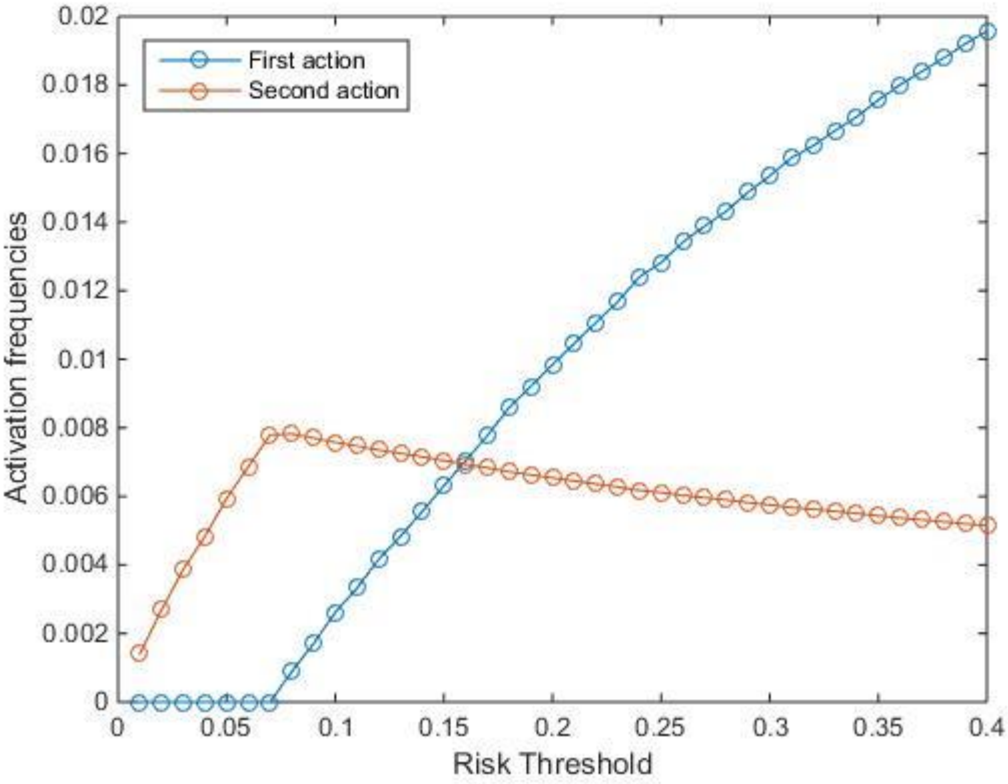


Figure 4.40: MM actions activation frequencies with variable RT, case 4.

Even with a random selection the system performs well, so some performance gain (only up to 0.2% with respect to random selection) is possible only setting very low RT. Also starvation probability is so small that the gain achievable, in this case, is almost null. The real benefit is the possibility to activate the shorter maintenance action, while the longer one is never carried off at low RT levels, because would impact too highly on the system.

All these aspects are due to the low failure rate, which makes available just a minimal range of action to maintenance as the system stops very rarely.

4.5.5 Case 5: 5 MM actions, high failure rate and low repair rate

After having verified that the policy works with two MM actions, two cases are presented now with a more tricky situation where the activities available are five. RT ranges again from 0.01 to 0.4 with a step of 0.01. A 4th grade polynomial approximation fit the path of the data.

Parameter	***Value***
B	20
p_2	0.01
r_2	0.1
n_1	18
n_0	10
tmm1	18
tmm2	16
tmm3	14
tmm4	12
tmm5	10
RT	variable
THb	0.8869
SPb	0.0255

Table 4.44: Parameters of case 5.

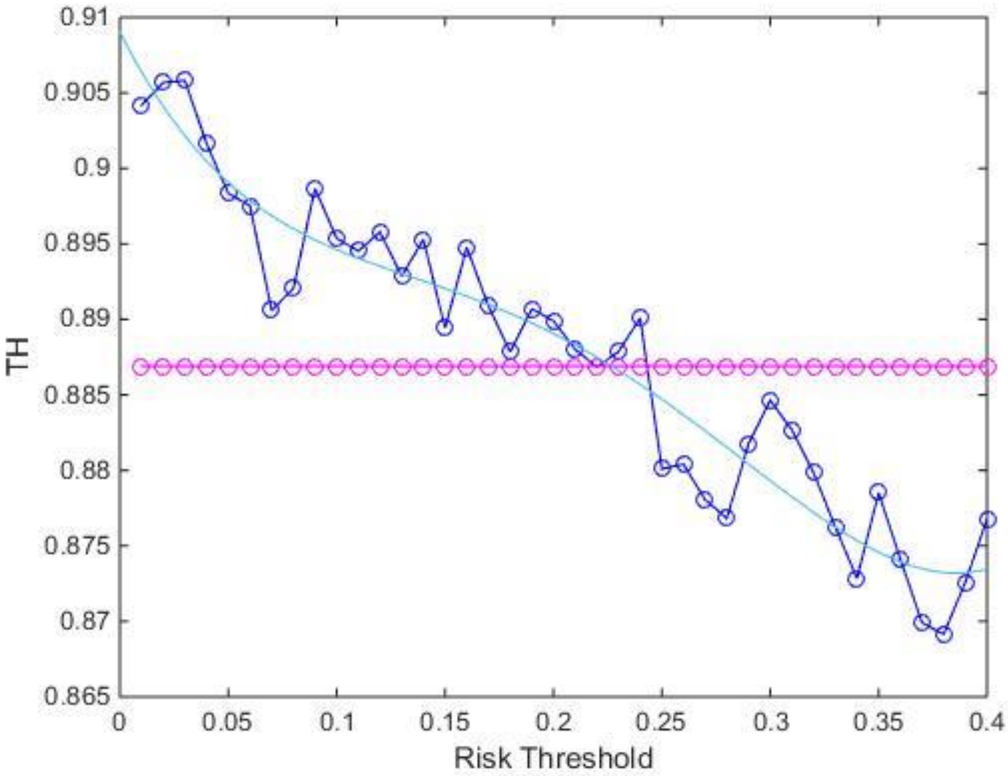


Figure 4.41: TH with variable RT, case 5.

The behaviour of the data looks very straight, almost linear. The most interesting fact is that large RTs are allowed (up to values over 0.2) with performances still better than the random selection. With respect to Case 1, which is similar in parameters but with only two tasks, the allowed RT doubled. Moreover, at the first threshold levels, the gain in TH available with respect to the random selection can be greater than 2%, again twice as Case 1.

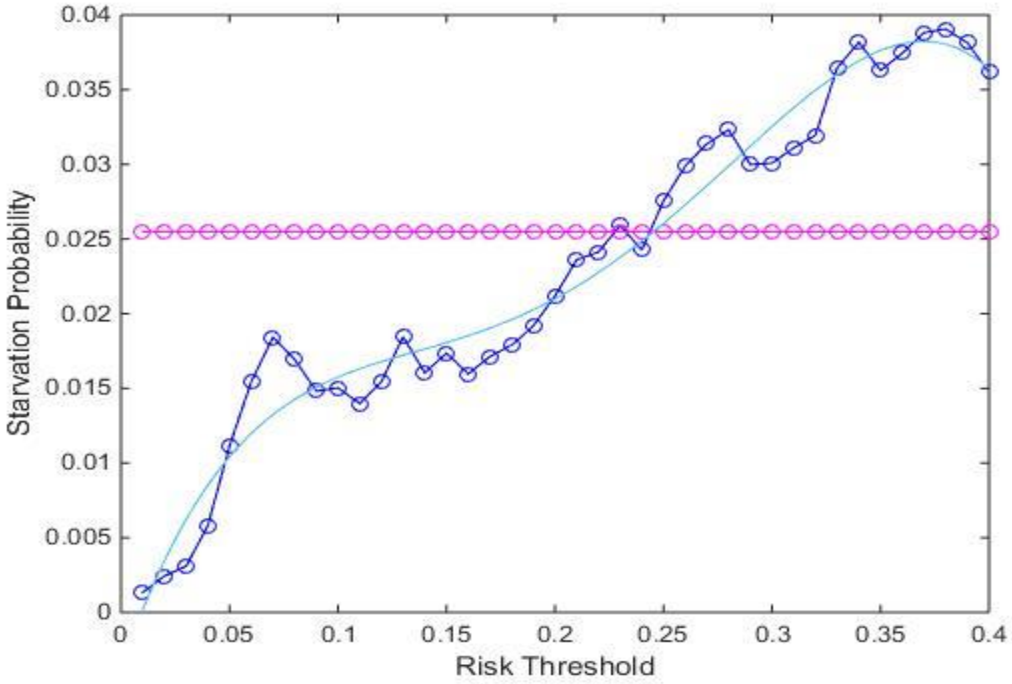


Figure 4.42: Starvation probability with variable RT, case 5.

The same considerations made for the TH are valid also for the starvation probability, where the RT must go up to 0.25 to reach the random selection performances. Even here the gain available at early stages is very high, almost 2.5%.

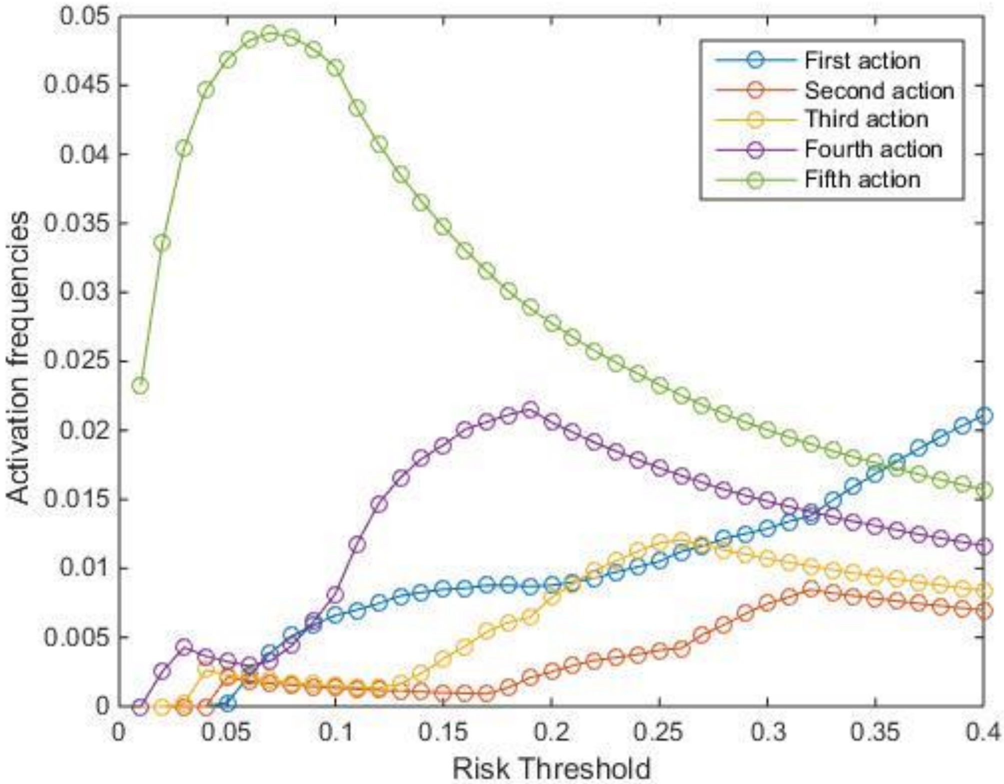


Figure 4.43: MM actions activation frequencies with variable RT, case 5.

It’s possible to notice this behavior for the activations: at the beginning shorter activities are immediately executed (4th and 5th in this case), due to the low acceptable risk. Going on increasing RT also longer activities begin being activated more and more frequently. At the same time, one by one, each of the shortest four activities reaches a peak and the start decreasing. This happens when the RT reaches a value that makes the policy considering more profitable executing a longer tasks (for example 5th activity around 0.07, 2nd activity around 0.32). Therefore exists a RT value over which just the longer activity goes on increasing its frequency. The effect of this process is also recognizable from the first activity path, whose slope becomes more and more steep any time a shorter action starts decreasing.

4.5.6 Case 6: 5 MM actions, high failure rate and high repair rate

In this second case with 5 available interventions, a M_2 easier to repair is considered. RT ranges from 0.01 to 0.4 with a step of 0.01.

Parameter	***Value***
B	10
p_2	0.01
r_2	0.2
n_1	9
n_0	7
tmm1	12
tmm2	10
tmm3	9
tmm4	8
tmm5	6
RT	variable
THb	0.9406
SPb	0.0114

Table 4.45: Parameters of case 6.

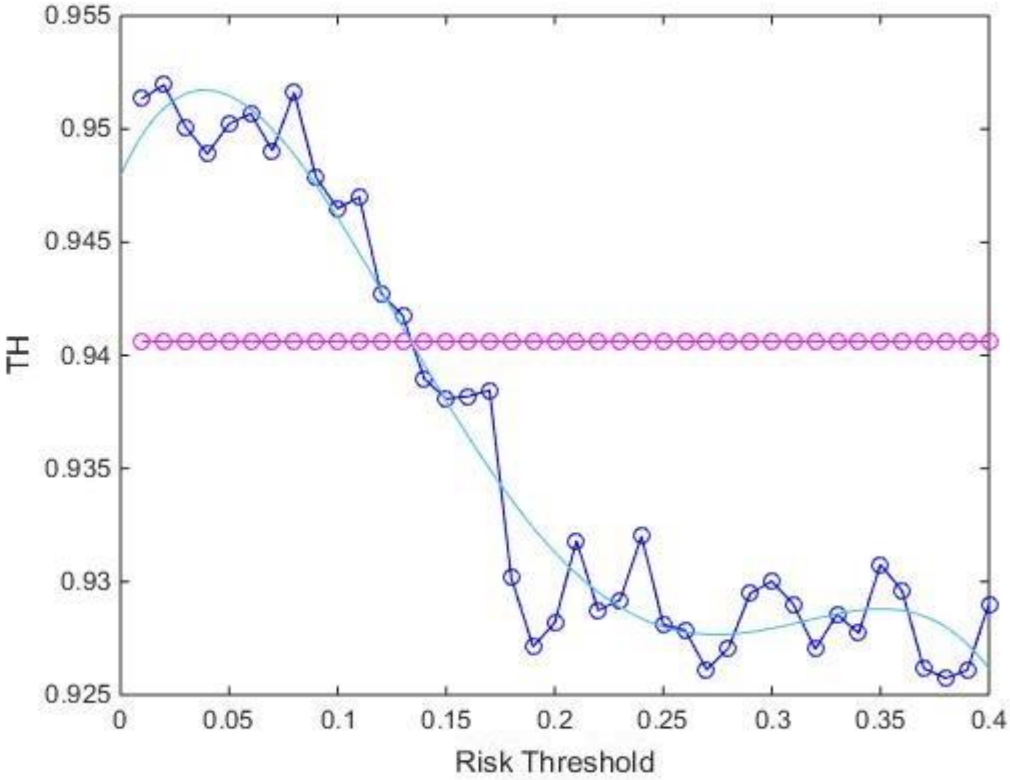


Figure 4.44: TH with variable RT, case 6.

Probably due to the higher r_2 with respect to the previous case, the RT allowable with performance better than random selection is just around 1.13. Anyway, if compared to Case 3, which represents a similar situation but with just two activities, the RT is almost two times greater.

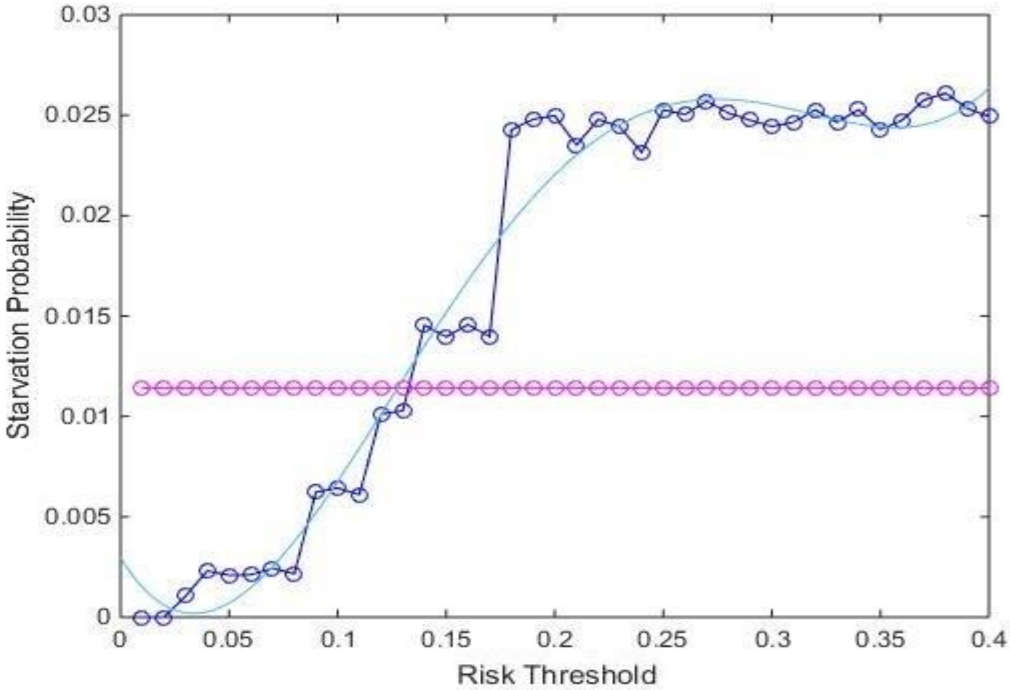


Figure 4.45: Starvation probability with variable RT, case 6.

Same considerations made for the TH holds also for starvation probability: lower RT with respect to Case 5 but twice than Case 3.

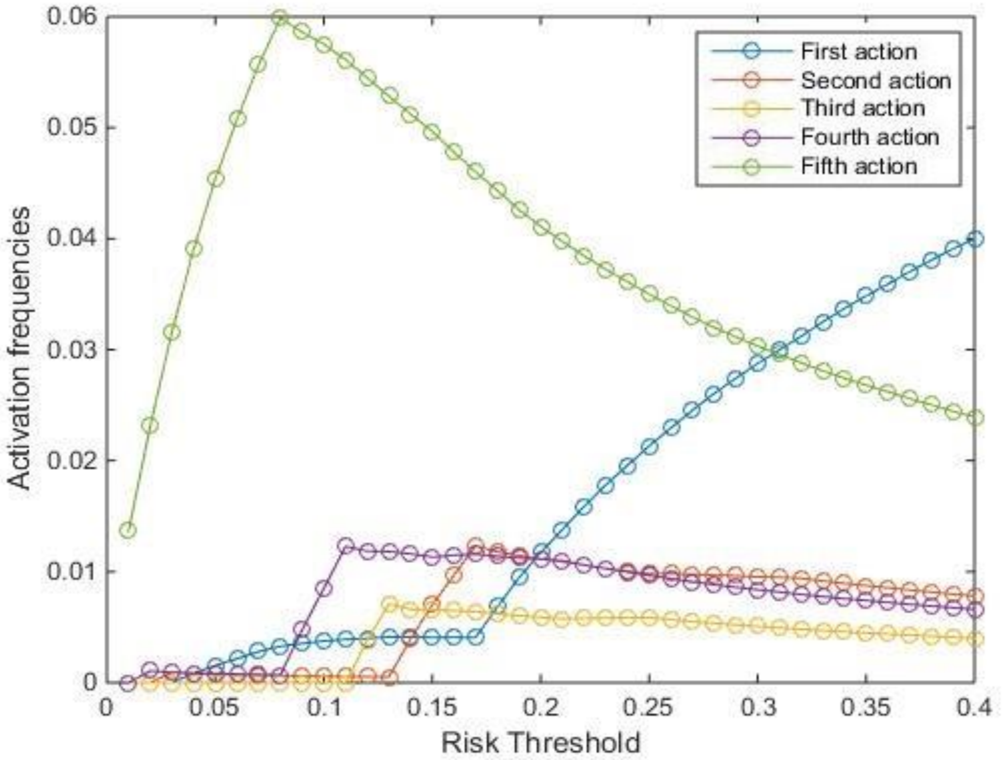


Figure 4.46: MM actions activation frequencies with variable RT, case 6.

Paths of the number of activations present a more clear step, as can be noticed in all the tasks.

Making now an overall consideration over these last two cases, it’s possible to observe that:

- Performance gain achievable with five activities is around twice than with only two activities.
- The same proportion holds also for the RT needed to reach random selection performances. RT is almost two times greater with five actions.

Therefore, with an increased number of available actions, the policy shows even more its strength with respect to the random selection.

4.6 Effects on production

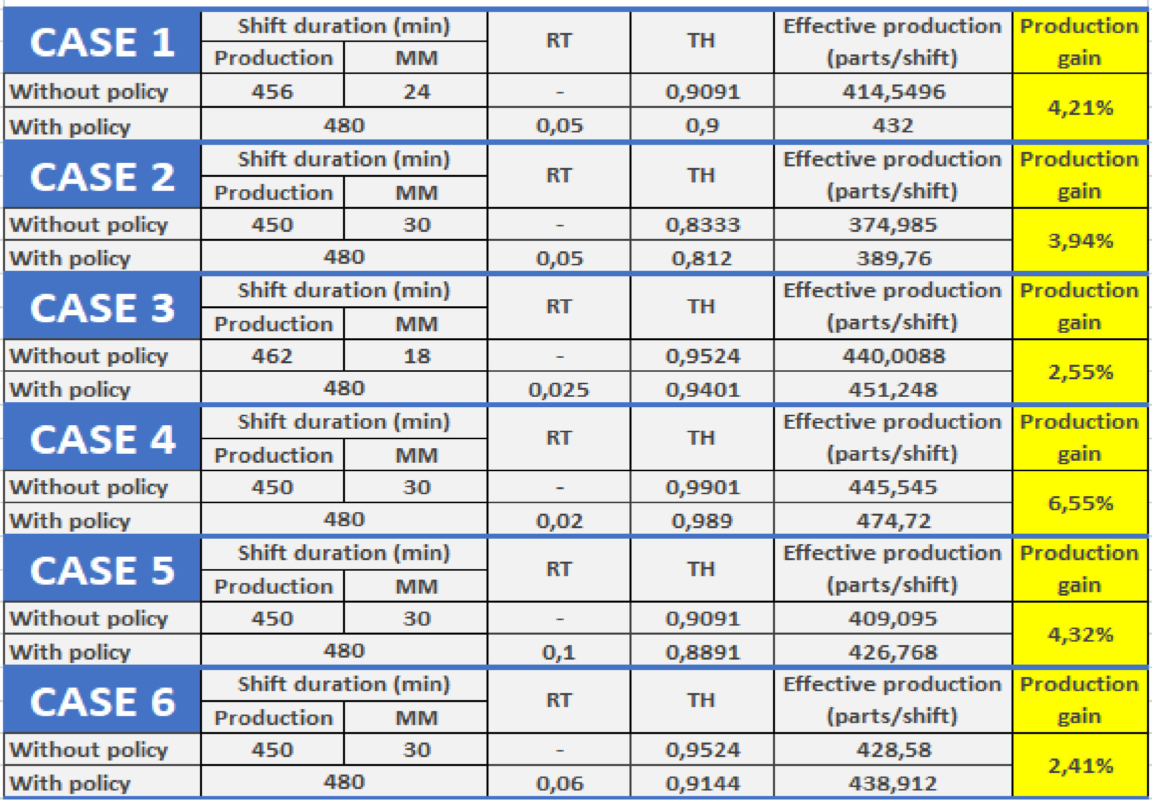
It was described how the policy works and how can be set to achieve benefits. In order to strengthen the validity of this opportunistic policy, a Table 4.46 is presented, which shows how a production gain in the previous six cases is concretely achievable. An 8 hour shift is considered, hence composed of 480 minutes, considering the equality 1 time unit=1 minute.

In the baseline case, without policy applied, a part of these 480 minutes, which is usually placed at the beginning or the end of the shift, is assigned to MM activities. Therefore only the effective production time of these 8 hours will contribute to effective production. The part of the shift allocated to maintenance is calculated as the time required to execute at least once each task on the list (so equal to the sum of the tmm), but a maximum of 30 minutes is set. Therefore Cases 4, 5 and 6 will have only 30 minutes available even if the summation of activities durations trespass this threshold.

In the policy case there isn't this distinction, as maintenance is carried out during production time.

The effective production (real number of parts produced) is equal to the throughput multiplied by the effective production time. In the baseline case TH is higher with respect to the policy case, but less time is available. The RT chosen are in the in the middle of the range with limits RT=0 and RT equal to the value where TH is equal to the random selection situation.

The gain achievable depends clearly on the part of time assigned to MM in each shift, but also on the RT chosen for the policy. Depending on the values set for these parameters in each specific application case the advantages can be more or less consistent.



CASE 1	Shift duration (min)		RT	TH	Effective production (parts/shift)	Production gain
	Production	MM				
Without policy	456	24	-	0,9091	414,5496	4,21%
With policy	480		0,05	0,9	432	
CASE 2	Shift duration (min)		RT	TH	Effective production (parts/shift)	Production gain
	Production	MM				
Without policy	450	30	-	0,8333	374,985	3,94%
With policy	480		0,05	0,812	389,76	
CASE 3	Shift duration (min)		RT	TH	Effective production (parts/shift)	Production gain
	Production	MM				
Without policy	462	18	-	0,9524	440,0088	2,55%
With policy	480		0,025	0,9401	451,248	
CASE 4	Shift duration (min)		RT	TH	Effective production (parts/shift)	Production gain
	Production	MM				
Without policy	450	30	-	0,9901	445,545	6,55%
With policy	480		0,02	0,989	474,72	
CASE 5	Shift duration (min)		RT	TH	Effective production (parts/shift)	Production gain
	Production	MM				
Without policy	450	30	-	0,9091	409,095	4,32%
With policy	480		0,1	0,8891	426,768	
CASE 6	Shift duration (min)		RT	TH	Effective production (parts/shift)	Production gain
	Production	MM				
Without policy	450	30	-	0,9524	428,58	2,41%
With policy	480		0,06	0,9144	438,912	

Table 4.46: TH gain with policy applied.

A production gain is always achieved. This supports once again the value of the model, which was confirmed to be more effective than a random selection, and now even more effective than the case where no policy is applied.

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Chapter 5

Interface

After having showed the effectiveness of the policy, the next step is to find a way to provide to the machine operator the information needed to realize concretely what is elaborated by the policy. A possible idea is to equip each machine work station with an user interface, known also as human-machine interface or man-machine interface, that tells the operator what to do, any moment during production time. After an introduction to interfaces, some ideas about an effective one for the policy will be presented, which can also be an example of device moving a company production process towards industry 4.0.

5.1 Interfaces introduction

An interface is the space where interactions between humans and machines occur. The objective is to optimize the control of the machine by the operators, while the machine or, as in this work case, the system of machines feeds information to improve the effectiveness of the decision making process. Of course real time information availability is a fundamental prerequisite.

The first and very rudimental types of interface appeared around 1945 and initially did not provide any great advantage as they required too much operator effort for their functioning. However, with all the technology development happened till today, interfaces can now be crucial for improving a system utilization and are able to supply great benefits.

It’s not easy to classify user interfaces as they are available in the more various types, so here a list is presented to show how wide is the range of possibilities

- Direct manipulation interface, a human–computer interaction style which involves continuous representation of objects of interest and rapid, reversible, and incremental actions and feedback (Kwon et al, 2011)
- Graphical user interfaces (GUI) accept input via devices such as a mouse and keyboards and provide a graphical out on a monitor.
- Web-based user interfaces, which accept inputs and provide output on the internet. They require a browser.
- Touchscreens, displays that can accept input by touch of a stylus or a finger.
- Hardware interfaces, physical interfaces that generally are made of buttons, sliders, knobs, switches.
- Motion tracking interfaces, which translates motions into commands.
- Non-command user interfaces, which observe the user to infer his / her needs and intentions, without requiring that he / she formulate explicit commands (Nielsen, 1993).
- Voice user interfaces, that can accept input and provide output by voice commands.
- Zero-input interfaces get inputs from a set of sensors instead of querying the user with input dialogs(Sharon, 2003)

- Holographic user interfaces, inputs are provided to equipment by passing a finger through reproduced holographic images of what would otherwise be tactile controls of those devices, floating freely in the air, detected by a wave source and without tactile interaction.

Many other examples could be made, but it's clear that try to make an overall classification is not an easy task. However any interface should have some features that guarantee its quality, and this features must be achieved during the design phase, that usually is accomplished through simulation and prototyping. These features are:

- Clarity, in order to avoid misunderstandings or ambiguity.
- Concision, which means being clear without over-clarifying each element of the interface, because it could make tedious to find out what is really needed, due to the abundance of information provided.
- Familiarity, in order to make to user comfortable with elements which can be familiar even if it's the first time he interacts with the interface.
- Responsiveness, as the interface should give feedbacks to the user about what is going on and whether inputs provided are being are being processed successfully.
- Consistency, because keeping your interface consistent across your application is important because it allows users to recognize usage patterns (Satzinger and Olfman, 1998).
- Efficiency, from a time perspective, through shortcuts and effective design choices which make user activity more productive.
- Forgiveness, as the interface should not just highlight user's errors but also provide possible solutions to solve them.
- Aesthetics, it is probably the least important feature, but making a user spend his time which something that beside doing effectively his work is also good-looking can turn the interaction into a more enjoyable activity.

In the following step a possible development of the interface for the policy will be presented, keeping attention to the quality principles just described.

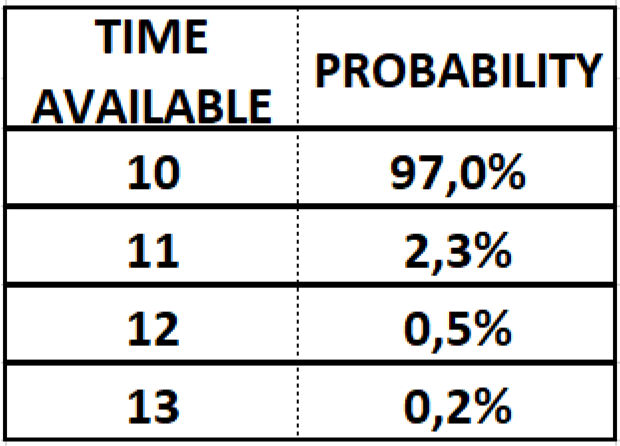
5.2 Interface model

The main principle to keep present is that the interface must help the operator in being effective during his working time. Therefore a crucial feature is that it must be easily accessible to the operator from any possible position that he occupies around his area of competence.

Considering that in this case the interface is represented by a screen, it must be clearly visible, without requiring any special movement from the worker to reach it, in order to face the eventuality in which the operator work is not made always from the same stable position, for example if he has to move to different sides of the production line.

It could be also possible to give to the interface the ability to produce a warning sound to inform the operator without requiring a continuous attention to the screen, so that he can be more focused on his tasks and would check the interface just when the system gets to the activation level. If the system data collection about buffers and machine status is well implemented, it's clear that much human effort will be saved from monitoring the production line.

The question is now what is useful to be shown on the interface. Following the path of this work, the first idea would be to show the time units available when an opportunity comes up, together with the probability of having that duration. This methodology is related to what presented in 3.3.1.



TIME AVAILABLE	PROBABILITY
10	97,0%
11	2,3%
12	0,5%
13	0,2%

Figure 5.1: Interface showing the probabilities of having certain time windows.

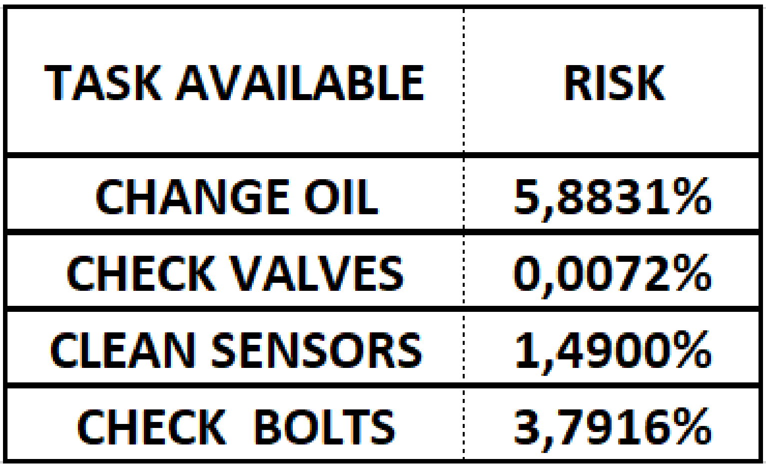
This way the operator will have a certain freedom in his selection of the activity to carry out, but must know the duration of each task. This flexibility could be also useful in case of actions durations affected by external factors (e.g. a tool to perform a certain task not immediately available, some spare parts unavailability, etc).

Another solution is instead basing the interface on what discussed in 4.4. It's possible to show directly on the screen the minor maintenance activity which is better to execute. The activation levels are supposed to be previously set by a supervisor or any person who is on charge of some kind of production process control, in order to achieve a certain trade-off between frequency of intervention and throughput desired. Therefore, when warned, operator will just have to check the screen and carry off the suggested activity. With this method operator would be spoiled of any decision responsibility, as he would simply have to follow the instructions on the screen. Depending on the MM tasks durations, can also happen that the suggested activity is to don't perform anything. Clearly this would not happen if activation levels are set paying enough attention to the activities, because it would make no sense to set a minimum level which can't even guarantee the execution of the shorter task.

CHANGE OIL

Figure 5.2: Interface directly showing the advised task.

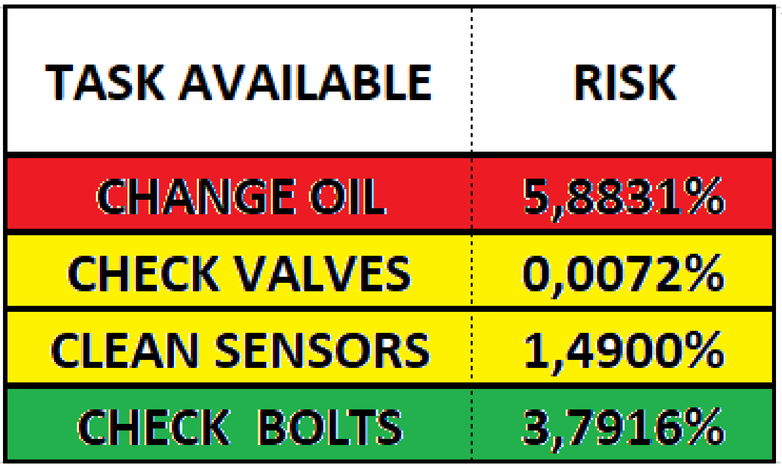
Another option could be instead to show on the screen, whenever an activation level is reached, all the activities with their related starvation risk percentage , and leave to the operator the final choice between them, clearly based on some instructions provided by a supervisor. This way the operator would probably feel more involved in his job thanks to this additional responsibility, but, on the other side, there is a risk of making mistakes which is instead deleted with a screen already showing the selected task. However, with this method a certain flexibility will be always kept, for example if an activity has not been executed for a long time it could be decided to be carried out, even if it is too risky or too short to exploit optimally the time window.



TASK AVAILABLE	RISK
CHANGE OIL	5,8831%
CHECK VALVES	0,0072%
CLEAN SENSORS	1,4900%
CHECK BOLTS	3,7916%

Figure 5.3: Interface showing the available tasks and their related starvation risk.

It could be also possible to guide the operator choice in this case assigning different colors to the activities in order to visually highlight which is the recommended one, the allowed ones and the ones that should be avoided

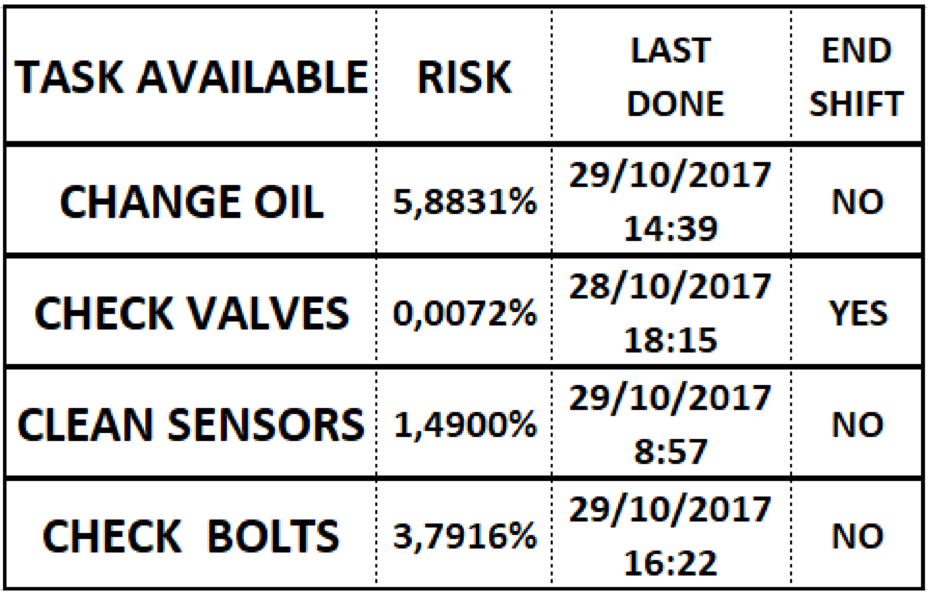


TASK AVAILABLE	RISK
CHANGE OIL	5,8831%
CHECK VALVES	0,0072%
CLEAN SENSORS	1,4900%
CHECK BOLTS	3,7916%

Figure 5.4: Interface showing the available tasks and their related starvation risk with suggestions(red for avoid, green for suggested, yellow for allowed).

In this case checking bolts is the suggested task, checking valves and cleaning sensors could be executed too while instead changing oil is not recommended.

Another feature that could be useful is an indication, in the selection interface, about the last day and hour an MM activity has been carried off. This way the operator, if well instructed and experienced, should be able to balance risk and frequency of the executions. Moreover, to further optimize the choice, also an indicator could be inserted showing if the activity will have to be executed anyway at the end of the shift or there won't be this immediate need, creating a sort of priority suggestion.

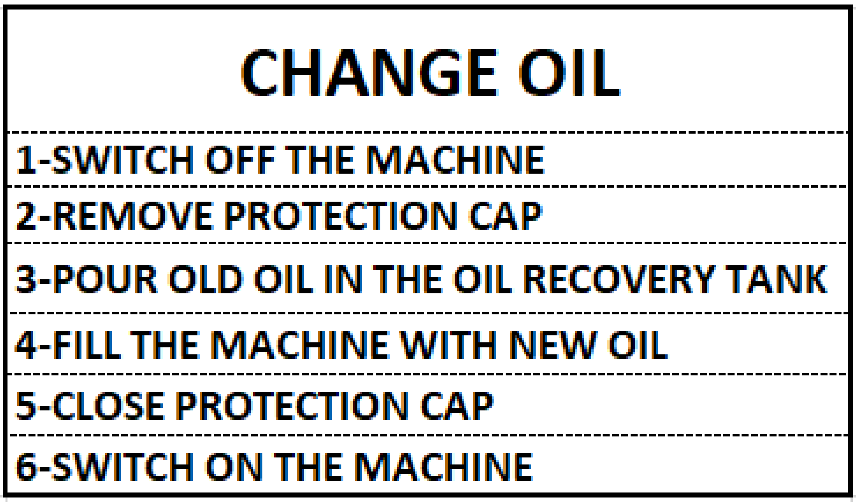


TASK AVAILABLE	RISK	LAST DONE	END SHIFT
CHANGE OIL	5,8831%	29/10/2017 14:39	NO
CHECK VALVES	0,0072%	28/10/2017 18:15	YES
CLEAN SENSORS	1,4900%	29/10/2017 8:57	NO
CHECK BOLTS	3,7916%	29/10/2017 16:22	NO

Figure 5.5: Interface showing available tasks and their risk, last execution and if the execution would be mandatory before next shift.

Another possibility would be also showing a predicted optimal date and execution time instead of the last column in the previous figure. Also the deterministic duration time could be shown beside the information already listed. It's easy to understand that the possible combinations available are a lot, so a choice of what will be communicated to the operator must be carefully evaluated by the decision maker.

In any case, when a selection is finally available, made automatically or by the operator, for sure it would be useful to provide on the interface a description of the desired task, in order to remember, all the time it is activated, its correct execution to the operator. Beside the execution, it can be crucial to stress also the safety perspective of each task, continuously trying to avoid injuries or dangerous situation.



CHANGE OIL

1-SWITCH OFF THE MACHINE

2-REMOVE PROTECTION CAP

3-POUR OLD OIL IN THE OIL RECOVERY TANK

4-FILL THE MACHINE WITH NEW OIL

5-CLOSE PROTECTION CAP

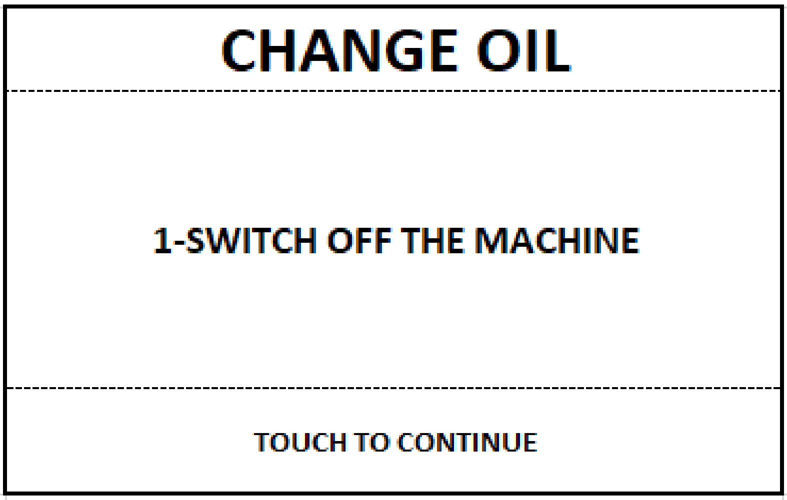
6-SWITCH ON THE MACHINE

Figure 5.6: Interface showing task instructions.

A further step to improve the execution can be also to attach some pictures or drawings to provide further details to some specific points of an activity list. An example could be to attach a picture of the position of the protection cap of point 2 in the previous figure in order to help new operators, who are not still familiar with the machine, to speed up their execution without wasting time looking for the cap. However this should be done only when strictly required, in order to follow the concision principle.

Another interesting point is if it’s better to have an active or passive interface. The two previous ideas can work as examples, as in the first case the operator just acquire information by the screen without any interaction except a visive one to receive the indications, while in the second case the choice made, before being executed, must be also somehow recorded, in order to have in the informatics system a register of what has been done to a machine. Therefore the operator will actively interact with interface trough something like buttons, dashboards or even without any additional hardware in case of a touchscreen monitor, to make his selection registered in the company system.

In this last case the interaction is mandatory, because the interface is making the operator touching the screen to make appear the instruction list. The instruction list could be also furtherly split, displaying just one instruction point at a time and forcing an interaction to move to the next one. This way it will be less probable the risk of skipping a point of the list.



CHANGE OIL

1-SWITCH OFF THE MACHINE

TOUCH TO CONTINUE

Figure 5.7: Interface that requires interaction to move through the instructions list.

Another possible improvement is to implement a measurement of response time for the operator to begin the MM task and real total duration, which in this work is assumed deterministic but in reality can vary from operator to operator. This will make possible analysis for example about the responsiveness of workers to the warning signal, real time task duration and even the duration of each single instruction. Moreover, making each operator login on the interface at the beginning of his shift, data about his behavior in term of speed and tendency towards suggested or more risky or more safe selection will become available. These data will provide a great benefit to production, because it will tell how an operator behaves and if his selections and working times are in an acceptable range and, from the other side, if a general mismatch between real data collected and theoretical values appears, a revision of policy parameters can be made. For example, if the shortest MM activity is on average found to last, in real interventions, less than the duration assigned in the policy software, its deterministic value can be lowered and the activation levels can be raised, with a consequent benefit in terms of production rate.

Note that increasing activation levels could also decrease activation frequency, so each change in the policy parameters is important to be always deeply evaluated in order to check if increasing a certain performance can lead to some advantages from other perspectives.

Finally, it seems that an active interface which, apart from providing data, also collects data, could create more value for a company. Indeed it could save resources directly, optimizing policy parameters to improve production, but also and indirectly, because it will be not needed to charge someone of time measurements tasks about times and operators’ selection choices as all the data will be directly available in a database, complete and eventually even personalized for each worker, instead of samples taken randomly.

Chapter 6

Conclusions

In this work an opportunistic policy is developed and studied in all its parameters. Benefits and possible risks are investigated.

The manufacturing system under evaluation is composed by two machines, with an intermediate buffer of finite capacity. System has the following behavior:

- Upstream machine is totally reliable, therefore it never fails, but must undergo some MM interventions. MM interventions have deterministic durations. Downstream machine is instead unreliable and characterized by one failure mode.
- System conditions are identified by the states of the machines and the buffer level.
- Maintenance strategy is a combination of corrective maintenance and minor maintenance.

MM is activated on the upstream machine whenever an opportunity arises. Opportunities depend on the reliability of downstream machine and the buffer level. Maintenance is always activated over a certain buffer level, or even at lower levels if downstream machine fails.

This method creates an additional risk of losing throughput, with respect to a situation where the policy is not applied, because it can happen that an MM action exceeds the opportunity window. This is due to the fact that the opportunity window is not deterministic but based on a probability distribution. However it is showed how this risk can be managed and kept under control. With the policy, even if the throughput is lower, more time becomes available for production. It is demonstrated how this larger effective production time compensates the lower throughput and allows an overall larger real production.

In addition also the frequency of maintenance can be controlled and increased, keeping this way the upstream machine, on average, in a better condition.

In Chapter 4 the policy is deeply analyzed in order to find out the most influencing factors and how they should be set in order to achieve a performances basic optimization. The risk threshold concept is introduced, in order to guide the software in the choice of what to suggest during opportunities. Results are then presented, proving the production gains achievable with respect to a random selection and the baseline case without policy applied.

Chapter 5 finally shows a possible implementation of the policy at operator location, through the installation of an interface which can guide his behavior when opportunities become available during production time. This is intended to be a base to make the step from theory to real application, giving a brainstorming about how an efficient a tool should appear and work in the situation under evaluation.

6.1 Future research

This work is developed on a basic manufacturing system and has to be considered as a step toward the concrete implementation of an effective opportunistic maintenance in real factories. There are many strong hypothesis which should be relaxed and aspects that need to be developed, in order to check the model even in a more general context:

- Upstream machine total reliability is clearly a very strict assumption and should be relaxed. This will give the opportunity to introduce the opportunity to carry out MM interventions also on the downstream machine.
- The policy should be verified also on longer and more complex lines, with more machines, buffers and different configurations.
- Deterministic durations of MM tasks could instead follow a probability distributions.
- More than one failure mode for the downstream machine can be considered, but also for the first machine, once the total reliability assumption is removed.
- It would be interesting to introduce the concept of machines degradation in the model.
- The policy should be tested also considering a larger MM actions list and different prioritization rules.
- The decisional method based only on the risk threshold can be complicated in order to check if the policy can become even more effective (taking into account for example a particular execution frequency required for each task, an importance ranking, etc).

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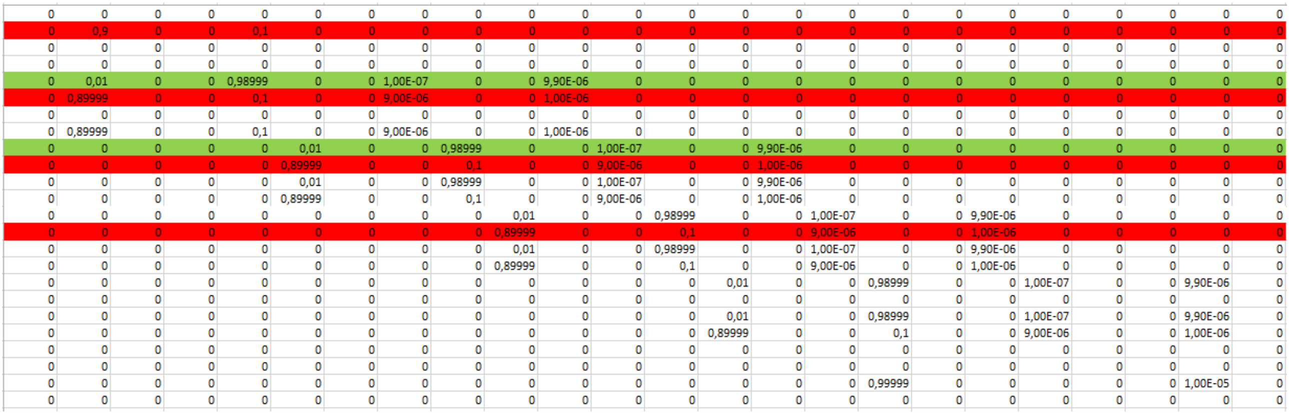
Appendix A: Construction of the probability matrix

In order to better understand the construction of matrix P, figures are provided, in the case of B=5, n_0=2, n_1=3, tmm=3.



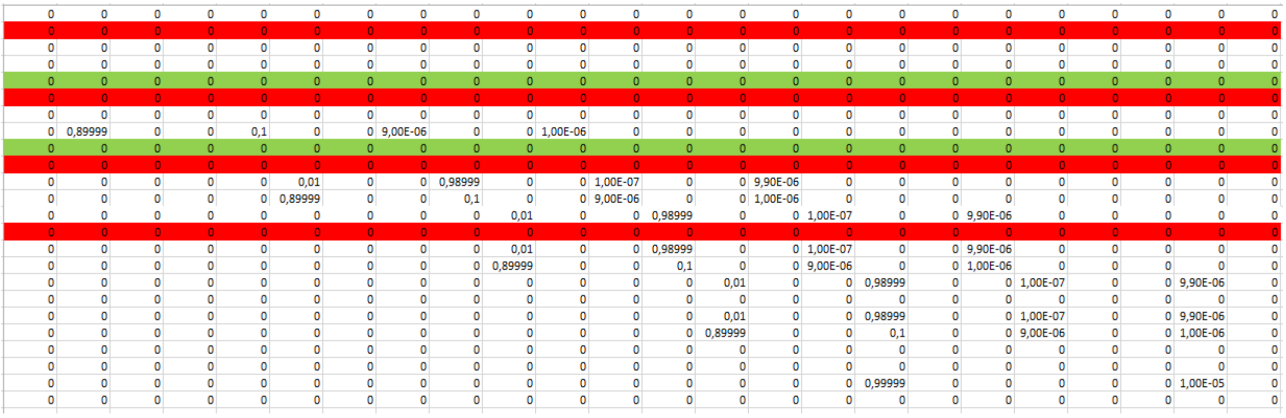
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0,9	0	0	0,1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0,01	0	0	0,98999	0	0	1,00E-07	0	0	9,90E-06	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0,89999	0	0	0,1	0	0	9,00E-06	0	0	1,00E-06	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0,89999	0	0	0,1	0	0	9,00E-06	0	0	1,00E-06	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0,01	0	0	0,98999	0	0	1,00E-07	0	0	9,90E-06	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0,89999	0	0	0,1	0	0	9,00E-06	0	0	1,00E-06	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0,01	0	0	0,98999	0	0	1,00E-07	0	0	9,90E-06	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0,89999	0	0	0,1	0	0	9,00E-06	0	0	1,00E-06	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0,01	0	0	0,98999	0	0	1,00E-07	0	0	9,90E-06	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0,89999	0	0	0,1	0	0	9,00E-06	0	0	1,00E-06	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0,01	0	0	0,98999	0	0	1,00E-07	0	0	9,90E-06	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0,89999	0	0	0,1	0	0	9,00E-06	0	0	1,00E-06	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0,01	0	0	0,98999	0	0	1,00E-07	0	0	9,90E-06	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0,01	0	0	0,98999	0	0	1,00E-07	0	0	9,90E-06	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0,89999	0	0	0,1	0	0	9,00E-06	0	0	1,00E-06	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0,99999	0	0	0	0	0	1,00E-05	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure A.1: Initial transition matrix P.

It's important to note that some states are not possible, and remain not possible after the implementation of the policy too, according to Figure 3.14.

Running the software now, as it could be expected, the TH lost and starvation probability are almost equal to zero, because M_1 is totally reliable so the only starvation state (0,D,U) is practically unreachable.

The next step is the innovative part, where a modification of the probability matrix is developed in order to model the opportunistic policy. First the rows of the matrix from B to n_0 (and M_2 down, highlighted in red in the figures) and to n_1 (and M_2 up, highlighted in green in the figures) are deleted. Then, for each buffer level, the quantities of the distribution p (for the levels from n_1 to B and M_2 up) and q (for the levels from n_0 to B and M_2 down) are calculated.

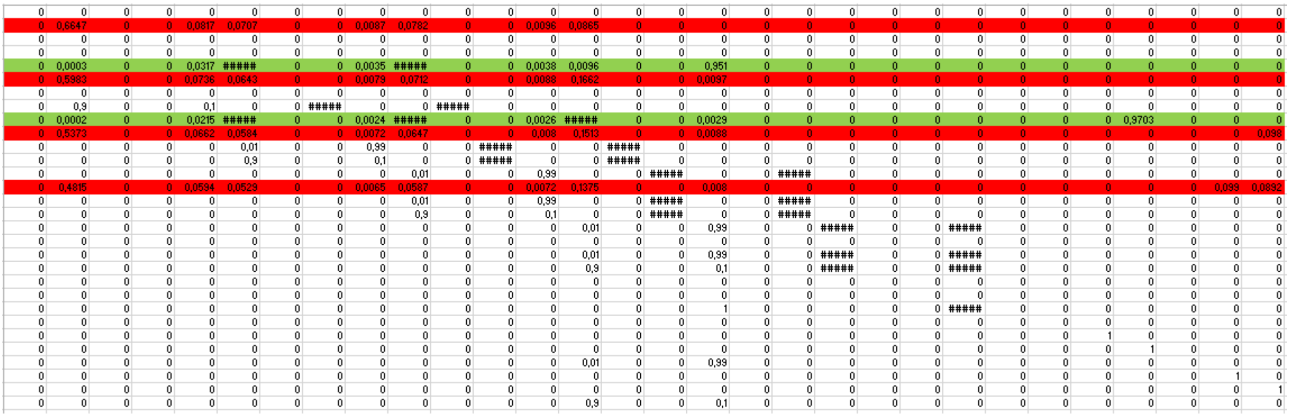


0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0,89999	0	0	0,1	0	0	9,00E-06	0	0	1,00E-06	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0,01	0	0	0,98999	0	0	1,00E-07	0	0	9,90E-06	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0,89999	0	0	0,1	0	0	9,00E-06	0	0	1,00E-06	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0,01	0	0	0,98999	0	0	1,00E-07	0	0	9,90E-06	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0,01	0	0	0,98999	0	0	1,00E-07	0	0	9,90E-06	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0,89999	0	0	0,1	0	0	9,00E-06	0	0	1,00E-06	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0,01	0	0	0,98999	0	0	1,00E-07	0	0	9,90E-06	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0,01	0	0	0,98999	0	0	1,00E-07	0	0	9,90E-06	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0,89999	0	0	0,1	0	0	9,00E-06	0	0	1,00E-06	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0,99999	0	0	0	0	0	1,00E-05	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure A.2: P with values deleted in the highlighted rows.

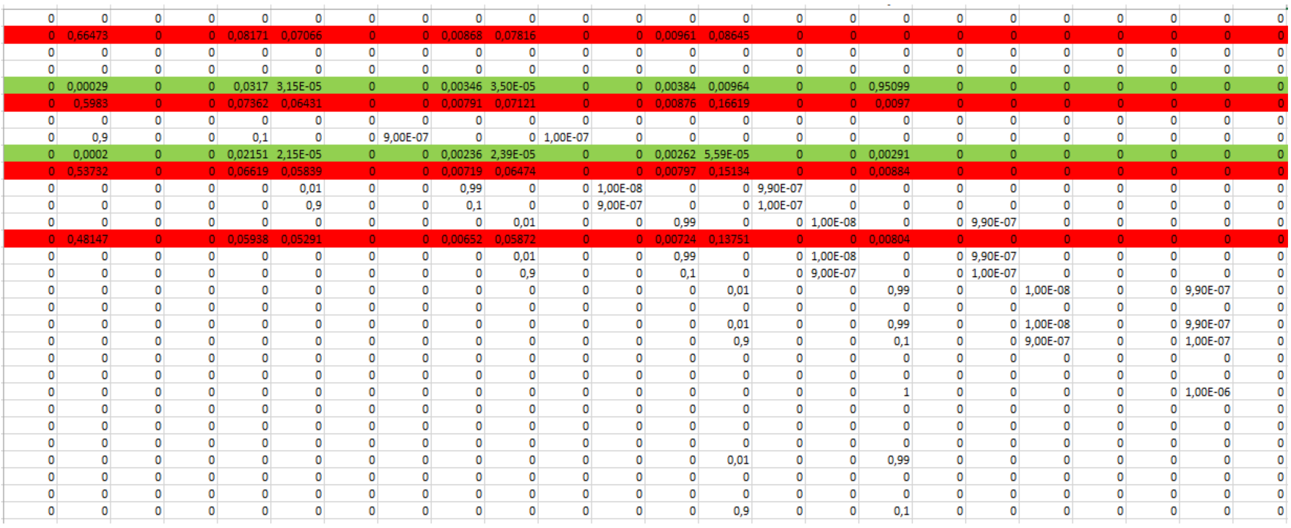
These just calculated quantities are than spread through the relative rows with a logic. The first tmm units of the distributions, which refer to the probabilities of the system going to starvation, are placed in the new starved states, that represent the starvation of

M_2 due to the policy. The remaining probabilities are placed in the states already existing, and represent the probability of having a time window long enough to avoid starvation. Longer windows will correspond to going back to a state with an higher buffer level. It's important then to split these probabilities between the up and down states of each level subjected to maintenance.



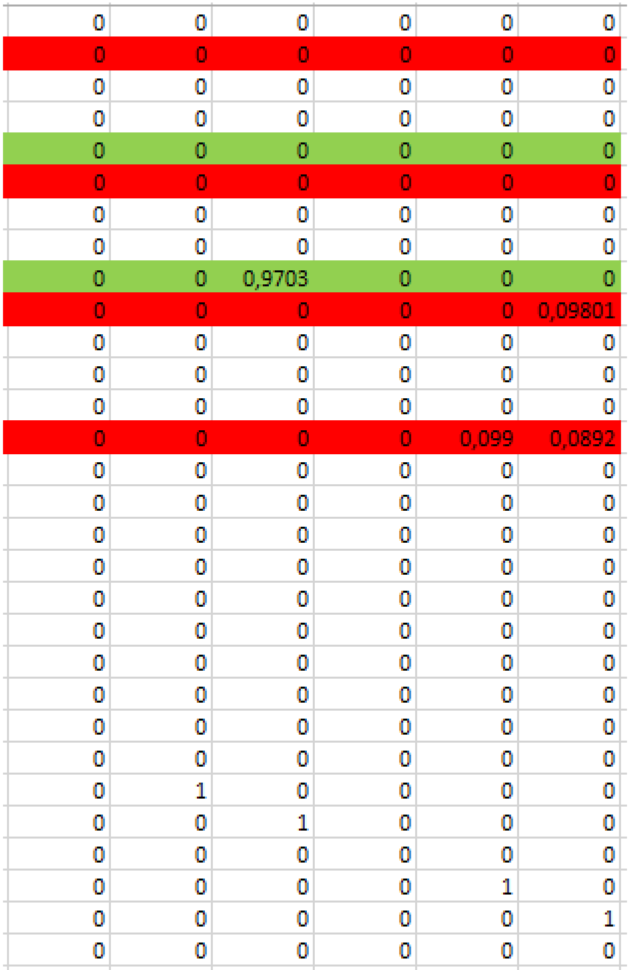
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0,6647	0	0	0,0817	0,0707	0	0	0,0087	0,0782	0	0	0,0096	0,0865	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0,0003	0	0	0,0317	#####	0	0	0,0035	#####	0	0	0,0038	0,0096	0	0	0,951	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0,5983	0	0	0,0736	0,0643	0	0	0,0079	0,0712	0	0	0,0088	0,1662	0	0	0,0097	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0,9	0	0	0,1	0	0	#####	0	0	#####	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0,0002	0	0	0,0215	#####	0	0	0,0024	#####	0	0	0,0026	#####	0	0	0,0029	0	0	0	0	0	0	0	0	0	0,9703	0	0	0
0	0,5373	0	0	0,0662	0,0584	0	0	0,0072	0,0647	0	0	0,008	0,1513	0	0	0,0088	0	0	0	0	0	0	0	0	0	0	0	0	0,098
0	0	0	0	0	0,01	0	0	0,99	0	0	#####	0	0	#####	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0,9	0	0	0,1	0	0	#####	0	0	#####	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0,01	0	0	0,99	0	0	#####	0	0	#####	0	0	0	0	0	0	0	0	0	0	0
0	0,4815	0	0	0,0594	0,0529	0	0	0,0065	0,0587	0	0	0,0072	0,1375	0	0	0,008	0	0	0	0	0	0	0	0	0	0	0	0,099	0,0892
0	0	0	0	0	0	0	0	0	0,01	0	0	0,99	0	0	#####	0	0	#####	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0,9	0	0	0,1	0	0	#####	0	0	#####	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0,01	0	0	0,99	0	0	#####	0	0	#####	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0,01	0	0	0,99	0	0	#####	0	0	#####	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0,9	0	0	0,1	0	0	#####	0	0	#####	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	#####	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0,01	0	0	0,99	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
0	0	0	0	0	0	0	0	0	0	0	0	0	0,9	0	0	0,1	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure A.3: The new P.



0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0,66473	0	0	0,08171	0,07066	0	0	0,00868	0,07816	0	0	0,00961	0,08645	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0,00029	0	0	0,0317	3,15E-05	0	0	0,00346	3,50E-05	0	0	0,00384	0,00964	0	0	0,95099	0	0	0	0	0	0	0
0	0,5983	0	0	0,07362	0,06431	0	0	0,00791	0,07121	0	0	0,00876	0,16619	0	0	0,0097	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0,9	0	0	0,1	0	0	9,00E-07	0	0	1,00E-07	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0,0002	0	0	0,02151	2,15E-05	0	0	0,00236	2,39E-05	0	0	0,00262	5,59E-05	0	0	0,00291	0	0	0	0	0	0	0
0	0,53732	0	0	0,06619	0,05839	0	0	0,00719	0,06474	0	0	0,00797	0,15134	0	0	0,00884	0	0	0	0	0	0	0
0	0	0	0	0	0,01	0	0	0,99	0	0	1,00E-08	0	0	9,90E-07	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0,9	0	0	0,1	0	0	9,00E-07	0	0	1,00E-07	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0,01	0	0	0,99	0	0	1,00E-08	0	0	9,90E-07	0	0	0	0	0
0	0,48147	0	0	0,05938	0,05291	0	0	0,00652	0,05872	0	0	0,00724	0,13751	0	0	0,00804	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0,01	0	0	0,99	0	0	1,00E-08	0	0	9,90E-07	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0,9	0	0	0,1	0	0	9,00E-07	0	0	1,00E-07	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0,01	0	0	0,99	0	0	1,00E-08	0	0	9,90E-07	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0,01	0	0	0,99	0	0	1,00E-08	0	0	9,90E-07	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0,9	0	0	0,1	0	0	9,00E-07	0	0	1,00E-07	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1,00E-06	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0,01	0	0	0,99	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0,9	0	0	0,1	0	0	0	0	0	0	0

Figure A.4: Left part (A and C).



0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0,9703	0	0	0
0	0	0	0	0	0,09801
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0,099	0,0892
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	1	0	0	0	0
0	0	1	0	0	0
0	0	0	0	0	0
0	0	0	0	1	0
0	0	0	0	0	1
0	0	0	0	0	0

Figure A.5: Right part (B and D).

The movement through the starved states is modelled with probabilities equal to 1, as a consequence of the deterministic duration of the MM activity, until the final step which brings back to the buffer states (first three columns for p, second three for q in the lower part of Figure A.5). These last probabilities must be split between the up and down state, at the lower accessible buffer levels ((1,U,U) and (2,U,D), in the lower part of Figure A.4).

As some states are not accessible, some probabilities are moved in the line after the creation of the matrix (summed to the next or previous buffer level). They are initially in the wrong positions to facilitate the automated modification of the initial probability matrix, for example as in the case of the spread probabilities going to the state (B,U,U), summed in the state (B-1,U,U).

Increasing the length of the vector of the initial state probability in order to consider the new starved states it's now possible to evaluate the performance of the system, and in particular the TH achievable and the starvation risk generated by the policy.