Recent Advances in Maintenance and Infrastructure Management

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Preface

This edited volume is the culmination of research presented at the past three International Conferences on Maintenance Management. These conferences are organized and promoted by CNIM (Italian National Committee for Maintenance) in conjunction with UNI (Italian Organization for Standardization) and CEN (European Committee for Standardization). The papers presented at this conference cover both theoretical issues and experimental techniques across a broad range of research and application maintenance management topics. The conferences have become the technical reference appointment for the field of maintenance, providing opportunities for an interesting exchange of ideas among academicians, technicians and field operators.

CNIM is a non-profit organization, which was founded in 1990 under the high patronage of the Italian Industry Ministry. With their legislative decree of December, 16th 1999, the Italian Ministry of Industry assigned to the CNIM the mission of coordinating all studies and research to develop the competence of Companies working or involved in the field of maintenance. Thus, the main objectives of the CNIM are the promotion, development and spreading of the culture of maintenance and innovation. Its main activities concern research, training, standardization, information and certification. The authors would like to gratefully acknowledge the support of CNIM, for without its active role in organizing and promoting the International Conferences on Maintenance Management this volume would not have been possible.

Additionally, we could not have completed our work without the supportive contributions of several individuals. First, Serena Liccardi coordinated and facilitated our collaboration on this book project. Second, Francesca Zucchi assisted us in preparing our manuscript for the published. Third, Stefano Valentini and Angelo N. Villa offered helpful suggestions for improving parts of this manuscript. We thank them for their assistance.

We must also thank the numerous scholars whose work is included in this volume. Their commitment to better understanding the field of maintenance and how it must be managed is to be commended. We look forward to learning more from their efforts in the years to come.

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1 Introduction

The etymology of the word maintenance can be traced to the need to appropriately preserve an asset. In this sense, maintenance can be considered an extremely ancient technical activity, at least as old as the activity of construction. The term *maintenance* has gradually been extended in step with industrial evolution (Fedele *et al.*, 2004). The term formerly referred to an auxiliary service in support of production in industrial companies, which was completely subordinate to production itself; and for civil works it referred to intervention for repairs or elimination of individual building or structure deterioration. Today, in every context of civil and industrial engineering, maintenance has a much wider meaning, including all actions taken to preserve even complex systems, with respect to their consistency and efficiency. Thus, the scope of maintenance has grown to include not only system repair, but also system safety, economic viability, quality, and the most appropriate use of environmental resources.

At the same time the need for maintenance has also grown as industrialization, transportation, and urbanization have undergone unprecedented growth in recent decades. With such technological evolution, maintenance has become more integrated into organizations. The field of infrastructure management has been developed to facilitate this integration. Infrastructure management employs a standardized, holistic approach to coordinating the physical workplace with the people and functions of the organization. It also integrates the principles of business administration, architecture, and the behavioural and engineering sciences. Together, therefore, maintenance and infrastructure management represent "a complex business area, entailing different processes and requiring the integration of a wide range of competences in order to provide an effective service to the customers" (Cigolini *et al.*, 2008).

Today, maintenance and infrastructure management activities have great economic value in at least two ways. First, they provide value to an organization because maintenance and infrastructure management activities may be characterized as high value added, while at the same time requiring relatively low specific investment. Moreover, they involve all three phases (construction, use and conservation) in the life of any instrumental asset. This economic value is further accentuated when developed countries are going through a phase of limited expansion of the productive system, as they are in this period; therefore the conservation of the means and infrastructures of production is particularly important. Alternatively, in recently industrialized countries, careful development in harmony with environmental and energy requirements are essential and must be undertaken through well-planned maintenance and infrastructure management activities.

The second way in which maintenance and infrastructure management activities provide economic value is through job creation (Fedele *et al.*, 2004). Indeed, these activities arise out of permanent requirements within an organization that must be met. Thus, a growing number of maintenance and infrastructure management companies have been started, due to the trend towards outsourcing tertiary activities. With increasing frequency, composite services are offered, with full responsibility for the results being taken by the enterprise (result multiservice; called “global service” in Italy), or a variety of services are offered in a topographically limited environment (facility management). In effect, the expansion of the tertiary sector has enabled enterprises that perform maintenance and/or infrastructure management services for many different companies to realize important scale economies, improve the level of personnel utilization and obtain greater uniformity in employment levels and service quality.

This state of affairs has created enormous potential. Nevertheless, maintenance and infrastructure management programs have not always implemented in the most desirable manner, for a variety of reasons. Recent advances have been made, however, through research activities focused on understanding how best to deliver maintenance and infrastructure management services. The purpose of this volume is to highlight the state-of-the-art in maintenance and infrastructure management. The papers included were written by some of the most active and well-known researchers and practitioners in the field from multiple disciplines representing countries from around the world. These experts presented their findings during the past three International Conferences on Maintenance Management held in 2005, 2006, and 2007. The conferences were organized by the Italian National Committee for Maintenance (CNIM), jointly with the European Committee for Standardization (CEN), the Italian Organization for Standardization (UNI), the Sapienza University of Rome, and the Politecnico di Milano.

The selection of papers presented in this volume represents the best papers presented at the Maintenance Management conferences. They have been categorized into four thematic areas:

1. reliability and maintenance;
2. mathematical modelling and metrics for maintenance;
3. maintenance management and organization; and
4. facilities management, outsourcing, and contracting.

The papers cover topics ranging from embedded sensors for structural diagnostics to organizational issues related to effective maintenance planning.

In summary, maintenance and infrastructure management are at the center of a strategic crossroads for the economic and social development of countries, first and foremost of which is the citizens’ quality of life and their social development. Indeed, maintenance and infrastructure management are necessary to maintain and improve a high standard of living for a host of reasons. For instance, they ensure safety in productive activities and improved utilization of all of a country’s infrastructures. Such activities can also help a country work toward the preservation of the environment through a more rational and long lasting utilization of all productive resources. Finally, maintenance and infrastructure management are essential components of economic viability as they promote more efficient management and conservation of civil and industrial assets. Through this volume, we hope to provide a snapshot of the latest developments with respect to tools and techniques available to maintain and manage complex infrastructures and systems.

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2 Technologies for Dependability and Maintenance

Lorenzo Fedele

Abstract. Maintenance is the science that studies the compendium of technical and management actions, from the point of view of planning as well as management, which enable an organisation to perform economic, safe, efficient and environmentally effective management, according to established quality standards, of any type of asset or group of assets (Fedele *et al*., 2004).Considering the general applicability to any merchandise, technical and productive sector, as well as the strategic scope of this science for the continuance of human livelihood, maintenance is one of the systems theory sciences, to which the general principles of systems engineering apply.

2.1 Introduction

The mathematical and theoretical basis upon which maintenance rests can be found in reliability engineering. Indeed, reliability engineering provides the mathematics, statistical, and analytical instruments to understand the logic of a technical system's operations, including the manner in which they breakdown and estimates of the probable requirements for repair. The fundamental role of this science in maintenance is therefore self-evident. Knowledge of reliability engineering of a given system, nevertheless, is closely related to the availability of historical data relative to its characteristic breakdowns, or the breakdowns characteristic of the family of identical production systems, in relation to the environment and the conditions of use. The availability of this data is generally limited, except in the aeronautics division, due to a lack of culture relative to the management and processing of data, which is often present in the organization, but not adequately managed (Bilinton *et al*., 1992).

In this section, we present five papers that, on the one hand, offer a sufficiently general and updated overview of the research and experimental techniques relative to reliability and maintenance. On the other hand, these papers also present a coherent set that highlight the range of research being conducted in this area. They, in fact, crescendo from theory to practical management. The first two (Basile *et al*.; Cassina *et al*.) are of a prevalently methodological nature by presenting techniques based on the consideration of asset reliability. The second two concern extremely innovative technologies, including extended sensor networks (Ball *et al.*) and radio frequency management of maintenance data (Mandelartz *et al.*). Finally, the last paper concerns applications and proposes a system of management for the maintenance of infrastructures (Gattulli). Each of these papers is introduced in the following paragraphs.

The first paper (Basile, Dehombreaux, and Filippi) starts from the basic assumption that knowledge about the reliability of any technical system is of fundamental importance for its management and maintenance. Thus, the researchers propose a method for the evaluation of reliability that overcomes traditional difficulties encountered in estimating the magnitude of reliability due to issues such as the complexity of the system, the dynamic nature of the stress to which it is generally subjected, and the scarce availability of historical data. The central theme of this work is to provide a solution for the problem of the lack of information, which can be attributed to the general inadequacy of the productive organizations in applying correct quality management to their assets and the need to have available an enormous quantity of data due to the sufficiently long historical period in the life of the system. For this purpose, the authors propose a method of reliability estimation of multi-component systems subject to variable stress, based on the theory of accelerated aging tests. Starting from the consideration of the possible operating conditions of a system, through the evaluation of specific physical magnitudes (Ang *et al.*, 2001; Tovo, 2001; Wei, 1997; Sheik *et al.*, 2003) and the methods proposed in the literature for the evaluation of system deterioration (Harlow et al., 1998; Harlow *et al*., 2002; Mao *et al*., 2000; Tebbi *et al.*, 2003; Sheik et al., 1995), a method is proposed that allows the effective and generalized correlation of all of these theories, whose effectiveness is validated through the consideration of two mechanical examples and the support of a Matlab® bookcase, especially designed by the researchers.

The second paper (Cassina, Taish, Zanotto, and Gerosa) proposed an effective method to overcome difficulties in preventive maintenance, which is fundamentally traceable to the insufficient availability of adequate reliability engineering statistics to prevent needless economic outlay for early replacement of components or to reduce the occurrence of unexpected breakdowns. To this end, the evolution proposed is through the logic of predictive maintenance, based on the observation of actual system operations, to ensure greater capability in accomplishing actual maintenance requirements (Mobley, 2002). Additionally, it is enriched by the introduction of diagnostics based on an expert system, to ensure improved and more efficient interpretation of the actual data relative to system operation. This approach requires a coherent, modern orientation in applied maintenance research, including the adoption of sensors to detect the physical and environmental magnitudes, the planning and training of the expert system, and, sometimes the consideration of veritable systems of telematic maintenance (Concetti *et al*., 2007). Therefore, the method proposed offers undoubted advantages and responds to the modern day requirements of many managers and users of assets.

The third paper (Ball, Ruqiang, Gao, and Deshmukh) is a logical consequence of the previous research presented above, which demonstrates how recourse to a predictive maintenance logic appears, in many cases, to be the most effective in modern applications. The recourse, in this case, may require the most evolved sensor technologies possible that are suitable for integration into maintainable systems starting from the early stages of design. One of the most frequent problems is therefore the design of appropriate sensor networks, especially for large-scale systems (consider, by way of example, an application to control and maintain the infrastructures in a transportation system), which poses important problems, for example, from the point of view of the energy consumed by the aforementioned sensors. The work of Ball, Ruqiang, Gao, and Deshmukh, therefore, proposes an interesting mathematical method to pursue optimal objectives from the point of view of energy. The method can presumably be extended to pursue other objectives of optimization in the design of sensor networks as well.

The fourth paper selected (Mueller, Richter, Plate, and Manderplatz) focuses on radio frequency management of maintenance data. This subject is extremely current, not only in the field of maintenance, because it concerns the possibility of making a technology available, in a rational and economic manner, that permits onsite recording of registry data and information relative to maintenance interventions performed for any asset subject to maintenance. This approach allows more rational management of technical systems and improves protection of responsibility, because the information relative to maintenance is immediately available onsite and is conserved in a more permanent manner than previous hardcopy efforts. Radio frequency technology can also be interfaced with information technology maintenance management systems, attributing an additional precious advantage from which the user can benefit. Several variants of these technologies already exist (for example, local memories that permit data transmission by contact, instead of via radio frequency), but radio technology currently seems to be the one with the greatest prospects and is, in fact, more widely used in industry.

The fifth and last paper selected (Gattulli) proposes a technical management method, which is of great interest for the maintenance management of infrastructural works, such as in the field of railway transportation systems. In fact, the research describes the perfection of various components of a maintenance management system for railway bridges, taking into consideration the classification and registration of the works, quantitative defect evaluation, inspection management and recording, and the information technology management of all the aforementioned modules. Undoubtedly, the application of this approach to similar management systems is destined to enjoy important success because of the economic benefits and improvements to safety and quality it provides, benefiting both the organization and the system users. The central and most delicate aspect of the work consists of defect evaluation. A sufficiently robust algorithm has been designed for this purpose that is continually perfected and validated. Indeed, its analytical structure permits several of the coefficients it employs to be updated, thereby continuously improving the algorithm's output.

2.2 From Repair Maintenance to Telematic Maintenance Services

The meaning of the term maintenance, as we have stated, has undergone important evolution over the last 60 years. Maintenance was originally understood as a prevalently manual activity, characterised primarily by repairs, replacement and reconstruction. In fact, this is the phase in which maintenance refers almost exclusively to repairing damage that has already occurred, referred to as "repair" maintenance. The need to guarantee a greater degree of dependability to particularly delicate and critical systems, such as aeronautic and nuclear systems, has given strong impetus to probability studies relative to breakdowns, imposing the development of preventive maintenance to avoid the occurrence of breakdowns. So a definitive separation was determined between repair logic and the consequent perfection of increasingly articulated and complex logic, even in relation to the availability of increasingly sophisticated (destructive and non-destructive) diagnostic, tribology and information technologies. Therefore, over a period of time, various programmed preventive logics have been developed (periodical, constant age or constant date and non-periodical), based on conditions, predictions and prognoses.

At the same time, new information and communications technologies have made it possible to implement maintenance and inspection action from a distance, further enriching the meaning of maintenance, which has already become an inspection service to improve possible prevention of breakdowns (with a view to economy, safety, the availability of systems, etc.) and is increasingly and rightfully seen today as a service to improve management of assets with reference to their entire life cycle, including the phase of disposal, which is particularly important for environmental purposes, with the prospect of virtuous recovery of reusable materials.

In the last analysis, it can undoubtedly be asserted that maintenance, which is an activity that is rich in manual content, has today become an activity that is rich in management content, with every more complex feature that this formulation entails and requires. The increasingly complex nature of maintenance, which has come about as a consequence of the more complex systems in use, together with increasingly binding requirements for preservation, have definitively marked the birth of the science of maintenance, which is ever more frequently being taught at universities and is a subject of theoretical and applied research.

In support of this short historical *excursus* and before taking a closer look at the theme of technologies and research underway to implement modern maintenance, it also seems useful to reiterate the definitions that have successively been applied to maintenance throughout history, including those contained in norms, in a succinct manner.

In a special deliberation in 1963, the Organisation for Economic Cooperation and Development (OECD) defined maintenance as "the company function responsible for the constant control of plants and the tasks of repair and revision necessary to ensure the regular operation and good state of repair of productive plants, services and works equipment".

In 1970 it was acknowledged that maintenance is the "science of preservation" and a new term was coined and associated to it on the occasion – namely "terotechnology" (from the Greek *teros* = to take care of; or literally, "the technology of preservation").

The British Standard Institute (the English organisation responsible for issuing norms) associated the following definition to the term terotechnology in 1970: "Terotechnology is a combination of management, financing, engineering and other disciplines, applied to physical assets, to pursue an economic cost of their relative life cycle. This objective is obtained through the planning and application of the resources and possibilities for maintenance of plants, machinery, equipment, buildings and structures in general, considering their design, installation, Maintenance, improvement or replacement, with all of the consequent feedback of information on design, performance and costs".

The definition of terotechnology is definitely wider than the definitions associated with maintenance up to that time, but also contains concepts that are not precisely pertinent to maintenance and is addressed primarily to the industrial environment.

Finally, in 2003, the commission of the European organisation responsible for issuing technical norms (CEN) that deals explicitly with maintenance, which is still coordinated today through the Italian National Committee for Maintenance (CNIM) introduced the terminological norm (EN 13306), which defines maintenance as "the combination of technical, administrative and management activities envisioned during the life cycle of an asset, to maintain it or restore it to a condition enabling it to perform the function required" (Cigolini *et al.* 2006).

2.3 Methods and Technologies Supporting Maintenance and Productivity

Undoubtedly, on the basis of the foregoing paragraphs, maintenance is today one of the most interesting competitive factors, not only on the level of public or private enterprise of any size, but it even represents an important factor of social development, when the socio-economic prospects that make it possible are taken into consideration.

In fact, maintenance is no longer a question of making repairs or, at most, defining more or less articulated programmes of prevention. On the contrary, it has today acquired the meaning of a complex management service, oriented towards the prevention of breakdowns, but also towards pursuing a variety of other objectives, ordered differently on the basis of a company's requirements and its reference environment, which may also be commercial in nature.

This explains why the science of maintenance is particularly multiform and transversal, not only from the point of view of its reference environment (which ranges from industry to the civil, health and environmental areas, etc.), but also in connection with its culture and content.

2.3.1 Maintenance in Different Productive Sectors

The areas of research on maintenance, on the basis of what has been set forth above, consequently refer to different sectors of technical and non-technical study and requirements for development are different in the various productive sectors of reference.

With reference to these various areas, first of all, the following priorities are indicated:

Industrial sector

Maintenance has always occupied a role subject to productive requirements in industry, whose purpose is to guarantee the availability of the machinery. Today Maintenance has acquired meaning as a factor of development and competitiveness (both internal, with the objective of satisfying company workers to a greater extent, and external, to reduce production costs and improve the quality of products); so on one hand we are witnessing an increase in the number of objectives and assets subject to Maintenance, and on the other, growing research on measures for rationalisation (in terms of planning and the economic timeliness of intervention) and the streamlining of organisation (which is also a general objective of companies) which, with increasing frequency, leads to externalisation of activities, the development of third parties that can be traced to the parent company and formulation of particularly efficient relations for the exchange of services, with results and a single provider of services. The objectives of organisational streamlining of maintenance, which can be at least partially traced to studies on *supply chain management* (or optimisation of management relations between companies, their suppliers and chain of distribution) are more feasible today, thanks to the development of information networks (even with Geographical Information Systems (GIS)), technologies for the collection and memorisation of data on individual items of Maintenance (Radio Frequency Identification: RFID) and more suitable information technology environments for the co-management of Maintenance information by the customer and supplier.

Civil Sector

While the trends underway in industry continue with respect to the development of the above-mentioned technologies, a fundamental requirement is noted here, justified by the age-old absence of planned and programmed Maintenance in the world of civil construction. This requirement is represented by the transfer of methodologies, practices and procedures employed in industry to the realm of civil construction. With all of its various structural components, techniques and technologies, on the strength of this trend, a building should be regarded in the same manner as a technical industrial system, in order to permit the implementation of policies and strategies of Maintenance similar to those that the world of industry has been accustomed to for decades. The significant initiatives of interdisciplinary collaboration that have been underway for several years at the Polytechnic of Milan, which was one of the first universities in Italy to establish a course in "Facility Management", must be interpreted in this sense. The almost total lack of dependable data relative to the various construction items of the building system, nevertheless, make the industrialisation of civil manufacturing management particularly uncertain today and justifies a special commitment to fill this gap.

Plant and technology sector

The number and variety of technological and standardised plants distributed throughout the territory to satisfy the most disparate requirements (industrial, civil, urban, environmental, etc.), as well as the need to ensure the most advantageous and effective possible Maintenance and management for them, and the significant number of human resources that this objective demands, requires a commitment to perfect a system of tele-management and tele-maintenance. Such systems are based on the centralised management of information collected in the field and transferred over the Internet and, in their general operational logic, they permit a very general applicability, once the network of sensors and transducers necessary has been designed. In this connection, it is interesting to cite the prototype of the tele-Maintenance system perfected by the Department of Mechanics and Aeronautics at the "La Sapienza" University of Rome (Concetti *et al.*, 2007). This prototype is based on a logic of management of geographical information and allows the intelligent processing of data with a view to making predictions (through neural software) and has been experimented on various types of equipment (elevator plants, acclimatisation systems, medical dialysis equipment).

The development of a neural system to monitor the aging of electrochemical batteries (for use in industry and electric vehicles), again by the Department of Mechanics and Aeronautics, is of a more specialist nature, and was dubbed Evalbatt. It is based on the detection and processing of electrical magnitudes of the battery alone (tension-voltage) and the temperature produced in every element of the battery, which indicates any phenomena of dissipation underway. The importance of this device is justified in consideration of the difficulty and uneconomic nature of the electric energy battery for use on an industrial scale.

Infrastructure sector

Transportation (roadways, railways, airports, ports, etc.), environmental (dams) and plant (pipelines, etc.) infrastructures, namely the great civil works of the country, pose management and Maintenance problems of an especially critical nature, from the point of view of both safety and economics (the national railways, for example manage some 60,000 railway bridges: the rationalisation of maintenance expenses on each work entails, overall, an inestimable economic benefit). The exceptional dimension of these works, as well as their uniqueness, makes maintenance particularly complex; it can be standardised as far as the procedures, but not where diagnostic and inspection activities are concerned, which generally require the intervention of specialists to examine the extent and implications of the defects detected. So in this environment, the most evident requirement is standardisation: the dimensions, complexity and strategic importance of civil works, as well as their number, impose flexible objectives of standardisation, through the perfection of census procedures, classification of types of works (in families and macro-families), types of inspections, analyses of defects (through defect catalogues created *ad hoc*) and indexes on the state of repair of each individual asset of the works (through empirical algorithms subject to constant revision of the fundamental parameters). The CNIM, in this connection, gained important experience between 2000 and 2004, through the realisation of the bridge Maintenance system on behalf of the Italian Railway Network, for the standard Maintenance of the 60,000 national railway bridges.

Medical sector

Three characteristics of particular importance for this paper take concrete form in the medical sector: first of all, every medical structure entails the realisation of a complex, varied and variously sophisticated system of technologies, which justify the assertion, which is being made with increasing frequency, that a hospital has various analogies with a complicated industrial plant; in the second place, health structures determine a special level of proximity with human beings, who are also in need of care, such as to make them particularly critical; in the third place, as a consequence of these two considerations, the medical environment entails extraordinary initial investments and Maintenance, within the ambit of the national medical policy, determining important repercussions with respect to the country's economic policy (Fedele 2007).

Definitively, all of the maintenance requirements already outlined in the analysis of the previously mentioned productive sectors take concrete form in the medical sector, and are made more serious by the urgency provoked by a general delay, which, day by day, with the progressive aging of health structures, is truly establishing the grounds for a veritable national emergency, which is ready to explode at any time, in the absence of a national policy for the correct management and maintenance of these structures.

2.3.2 Studies and Research on Maintenance

In order to delve more deeply into studies underway in the field of maintenance and briefly illustrate the state of the art in this connection, we shall now take into consideration the science of reliability engineering, which provides the mathematical and theoretical basis upon which maintenance rests. *Reliability Engineering provides* the mathematics, statistical and analytical instruments to understand the logic of operation of technical systems, understand the manner in which they break down and estimate the probable requirements. The fundamental role of this science in Maintenance is therefore self-evident. Knowledge of the reliability engineering of a given system, nevertheless, is closely related to the availability of historical data relative to its characteristic breakdowns, or the breakdowns characteristic of the family of identical systems of production, even in relation to the environment and the conditions of use. The availability of this data is generally limited, except in the aeronautics division, even due to a lack of culture relative to the management and processing of data, which are often actually present in the productive organisations, but are not adequately managed (Bilinton *et al,* 1992).

Studies and research in the field of reliability engineering, therefore, are considered to have two fundamental orientations:

- the first towards the development of mathematical algorithms, generally of logical and/or empirical origin, through which to arrive at a more or less precise quantitative definition of useful Maintenance indicators for the management of the assets; this includes, for example, algorithms conceived for the purpose of diagnosis, based on visual inspections of civil constructions (for which the availability of historical data is even scarcer) and plants; namely data processed for the primary purpose of accident prevention and therefore oriented towards estimating risk analysis; and
- the second is oriented towards designing logical-mathematical models in substitution of missing historical data; these models include calculations used to estimate the reliability of the assets, with accelerated trials, or analysis models which, under particular conditions established on a time by time basis, permit estimation of the reliability of the assets, in spite of the fact that historical data is not available.

Another important and wide area of innovation in the field of Maintenance is represented by new *organisational, management and contractual formulas,* which, as partially stated earlier, are oriented towards the streamlining of the organisations that own the assets, towards the specialisation of Maintenance service providers, as well as pursing objectives relative to results, characterised by a greater degree of transparency and economic viability.

Streamlining and specialisation are consequences of the process that has been going on for several years now in the most important and largest productive organisations, of moving some non-characteristic services to the tertiary sector, with the consequent development, often determined by the externalisation of historical services, of new enterprises specialised in specific Maintenance activities. The evolution of this trend has led to the birth of multi-service companies, or enterprises with prevalent management and financial content, oriented towards the management of a variety of services for specific assets (*facility management* companies) with undoubted organisational simplifications for the buyer companies, which deal with a single supplier instead of a great number of suppliers. This important benefit increases further when contractual formulas providing for results are introduced, on the basis of detailed planning of Maintenance, or on the basis of the identification of technical and economic indicators for the periodical calibration of the buyer’s expected results, which are guaranteed by the supplier. It is easy to understand that this is an extremely important innovation, not only from the point of view of the buyers' ability to plan their economic commitment, but also from the point of view of transparency, which is a factor of primary importance in a variegated and somewhat intangible world like Maintenance services, which are precisely intangible products. The requirement for new and much more demanding organisational and contractual formulas, with respect to the past, as previously stated, has consequently determined greater depth in *Maintenance planning methods* (Fedele *et al*., 2004, Duffua *et al*., 1999), with respect to the organisational characteristics of the Maintenance plans and the technical characteristics, for which what was said earlier about reliability applies.

Particularly complex maintenance plans, with respect to the vastness of application, heterogeneousness of systems and uncertainty due to the frequent lack of experience, mathematical algorithms and data, have made important inroads in simplification and resolution in disaggregation with respect to time (we are speaking of short-term, mid-term and long-term plans), in the hierarchical disaggregation and type of systems in sub-groups and simple elements and in the introduction of index figures suitable for the needs that crop up from time to time.

The third important line of innovation in Maintenance, which has been proposed in recent years, is the development of *new technologies* in support of *diagnosis* (destructive and non-destructive), of *measuring the physical magnitude* (sensors), of local memorisation of information and transfer of data over a distance (RFID systems, cabled and wireless networks); as well as the development of increasingly articulated and detailed *information systems* (registration, management and "intelligent" processing of data), which adhere to the requirements of real systems. It is quite difficult in this field to be exhaustive, especially since one runs the risk, in the short run, of having to update everything he has written. The frontiers of electronics, information technology and other mixed technologies are in continuous evolution, permitting increasingly rapid and effective processing of information, which is of fundamental importance in the management and Maintenance of systems. The recent interest inspired in various fields and for various applications of the so-called *nano-technologies* must also be taken into consideration and are no less important. In the field of maintenance, for example, nano-technologies can be effectively applied to improve the durability of materials, through the deposit of suitable linings. Pure *materials***,** on the other hand, is a field in continuous fermentation and is of fundamental importance, not only in designing systems with increasingly higher performance, but also with a view to their preservation for a longer and economically sustainable period of time (imagine, for example, the economic impact of maintenance and failing performance, due to unsuitable materials utilised in the realisation of great civil infrastructural works).

2.4 Conclusion

As mentioned, maintenance is at the centre of a strategic crossroads for the economic and social development of the countries, first and foremost in which is the quality of life of the citizens and their social development; safety in productive activities and utilisation of all of the country's infrastructures; the preservation of the environment through a more rational and long lasting utilisation of all productive resources; the economic viability of management made possible by a more efficient management and conservation of civil and industrial assets.

Despite the strategic importance of Maintenance and perhaps because of its intangible nature and widely transversal technical and cultural nature, the potential of this science is sometimes hard to realize. For this reason, in 1990, in Italy, public institutions and large national companies, under the high patronage of the Ministry of Industry, Commerce and Artisan Crafts, constituted the Italian National Committee for Maintenance (CNIM), a non-profit organisation whose statutory mandate is, according to the CNIM Articles of Association: "to be a national and international point of reference for all Italian sectors of production of goods and services, in order to organise, in concert with the interested parties, specific actions of promotion and intervention in the field of maintenance". To create awareness among the various stakeholders (government and non-government) of the importance of correct and well-planned maintenance, for social, economic and civic development.

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2.5 Selection of Scientific Research Relative to Technologies for Reliability and Maintenance

2.5.1 Foreword

On one hand, the need to offer a sufficiently general and updated overview of the knowledge gained from research and experimental techniques relative to the subject matter was born in mind in selecting the scientific work presented below; on the other, the need to propose as unitary a key as possible for a reading of the material was acknowledged, which was coherent with the introduction in the previous paragraph and stimulates growth of the reader's Maintenance and reliability culture.

Of the five projects selected, in fact, almost in a crescendo from theory to practical management, the first two (Basile *et al*., Cassina *et al*.) are of a prevalently methodological nature, relative to reliability – a basic magnitude in every Maintenance environment – and techniques based on the consideration of asset reliability. The second two concern extremely innovative technologies, which it seems indispensable to refer to in the Maintenance of more complex assets, including the extended sensor networks (Ball *et al*.) and the radio frequency management of data relative to the assets subject to Maintenance (Mandelartz *et al*.). Finally, the last project concerns applications and propose a system of management for the Maintenance of infrastructures (Gattulli).

2.5.2 Overview

The first project (Basile, Dehombreux, Filippi) starts from the basic assumption that knowledge on the reliability of any technical system is of fundamental importance for its management and Maintenance and proposes a method for the evaluation of reliability, whose purpose is to overcome traditional difficulties encountered in estimating this magnitude, which can be traced primarily to the complexity of the system, the dynamic nature of the stress it is generally subject to and the scarce availability of historical data. Precisely the problem of the lack of information, due to the general inadequacy of the productive organisations in correct quality management of the assets and the need to have the availability of an enormous quantity of data – also referable to a sufficiently long historical period in the life of the system – constitutes the central theme that this work attempts to provide a solution for. For this purpose, the authors propose a method of reliability estimation of multi-component systems subject to variable stress, based on the theory of accelerated aging tests. Starting from the consideration of the possible operating conditions of a system, through the evaluation of specific physical magnitudes (Ang *et al.,* 2001, Tovo 2001, Wei 1997, Sheik *et al.*,1995, Shi *et al.*,2003) and the methods proposed in literature for the evaluation of system deterioration (Harlow et al., 1998, Harlow *et al.*, 2002, Mao *et al.*, 2000, Tebbi *et al.*, 2003, Sheik *et al.*, 1995), a method is proposed that allows the effective and generalized correlation of all of these theories, whose effectiveness is validated through the consideration of two mechanical examples and the support of a Matlab® bookcase, especially designed by the researchers themselves.

The second project (Cassina, Taish, Zanotto, Gerosa) proposes an effective method to overcome difficulties in preventive Maintenance, which is fundamentally traceable to the insufficient availability of adequate reliability engineering statistics to prevent needless economic outlay for early replacement of components, or to reduce the possibility of occurrence of unexpected breakdowns. To this end, the evolution proposed is through a logic of predictive Maintenance, base on the observation of the actual conditions of operation of the system, to ensure greater capability in accomplishing actual maintenance requirements (Mobley 2002).

Therefore, the method proposed offers undoubted advantages and responds to the modern day requirements of many managers and users of assets. Additionally, it is enriched by the introduction of diagnostics based on an expert system, to ensure improved and more efficient interpretation of the actual data relative to operation of the system. This approach requires the adoption of sensors to detect the physical and environmental magnitudes, as well as the planning and training of the expert system, coherently with modern orientation in applied maintenance research, sometimes also addressed to the consideration of veritable systems of telematic maintenance (Concetti *et al*., 2007).

The third project (Ball, Ruqiang, Gao, Deshmukh) is a logical consequence of the previous research presented above: in fact, it was seen how recourse to a predictive maintenance logic appears, in many cases, to be the most effective in modern applications; this inevitably requires recourse to the most evolved sensor technologies possible, suitable for integration in the systems subject to maintenance, starting from the early stages of design. One of the most frequent problems is therefore the design of appropriate sensor networks, especially for large-scale systems (consider, by way of example, an application to control and maintain the infrastructures in a transportation system), which poses important problems, for example, from the point of view of the energy consumed by the aforementioned sensors. The work of Ball, Ruqiang, Gao and Deshumkh, therefore, proposes an interesting mathematical method to pursue optimal objectives from the point of view of energy. The method can presumably be extended to pursue other objectives of optimisation in the design of sensor networks as well.

The fourth project selected (Muller, Richter, Plate, Manderplatz) centres on the theme of radio frequency management of Maintenance data. This subject is extremely current, not only in the field of maintenance, because it concerns the possibility of making a technology available, in a rational and economic manner, which permits on site electronic recording (on the asset subject to maintenance) of registry data of the assets and information relative to maintenance intervention performed. This allows more rational management of technical systems and improves protection of responsibility, because the information relative to maintenance is immediately available on site and is conserved in a more permanent manner than it would be on hard copy supports. Several variants of these technologies already exist (for example, local memories that permit data transmission by contact, instead of radio-frequency), even if the radio technology currently seems to be the one with the greatest prospects and is, in fact more widely used on the industrial level. Radio frequency technology can also be interfaced with information technology maintenance management systems, attributing an additional precious advantage, from which the user can benefit.

The fifth and last project selected (Gattulli) proposes a technical management method, which is of great interest for the management of Maintenance of infrastructural works, such as in the field of railway transportation systems, for example. In fact, the work describes the perfection of various components of a management and Maintenance system for railway bridges, taking into examination the aspect of classification and registration of the works, the aspect of quantitative evaluation of defects, the aspect of management and recording of inspections and the aspect of information technology management of all the aforementioned modules. Undoubtedly, recourse to similar management systems, in addition to being a useful example in every field, is destined to enjoy important success in future because of the economic benefits they provide and in order to pursue a greater degree of safety and quality, for the benefit of users. The central and most delicate aspect of the work consists of evaluation of defects, namely, the perfection and validation of a sufficiently robust algorithm for the purpose, subject to continuous improvement, thanks to its analytical structure, which permits updating of several of the coefficients it employs.

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2.6 On the Reliability of Mechanical Systems under Variable Constraints

Olivier Basile, Pierre Dehombreux, Enrico Filippi

Abstract. This communication presents the accelerated life testing theory in order to model the reliability of complex systems subject to variable solicitations. The reliability models of series and parallel systems are established and compared with the Cox's proportional hazards model. A methodology of reliability determination according to solicitations varying with time is presented and applied to the Weibull distribution. This study is illustrated on the basis of two mechanical examples treated with *Reliabilitix*, a MATLAB® library we have developed to determine reliability of complex systems under variable constraints.

2.6.1 Introduction

The reliability of a system is defined by the probability that the system will perform its required function for a given period of time when used under steady operating conditions; a reliability law makes sense only if the operating conditions are fixed. The proposal of this article is to establish a methodology to estimate reliability of multicomponent systems subject to variable solicitations. According to operating conditions described through variables such as flow, power, mechanical load, temperature,…, we will observe one or more degradation modes such as fatigue (Ang *et al.*, 2001; Tovo, 2001; Wei, 1997), pitting, wear or corrosion (Sheik *et al.*, 1995; Shi *et al.*, 2003).

From literature, two methods emerges to characterize these physical mechanisms of degradation. The first one is interested in characterizing the physical phenomena which are at the origin of the failure modes like cracks propagations (Harlow *et al.*, 1998; Harlow *et al.*, 2002; Mao *et al.*, 2000). The second method consists in establishing, on the basis of experimental tests a statistical model according to degradation modes and solicitations (Tebbi *et al.*, 2003; Sheik *et al.*, 1995); the Wöhler's model of fatigue belongs to this second category. A first link between these statistical models of degradation and the reliability will be established thanks to accelerated tests theory; we will point out some theoretical elements necessary to estimate the reliability under variable solicitations. Next, we will study some models used to determine the reliability of complex systems, *i.e.* which associate in series or in parallel different components subject to variable constraints.

We will introduce the Cox's proportional hazards model (Ansell, 1997; Garden *et al.*, 2001, Jóźwiak, 1997; Mazzuchi, 1989; Pham, 2003) and establish the expressions of the reliability laws of a series and a parallel system composed of identical components subject to different load constraints.

After, we will state a method to determine reliability according to solicitations varying with time. We will present *Reliabilitix*, a MATLAB® library we have developed and used to determine the reliability of systems subject to variable solicitations.

2.6.2 Theory of the Accelerated Tests

In accelerated tests context, many statistical models were developed that correlate lifespan and failure modes (Nelson, 1990; Pham, 2003; Sheik *et al.*, 1995; Tebbi *et al.*, 2003). In this paragraph, we will present some elements of the accelerated tests theory and their application in the mechanical field.

Theoretical Concepts

During accelerated tests, the components are subject to various levels of constraints $s_1, s_2, \cdots, s_n$ generally higher than nominal levels. From these tests we get failure times according to the solicitations imposed which allow the establishing of reliability models according to the constraints. Moreover, the accelerated tests results frequently point out that considering two levels of solicitations, the ratio between times to failure is constant whatever the level of reliability considered and that times to failure follow the same distribution whatever the level of constraints. In this study, we will maintain these two assumptions and will assign the indices ref to the reference constraints and the indices s to the solicitation levels in test.

Assumption number 1

Let us suppose two different levels of solicitations. Let us call t_{ref} the time to failure at the reference constraints and t_s the time to failure at the levels of test. Whatever the value of reliability *R*, the relationship of proportionality between t_{ref} and t_s is defined by the following relationship:

$$t_{ref,R} = A_F \, t_{s,R} \tag{2.1}$$

where A_F is the acceleration factor which is a function of the failure mode and the solicitations associated.

Assumption number 2

The second assumption postulates that times to failure follow the same distribution and that whatever the level of constraint. By consequent, it is very simple to deduce the failure function $F_s(t_s)$ (written $F(t)$) at various solicitations levels (the reliability is $R(t)=1-F(t)$) :

$$F_{ref}(t)=F\left(\frac{t}{A_F}\right)\rightarrow R_{ref}(t)=R\left(\frac{t}{A_F}\right) \tag{2.2}$$

And the inverse relationship considered in this study:

$$F(t)=F_{ref}(t\times A_F) \tag{2.3}$$

The derivative of the failure distribution with respect to time yields the density function according to the acceleration factor:

$$f(t)=A_F\, f_{ref}(t\times A_F) \tag{2.4}$$

The density function divided by the reliability function yields the failure rate:

$$\lambda(t)=A_F\,\lambda_{ref}(t\times A_F) \tag{2.5}$$

Acceleration Factor and Failure Modes

In order to calculate the acceleration factor, we have to know the relationships which correlate lifespan and solicitations level for different failure modes. Among these relationships, we can quote the *Arrhenius* model and the *inverse power law*. We will consider that these laws apply for any value of reliability.

Model of Arrhenius

The model of Arrhenius correlates temperature and lifespan. Based on the Arrhenius Law for simple chemical- reaction rates, the relationship is used to describe many products that fail as a result of degradation due to chemical reactions or metal diffusion; its expression is:

$$t = A\exp\left(\frac{B}{T}\right) \tag{2.6}$$

where T is the absolute temperature, A and B are experimental parameters. The expression of the acceleration factor is:

$$A_F = \exp\left(B\left(\frac{1}{T_{ref}} - \frac{1}{T_s}\right)\right) \tag{2.7}$$

Inverse Power Law

The inverse power law is a general model generally used to correlate mechanical solicitations (pressure or constraint) and lifespan; its expression is given by:

$$t = \frac{A}{S^b} \tag{2.8}$$

where S is the constraint, A and B are experimental parameters. The acceleration factor relating to the law is defined by:

$$A_F = \left(\frac{S_s}{S_{ref}} \right)^b \quad (2.9)$$

For example, the Wöhler's fatigue model has the same expression than equation 2.9; that is:

$$\frac{N_r}{N_D} = \left(\frac{\sigma_D}{\sigma_a} \right)^b \quad (2.10)$$

where N_r , is the number of cycles until rupture; N_D the number of cycles at the endurance limit and *b* is an experimental parameter.

2.6.3 Cox's Proportional Hazards Model

In order to take into account the environment in survival analyses, the Proportional Hazards Model (PHM) was developed by Cox. In a first time, this model was of used in the medical field and after for the determination of reliability of electronics systems. In *PHM*, the failure rate λ depends on time but also on covariates $Z = (z_1, z_2, \cdots, z_n)$ relative to the environmental conditions *i.e.* $\lambda = \lambda(t, Z)$. More precisely, the failure rate is expressed as a product of two factors which are: a reference failure rate $\lambda_{ref}(t)$, which does not depend on the covariates, and the hazard function $g(Z)$, function only of the covariates Z . That is:

$$\lambda(t, Z) = \lambda_{ref}(t) g(Z(t)) \quad (2.11)$$

Consequently, the reliability model becomes:

$$R(t,Z) = R_{ref}(t)^{g(Z(t))} \tag{2.12}$$

Generally, the hazard function has an exponential form:

$$g(Z(t)) = \exp(WZ(t)) \tag{2.13}$$

where W is a vector $(w_1, w_2, \cdots, w_n)$ of weights associated to each covariate z_i.

For this study, we will consider the general expression of the equations (2.12) and (2.13) and the covariates $Z(t)$ are the constraints $S(t)$.

2.6.4 Reliability Models for Complex Systems

In this paragraph, we will estimate the reliability of complex systems. The accelerated tests theory indicates how to evaluate a reliability function according to the level of solicitations. Does a general model exist which can model the reliability of a complex system combining several reliability functions according to the constraints it is subject? To answer this question, we will evaluate the reliability of a series system and a parallel system of identical components.

Series System configuration

Let us consider a series system of n blocks characterized by an identical law of reference but undergoing different levels of solicitations, *i.e.* presenting different acceleration factors. If the law of reference is the Weibull one, the expression of the reliability of system is:

$$R(t) = \prod_{i=1}^{n} \exp\left[-\left(\frac{t}{\eta / A_{F_i}}\right)^{\beta}\right] = \left\{\exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right]\right\}^{\sum_{i=1}^{n}(A_{F_i})^{\beta}} \tag{2.14}$$

We note that the reliability expression has the form of the Cox's proportional hazards model: $R(t) = R_{ref}(t)^{g}$. The main difference with *PHM* lies in the fact that the hazard function depends on the reference law by the β parameter. Moreover, the expression of the hazard function $g(A_F)=\Box_i(A_{Fi})^{\beta}$ is not exponential like in Cox's model (2.13).

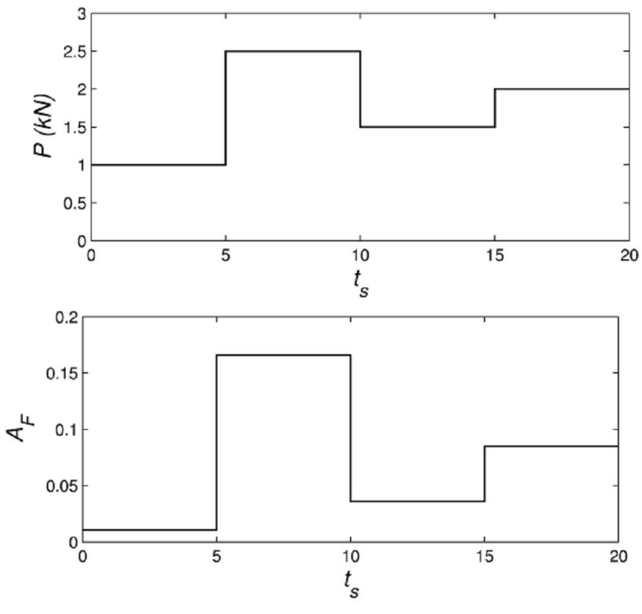

Figure 2.1 Evolution of load P and acceleration factor A_F with time

Parallel System Configuration

Let us consider a system constituted of two components in parallel which present a same reliability law of reference. In this case, the reliability of the system is calculated by:

$$R(t) = \exp\left[-\left(\frac{t}{\eta / A_{F_1}}\right)^{\beta}\right] + \exp\left[-\left(\frac{t}{\eta / A_{F_2}}\right)^{\beta}\right] - \left\{\exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right]\right\}^{(A_{F_1})^{\beta} + (A_{F_2})^{\beta}} \tag{2.15}$$

Contrary to the series system of the previous paragraph, the expression of the reliability is not equivalent to the proportional hazards model any more.

2.6.5 Synthesis of the Reliability Law according to Solicitations

It is obvious that the reliability of a system depends on the history of solicitations. The accelerated tests theory allows to determine the reliability law under constraints on the basis of a reference law thanks the relationship: $t_{ref} = t_s A_F$. Considering the Weibull model, we can establish a more general relationship between t_{ref} and t_s :

$$t_{ref} = (t_s - \gamma) A_F \tag{2.16}$$

where γ is a "historical" parameter. Indeed, let us suppose that at the moment $t_s = t^*$ there is a change of constraint level. Let us affect the indices $(i-1)$ to the system state

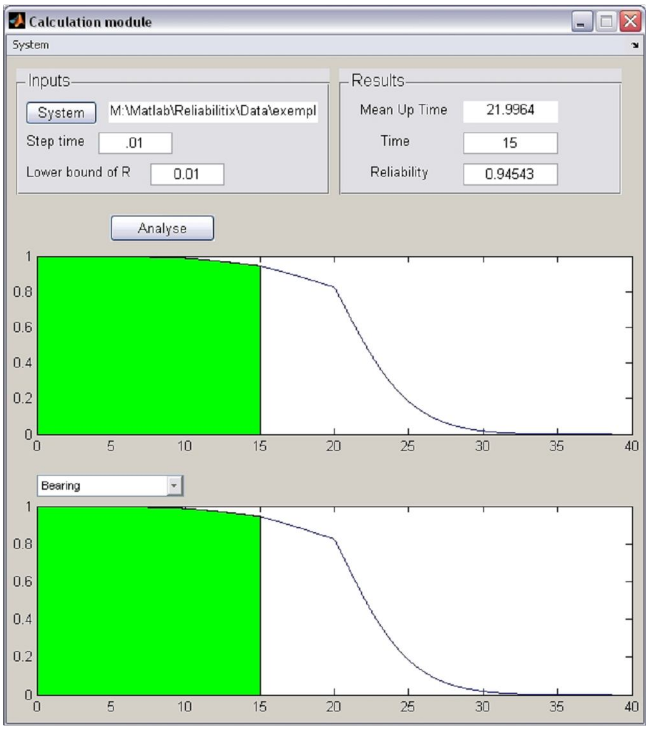

Figure 2.2 *Reliabilitix* menu

before the change and the indices (i) after (figure 2.1). At the instant t^* of change, we can write:

$$R_{i-1}\left(\left(t^* - \gamma_{i-1}\right)A_{F_{i-1}}\right) = R_i\left(\left(t^* - \gamma_i\right)A_{F_i}\right) \tag{2.17}$$

that implies:

$$\left(t^* - \gamma_{i-1}\right)A_{F_{i-1}} = \left(t^* - \gamma_i\right)A_{F_i} \tag{2.18}$$

that yields:

$$\gamma_i = t^* \left(1 - \frac{A_{F_{i-1}}}{A_{F_i}} \right) + \gamma_{i-1} \frac{A_{F_{i-1}}}{A_{F_i}} \tag{2.19}$$

This relationship of recurrence indicates that all the history will be included in the γ_i parameters. That implies that we only have to calculate and store the new value of the parameter γ_i at each change of solicitation level.

2.6.6 MATLAB® Library: Reliabilitix

Reliabilitix (Figure 2.2) is a MATLAB library used to calculate reliability of complex systems, *i.e.* systems that can functionally be described by a block diagram which associates, into series or in parallel, components (or failure modes) of which the reliability model must be known *a priori*. Figure 2.3 represents a simplified assembly including a shaft and two bearings and the block-diagram associated. *Reliabilitix* contains two types of components whose characteristics are specified in a text file. The first component is a general component characterized by a name or an identifier and a reliability law. Other parameters can

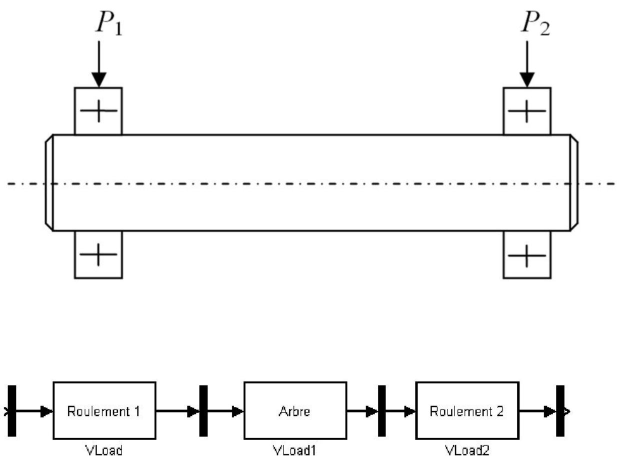

Figure 2.3 Shaft supported by two bearings and block diagram associated

be integrated in the reliability calculation; let us quote the working time that the component already achieved, a control of good operating state before a new mission of the system and its replacement by an identical component in case of failure, this last component can be subject to a failure distribution when it is in stock.

The model associated to the second component is the inverse power law; it is characterized by a name or identifier, a reference law of reliability, a reference load, the value of *b* exponent and the load history with time.

The algorithm of analysis of the block diagram implemented in this library is inspired from graph theory; that is the “Latin composition” method and yields a numerical function of reliability (Kaufmann *et al.*, 1975). This method associates a reliability network to a block diagram; the objective is to get the minimal path sets of the network. The path sets of the system are obtained by a specific multiplication of matrices called “Latin” matrices. Next, the reliability function is calculated on basis of the path sets.

2.6.7 Applications

Reliability of a Component Subject to a Variable Load

Let us consider a one-component system of which the reliability model is the Weibull one of which the expression according to the factor of acceleration is:

$$R(t) = \exp\left(-\left(\frac{t-\gamma}{\eta / A_F}\right)^{\beta}\right) \tag{2.20}$$

where β is the shape parameter, η the scale parameter and γ the shift or location parameter. We note that β is independent of the acceleration factor; only the scale parameter will be affected.

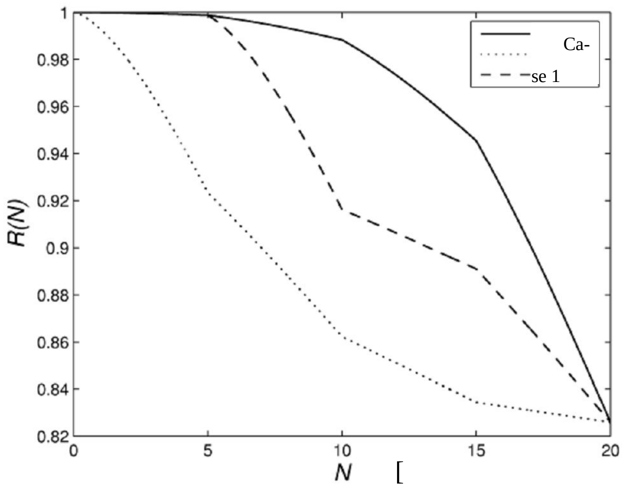

Figure 2.4 Reliability according to the order of loads application

Once the reliability law according to the acceleration factor is known, we can calculate and study the reliability models for various values of the acceleration factor. We will illustrate this method thanks a bearing application of which the expression of lifespan according to load is:

$$N = a_1 a_2 a_3 \left(\frac{C}{P} \right)^n \tag{2.21}$$

where $n = 3$ for deep grove ball bearings and $n = 10/3$ for cylindrical roller bearing and needle roller bearing; a_1 is the reliability factor; a_2 is the material factor; a_3 is the lubrication factor; *C* is basic dynamic load rating; *P* is the bearing load considered.

Furthermore, we know that a_1 is common to all bearings and considering $a_2 a_3 = 1$, from equation (2.21), we can deduce the acceleration factor expression of bearings:

$$A_F = \left(\frac{C_{ref} / P_{ref}}{C_s / P_s} \right)^n \tag{2.22}$$

The tables of reliability according to a_1 parameter, provided in bearing catalogues, correspond to a Weibull reliability model of which the shape parameter β , independent of the acceleration factor, is equal to 1,5. To determine the value of η parameter, we have to chose a bearing of reference and a load of reference; next η will be corrected by the acceleration factor A_F . For example, if the reference bearing if characterized by $n = 3$, $a_2 a_3 = 1$, $C = C_{ref} = 4.55\,\text{kN}$ and if the reference load is equal to $P_{ref} = C$, then $\eta = 4.470$ Mc.

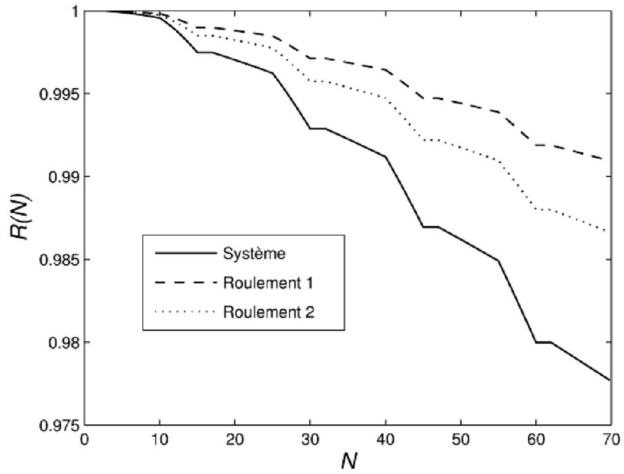

Figure 2.5 Reliability of a complex system

It is obvious that the reliability evolution with time depends on the order of loads but finally reliability converges always towards a same value according to the assumption of independence of the order of load application considered for damage determination. Let us consider the loading cases in table 2.1 and applied to the reference bearing.

Table 2.1 Load cycles for application 1

	Case n°1		Case n°2		Case n°3	
N (MCycles)	*P* (kN)	γ	*P* (kN)	γ	*P* (kN)	γ
0-5	1	0	2.5	0	1	0
5-10	1.5	3.52	2.0	-4.76	2.5	4.68
10-15	2.0	7.27	1.5	-25	1.5	-14.63
15-20	2.5	11.04	1	-120	2.0	2.5

We get the reliability law represented in figure 2.4. We can note that the reliability converges to a same value at $t = 20$ Mc whatever the load order. We also note that the evolution of the γ parameter is roughly different for each case.

Reliability of a Complex System

Let us consider the system composed by a shaft supported by two bearings and represented in figure 2.3. We assume that the lifespan of the shaft is very large in comparison to the one of the bearing; than we will consider its reliability equal to one. The dynamic load of the bearing number 1 is equal to 29 kN and of the bearing number 2 equal to 14 kN. Let us consider the load cycles of table 2.2.

Using *Reliabilitix*, we have calculated the different laws represented in figure 2.5. Thanks such a figure the reliability evolution for each component can be compared themselves and compared to the reliability of the system. We note that the bearing number 2 is weaker from the point of view of reliability than the bearing number 1 and that although it supports a lower load.

Table 2.2 Load cycles for application 2

N (cycles)	P_1 (kN)	P_2 (kN)
0-2000	0.225	0.121
2000-10000	3.5	1.88
10000-15000	5.35	2.88
15000-17000	0.225	0.121
17000-25000	3.5	1.88

2.6.8 Conclusion

The object of this article is the determination of the reliability of the complex systems subject to variable solicitations. First, the accelerated tests theory allows the determination of the system components reliability according to the acceleration factor A_F. This acceleration parameter will depend on load and failure mode. In this article, we pay a special attention to *inverse power law* model classically used to model the phenomenon of fatigue.

Second, we have established the expressions of the reliability models of complex systems on the basis of the reliability laws of their components. For that, we have considered a series system and a parallel system of which those components have the same reference law. As regards series system, the resulting law has the form of the Cox's proportional hazards model (*PHM*); the main differences lie in the fact that (1) the hazard function depends on the reference function and that (2) the expression is not exponential. As for parallel system, the model is not of the *PHM* type any more.

Thirdly, we have presented a method to integrate the load history in the determination of a reliability law. For that, we have introduced a "historical" parameter γ in which all the system history is condensed. This method enables us to follow the evolution reliability when the load varies with time. This method was implemented in the MATLAB® library *Reliabilitix* which allows us to illustrate this study on the basis of two examples.

Nevertheless, the method proposed in this article presents some limitations. Indeed, loads on the components of a complex system are not independent each others. According to incidents, the solicitations supported by the system components will be redistributed. A way to solve this problem would be to provide *Reliabilitix* a module that calculates the load repartition inside of the system according to the circumstances.

Acknowledgments

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2.7 Proposal for a Methodology for the Development of Predictive Maintenance Decision Support Systems Based on Artificial Intelligence

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Abstract. In this paper a methodology for developing predictive maintenance decision support systems based on artificial intelligence will be presented. The formalised methodology is centred on the development of a diagnostic tool capable of drawing conclusions and making predictions about the product state starting from measurements monitored during the product working cycle. All these measurements are collected by sensors already installed on-board the products, meaning that no additional cost is imposed in order to get the desired result. The methodology has been applied to three different test cases in order to test the single macro-phases in which the methodology can be separed. The cases regard three different products: a home boiler, a fridge and a range of sophisticated milling system. All the tests demonstrated how well the methodology can guide the user in the creation of a powerful predictive maintenance decision supprort system which proved to significantly outperform the techniques currently used by our application partners to estimate the ageing level of their goods.

2.7.1 Introduction

Over the years maintenance got more and more important. The trend originated in the industrial sector and is progressively spreading to consumer durables and different kind of consumer goods.

This growing attention on maintenance can be put down to the increasing pressure on product quality and to the tight times characterising contemporary markets.

While in the past traditional run-to-failure maintenance was considered a good instrument to match customers' necessities, it proved to be inadequate to face the changing needs and new policies emerged. At first preventive maintenance was considered a good solution. Despite proving to be adequate in some cases, the fact that in preventive maintenance actions are planned on a statistical basis carries two different side effects. First of all the statistical approach forces to substitute components on scheduled periods, causing parts with potentially long residual life to be changed. This translates in higher costs due to the use of more spare parts than strictly necessary, to the higher number of maintenance interventions needed, and to increased machine off-time necessary to perform maintenance tasks. Secondly, even good statistical models cannot avoid the occurrence of rare and unexpected failures, forcing very frequent main maintenance actions on all those goods whose failure could have catastrophic effects.

In order to overcome these problems, predictive maintenance, known with different names such as condition based maintenance, diagnostics and others, emerged as a possible solution.

Differently from the statistical approach characterising preventive maintenance, predictive maintenance is based on the monitoring of real product parameters which allow to make considerations about the consumption of the components of interest and, ultimately, about their residual life. Such an approach guarantees an early detection of impending faults, allowing to maintain a good only if it is really needed and only when it is really needed, improving product quality, productivity, and ultimately profitability of manufacturing and production plants (Mobley 2002).

2.7.2 PROMISE

PROMISE (the acronym stands for PROduct Lifecycle Management and Information tracking using Smart Embedded Systems) is a framework project founded by the European Union. The project aims at closing the product lifecycle information loop, managing the flow of data from the products and exploiting it, creating a process of seamless e-Transformation of Product Lifecycle Information into Knowledge. This transformation is planned to happen in all the phases of the product lifecycle and thus it can improve products and service quality, efficiency and sustainability, creating value for different stakeholders.

Within PROMISE, different fields are subject of both theoretical and applied research; among them the main research areas are: information systems modelling, smart embedded systems, short and long distance wireless communication technologies, data management and modelling, statistical methods for preventive maintenance, End Of Life planning, adaptive production management and Design for X.

One of the expected results of PROMISE is the development of a prototype PROMISE PLM System, partly already functional, intended to test the developed techniques and technologies. The test of this prototype is planned to be performed on 11 case studies, thanks to the cooperation of applications partners belonging to different sectors such as Automotive, Railway, Heavy Load Vehicle, EEE, White and Brown goods.

The authors are involved in the development of different parts of the project, such as the data model to store information about lifecycle data and the predictive maintenance algorithms. This last task is performed with the collaboration of three application partners: MTS, WRAP and FIDIA.

The MTS (Merloni Termo Sanitari) Group is one of the world leaders in the manufacture of water heaters, boilers, burners and components. It is located in Central Italy. It is a leading international Group focused on manufacturing and delivering central heating and domestic water heating solutions. MTS Group's aim is to contribute to the improvement of the quality of life by offering its customers high technology products which have a limited impact on the environment.

WRAP was born in June 2000 as the spin-off of the Corporate Electronics R&D unit from Merloni Elettrodomestici. Today WRAP is the advanced research centre of the Merloni Elettrodomestici Group and focuses its efforts in the development a fully networked set of digital household appliances, communicating with each other and capable of exchanging information over the Internet.

Finally, FIDIA is a world leader in the design, construction and marketing of integrated systems for the machining of complex forms for the moulds and dies industry.

2.7.3 Predictive Maintenance Application

Over the last few decades several attempts have been made to codify both formalised and implicit human knowledge in an effort to make it available on a large scale.

Particularly in maintenance, the expected advantages ranged from quicker and more precise diagnosis, and hence lower overall maintenance costs (Baur 1996), to wider availability of high-profile knowledge (Su 2006, Weiss 2006), to considerable aid in those realities where a single operator is responsible for the monitoring of a variety of different subsystems (Zhou 2000).

Artificial neural networks and fuzzy logic were widely applied to a variety of problems with very good results, despite each had drawbacks that made it not applicable in specific cases. To overcome these limitations different kind of systems were combined together in an attempt to integrate their strengths and mitigate their undesirable side effects and neuro-fuzzy systems and fuzzy expert systems appeared.

At present research is pushing the limits of integration further and several extremely interesting applications are described in scientific publications.

An analysis of the state of the art has been conducted and the works done have been divided into five main categories:

- durable goods;
- military and space;
- industrial plants;
- industrial machines; and
- health diagnosis.

In all five categories many different systems have been developed.

For example experts systems for cars engines have been proposed by Gelgele and Wang (Gelgele 1998) being expressively designed for helping mechanics during car engines maintenance; another example is an expert system for motorcycle maintenance (Su 2006).

The military and space sectors are source of high investments in research for practical application of new technologies. Quite often, though, the achieved results are not published for security reasons. Some applications of artificial intelligence and soft computing techniques have been however reported and explained, like a user-friendly and costs saving maintenance system for the Abrams tank (Baur 1996) and a sophisticated monitoring tool for a military jet engine (Diao 2004).

Predictive maintenance has been also investigated for industrial plants, like for example in the works of Dabbaghchi (Dabbaghchi *et al.*, 1997) and Kalles *et al*., who proposed a system to diagnose power plants, or in the works of Ozyurt and Kandel (Ozyurt 1996) and Zhang and Morris (Zhang 1996) who worked on chemical plants.

Predictive maintenance researches have interested also industrial machines, like turbomachinery (Siu 1997), gearboxes (Joentgen 1999) and tool breackage (Chen 2000).

Finally many researches have been conducted to provide health diagnosis, to evaluate Electrocardiography (ECG) (Silipo 1998) and others medical exams

2.7.4 Aim of the Work

What emerged from the literature review is a substantial lack of comprehensive decision support systems for predictive maintenance. While some interesting systems have been proposed, several trends can be identified:

1. the proposed systems tend to be focused on the diagnosis and do not provide an integrated maintenance management of the products since they are generally intended as local systems installed either on-board or as a component of the maintenance equipment;
2. most of the proposed systems are focused on the analysis of specific signals and hence cannot be generalised to other cases;
3. only few of the proposed systems consider on-board sensors as a constraint, and test cases have often been constructed with the installation of desired sensors. While this can be seen as a natural way of approaching the problem, no guarantee is posed on the possibility to actually implement the system when the monitored signals are pre-determined;
4. from the previous point derives that most of the systems can be implemented only either on products with needed sensors already on-board, or in situations where the installation of a new sensor is recognised as an advantage by the customer who is hence incline to pay an additional price for it. This puts serious constraints on the applicability of such methodologies to

consumer goods, where the attention on costs is such that even the addition of a single sensor is not acceptable as emerged from interviews with sector experts.

The concept behind our work is a decision support system for predictive maintenance which integrates the diagnosis of impending faults and the management of the maintenance missions or operations. In order to guarantee a wide applicability to real cases, the decision to design the diagnostic module to work only on data coming from sensors already installed as components of the monitored good had been taken. This approach has been chosen because it represents an economic optimum, implementing the best diagnostic tool possible without the charge of additional costs on the product of interest. A system needing more sensors could have been more complete, but the no-impact policy on the products costs structure, confirmed by application partners as the best way to proceed, was considered paramount, addressing research in the aforementioned direction.

Another important feature is the two-layer structure of the system. The first is the product layer, where signals are measured and possibly transformed, while the second is the central unit layer, where the measured data are sent for the diagnostic process. Once the diagnostic module has provided a complete analysis of all the monitored products, giving an estimate of the products ageing and reporting any impending or occurred fault, the maintenance management module allows to better organise maintenance missions providing a complete view on products needing maintenance actions. This two-layer architecture is important since it guarantees applicability even to households and consumer products which have sensors used for operative monitoring but no processing units capable of executing computational tasks. A modified architecture has been investigated for those industrial products which have computer units integrated in them. In this case the diagnostic task can either partially or entirely be carried out at product level while the central unit is only responsible for the maintenance management. Even if this distributed architecture is applicable only to particular situations, needing a computer unit on-board the monitored products, the possible advantages are many and important. First of all a new actor, the product owner, can gain benefits, having a direct view on the conditions of their goods. This can be important since the user can decide to act according to the ageing level, changing working parameters in order to prevent early or in-working failures. Another important aspect is the substantial decrease in the computational load of the central unit. When the number of monitored products grows, the central system is loaded with a continuous flow of data needing analysis, creating potential delays if the central unit is not powerful enough. Distributing the diagnostic module would have the beneficial effect of limiting the operations required to the central system, ensuring its availability for important tasks (e.g. additional analysis on complex or doubtful cases).

Two more advantages are obtained as consequences of the presence of a central unit collecting products data. On one hand the collected data can be used to enhance the diagnostic system generating new knowledge about failure and pre-failure operation modes, on the other hand, a database containing a big amount of data regarding products working conditions and faults can be extremely valuable for companies in order to correct possible design issues in new product releases closing the product lifecycle information loop. Finally these information can be used to achieve maintenance and spare parts management as will be explained in the following.

It is very important to clarify that the real focus of our work has never been the diagnostic system in itself, but rather the methodology used to develop the system. This is a fundamental concept since the identification and formalisation of a specific methodology allows to easily obtain systems for monitoring virtually any kind of product.

2.7.5 Proposal for a Methodology

In the previous section a brief description of the target diagnostic system has been given. This section will focus on the methodology which has been formalised to guide the user through the creation of such a system.

The reasons behind the proposal for a methodology, rather than for a system, are extremely important.

First of all developing a methodology is the only possible way to ensure applicability to different realities, making the resulting system fit a range of dissimilar applications. Secondly, following the different development steps it is possible to tailor the diagnostic module to the specific case, considering what is relevant and using only the data acquired by sensors already installed on-board the product, avoiding changing its cost structure and considering the product, and not the diagnostic system, the real centre of the implementation process. This flexibility represents one of the most important features of the methodology, which aims at going beyond the single case, creating a general framework easily customised for each specific product. Moreover, since the final target is an integrated maintenance management system capable of dealing effectively with a number of installed products, a general methodology is the only way to grant that all the different structures of maintenance processes can be mirrored in the system. A pre-codified solution could have hardly granted the desired flexibility.

In order to obtain all the features, three macro steps have been identified to guide the user from the definition of the scope of the monitoring to the implementation of the system in all its different parts.

The first step is entirely dedicated to the formalisation of the necessities and to the definition of the monitored systems and subsystems, the second one regards the creation of the diagnostic and prognostic module and the final one aims at the development of the maintenance management module.

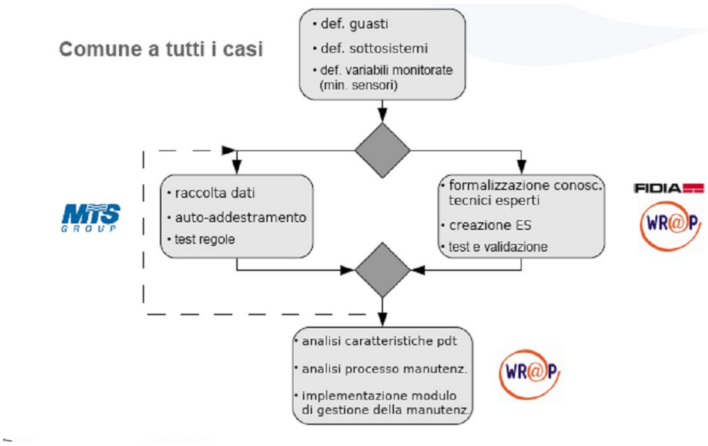

Figure 2.6 Steps of the work

A quick view on the different parts of the methodology can be given by the list of the different steps which have been formalised:

Definition of the System

- definition of the faults which must be avoided with anticipated maintenance actions;
- definition of the subsystems in which the previously defined faults happen or in which the faults have any kind of effect; and
- definition of the signals which have to be monitored in order to detect the impending faults in advance.

Creation of the Diagnostic Expert System

- formalisation of the diagnostic knowledge;
- creation of the expert system; and
- test and validation of the expert system.

Creation of the Maintenance Management Module

- analysis of the product characteristic features;
- analysis of the product maintenance process; and
- implementation of the maintenance management module.

The next few subsections will look into each single step in order to better describe the different activities.

First Step: Definition of the System

The very first step to be taken is the analysis of the necessities which the system will have to answer. Being the system operation centred on the product to be monitored, a refined analysis of what will be monitored and what will not is extremely important. The choice of the faults which will be monitored is fundamental: while none of the relevant faults can be ignored, there are often a number of faults which cannot be detected in advance because they give no significant pre-fault signal, and others whose advanced detection creates no significant advantage. Monitoring all the faults, instead of a significant subset of the all possible ones, can result in a necessity for a lot of band to transfer data, for big storing devices and for powerful elaboration units while giving no significant advantage. Skimming off the most relevant faults is thus necessary to obtain a precise diagnostic system while keeping the leanest structure possible.

Once the subset of relevant faults has been identified, a second analysis must be done in order to understand in which subsystem of the product of interest the different faults have effects. Creating such a map is extremely important since it allows to split better the Expert System in sub-modules each focused on a particular part of the product. Operating this way it is possible to avoid the creation of a monolithic system which would be impractical for products with a medium to high level of complexity.

The subsequent analysis is focused on the definition of the smallest possible subset of signals which allows to effectively detect and recognise each of the impending faults selected for monitoring. The minimisation of the number of signals to be controlled is another important point for obtaining a lean system. According to the choice of avoiding any additional cost on the product, only the signals monitored by sensors already installed on the product must be taken into consideration.

Second Step: Creation of the Diagnostic Expert System

The second step includes all those activities which must necessarily be taken in order to create the diagnostic module of the system. As reported before, the diagnostic module is basically an expert system based on a fuzzy inference engine (specifically a Mamdani fuzzy system).

There are several reasons behind the choice of using soft computing and artificial intelligence techniques instead of adopting a mathematical approach. First of all the mathematical formalisation of the behaviour of many goods, being them industrial or consumer products, can be extremely difficult implying the necessity for a deep knowledge of mathematical relations existing between different variables. Secondly, what traditionally made human experts much more apt for diagnosis than machines is their flexibility and ability to deal with situations hardly classifiable with certainty. Then, in order to to guarantee a wide applicability of the system, the methodology could not imply long or expensive studies in search for a proper model. The cheapest and readily available knowledge regarding diagnostic tasks is generally that of experienced technicians and hence the idea to exploit this knowledge, often not formalised in mathematical models, could be pursuit only with techniques capable of managing unstructured knowledge such as expert systems. Finally, even where mathematical models of the products exist, some of the variables in these models may not be monitored during the normal operation because of the absence of dedicated sensors. Since one of the most important points in the development philosophy is to create a system capable of performing diagnosis only with sensors already included in the good, mathematical models are practically not usable and other techniques must be applied to link observed variables to working states.

In order to develop a diagnostic expert system, the rulebase, representing the codified diagnostic knowledge, must be created and validated through a test session. Two different cases can be identified here, the first one concerning cases in which the diagnostic knowledge is already present, in any form, into the company know-how; the second one regarding all those cases in which no knowledge has ever been acquired. In the former situation, the methodology prescribes to formalise the diagnostic knowledge into if-then rules, to integrate them into a consistent and comprehensive rulebase, and finally to test it with experimental data. Very different is the latter situation. In this case no knowledge can be formalised and hence it is necessary to create the diagnostic knowledge. In order to obtain a rulebase, the proposed methodology suggests the use of a neuro-fuzzy system capable of extracting rules from experimental data (self-training process).

Once the expert system has been codified and validated, the last step, concerning the creation of the maintenance management module, can take place.

Third Step: Creation of the Maintenance Management Module

The last step of the methodology regards the creation of the maintenance management module. Once the diagnostic module is ready for operation, a second module is necessary to plan the maintenance actions maximising the economic efficiency of each mission. In order to create such a module, different analysis have to be done. First of all the characteristics of the product must be closely considered in order to understand how to gain the most benefit possible from a single maintenance mission. The cost of each component, for example, can be extremely important to decide whether to change or not a subsystem with still relatively short residual life when a mission is planned to maintain a product in the same geographical area.

Secondly the maintenance process must be analysed and considered in its most important features. The maintenance management module must mirror the structure of the process in order to be effectively used in practice. Finally, the maintenance management module can be implemented to get a tool capable of considering a number of installed products at the same time, of planning the missions on the estimated ageing values and of matching the needs of the single company reflecting the structure of its own maintenance process.

2.7.6 Application of the Methodology

As stated before, within the PROMISE project, three application partners have been selected as test cases for the methodology. In order to test the whole methodology in a short amount of time, each case has been used to test a subset of activities allowing parallel development and evaluation. The other advantage of working this way is the focalisation of each partner on a single task which ensures an higher concentration of the assigned resources.

Thanks to the peculiarity of each case, it has been quite easy to decide which partner would have been assigned to which phase.

MTS, for example, was chosen to test the automatic development of the diagnostic module exploiting the self-training capabilities of the neuro-fuzzy system; Fidia was chosen to test the development of the expert system starting from the diagnostic knowledge retained by expert maintenance technicians; WRAP was involved both in the expert system implementation, similarly to Fidia, and in the development of the maintenance management module. Obviously the first step (definition of the system) had to be taken in all the cases in order to decide how to structure the system.

In the first application case, the MTS scenario, the specific task regarded the estimate of the ageing of the primary circuit heat exchanger of a home boiler. In the primary circuit, the opening of the gas valve is controlled in order to make the domestic hot water temperature match a defined set point. What happens in normal operation is that impurities, found in the water fed to the boiler, tend to accumulate into the heat exchanger causing inefficiencies in the heating process. As the accumulation proceeds, the boiler is progressively less capable of guaranteeing a good heat exchanging rate and hence less capable of matching the specific set point for the domestic hot water temperature. As a result, an increase in the difference between the primary circuit return temperature and the domestic hot water temperature can be observed. The final stage of the ageing process is represented by a complete filling of the exchanger which causes the boiler to loop between the maximum operation level and the security block state induced by the excessively high temperature reached by the water in the primary circuit.

Given the amount of data available thanks to accelerated life simulations made on two boilers in a MTS test facility, the application scenario was well suited for the validation of the part of the methodology regarding the self-extraction of knowledge from data relative to real operation conditions.

In order to create an appropriate training data set, an expert from MTS was required to rank the ageing level reached from the boiler starting from the characteristic measurements obtained in the test. The request was for a rough estimate, with three possible conditions: new (whose numeric codified value was chosen as 5 an a 0-100 scale), middle of life (numeric representation 50) and end of life (numeric representation 100). The value 0 was avoided in order to guarantee the possibility to use the 0-5 interval for possible future end of production line tests based on the same system.

A training data set was then built for the self-learning process carried out by the neuro-fuzzy software. The considered input variables were the difference between primary circuit return temperature and domestic hot water temperature, and the gas valve aperture, while the target output variable was the estimated ageing given by the human expert. The process gave a rulebase as a result and a test dataset was built starting from experimental data. The data came from three different boiler conditions (new, middle of life, end of life) working at three different domestic hot water set points.

After some filtering and averaging of the results, aimed at smoothing the effects of particular working states, the obtained ageing estimates were found to be consistent with the real conditions of the boiler as can be seen in table1.

Further analysis would have been needed to understand if the system underestimated the ageing of the boiler classified as in the last part of the life or if the boiler had still about 10% of residual lifetime, but MTS opted out of PROMISE and hence no more data were provided.

Table 2.3 Example of boilers conditions during LC

Set Point (° C)	Boiler condition	Ageing estimate (%)
40	new	10,67
49	new	6,59
58	new	6,69
40	middle of life	48,37
49	middle of life	60,09
58	middle of life	55,91
40	end of life	88,40
49	end of life	88,38
58	end of life	88,35

A second test was made comparing the output of the rulebase generated by the neuro-fuzzy system with the ageing estimate obtained with a set of crisp rules codified on the basis of MTS technicians' experience. The step ladder behaviour which characterises the crisp expert system make it overestimate the ageing, reporting the passage over the alarm level (fixed to 80%) about four months earlier than the fuzzy expert system. Since data were collected during an accelerated life test with acceleration factor set to eight, in a real case, according to the data, the crisp expert system would have reported a pre-failure state about thirty-two months earlier than the fuzzy expert system causing an unneeded maintenance action with the related unneeded costs. While as in the previous test no end-of-life data were available to verify if the ageing estimate was correct, what is known is that the boiler was still running after the last dataset considered, meaning that the fuzzy expert system would have reported the pre-failure state consistently before the actual failure.

To sum up, the use of the neuro-fuzzy system proposed to extract knowledge from data proved to be a powerful procedure to generate a set of fuzzy rules describing the deteriorating behaviour of a product of interest. The software was able to generate the rulebase in a very short computational time and without requiring high computational resources, while the execution of the inference process on each single dataset, made of about 2000 input-output data pairs each, was very quick, making it suitable for any kind of computers currently available on the market. The only drawback presented is the number of rules which is sensibly higher (three to five times according to the rule-pruning policy used) than that of an expert system codified using the knowledge of the human expert formalised in if-then fuzzy rules.

In conclusion, the test of the part of the methodology regarding the use of a neuro-fuzzy system to extract knowledge and generate fuzzy rules from experimental data was successful, leading to the creation of an expert system capable of properly categorise data coming from real working products.

The second case, involving Fidia as application partner, was planned to validate the procedure proposed for the creation of the expert system starting from formalised knowledge represented by technicians' knowledge in this specific case. This particular application scenario was chosen for the complexity of the monitored product (a 5-axis milling machine) and served as a test to verify the real possibility of implementation of an articulated expert system with the proposed methodology.

The goal of the fuzzy expert system is to produce an estimated ageing value for each of the spindles of the analysed milling machine starting from specific measurements obtained during the execution of particular tests currently used by Fidia technicians to monitor the conditions of the machines.

Even in this case the system was projected to use, as predictive variables, only measurements coming from data already monitored on the machines, without any need for additional sensors. In particular all the predictive tasks were performed without any vibration measure, in contrast with what emerged from the review of literature as the mainstream practise. This was done to validate the methodology in every single aspect including the choice of not requiring any change to the products under analysis.

The formalisation of diagnostic knowledge in if-then rules was easily obtained for each of the single measurements of interest with simple interviews to an expert technician.

Considering the advantages it would have given in terms of flexibility and development simplicity, a modular structure was chosen for the diagnostic system, where each module analyses the data coming from a specific test and provides an ageing value for each of the spindles. A final module takes all the estimated values and generates a global ageing esteem.

While some datasets coming from reduced test sessions have been analysed during the first phases of the research, only five complete cases have been evaluated using the decision support system developed, due to the difficulty Fidia has in collecting data from machines working in customers' facilities. Even though the sample is too small to draw statistically reliable conclusions, a positive trend could be observed since the expert system demonstrated to correctly assign low ageing values to new machines. What is considered more important, though, is that the system was able to highlight an unusual machine behaviour for two machines previously classified as properly working by the technicians who analysed the data coming from the tests. The abnormal situation was confirmed after a subsequent analysis of disaggregated test data. At present, Fidia is collecting a wide set of data which will be used to validate

the system and to improve all the parameters definitions in the near future.

The third application scenario concerns the predictive maintenance of a fridge WRAP is currently working on for one of the companies belonging to the same industrial group. The case is interesting for two main reasons. First of all it allows to codify a second fuzzy expert system using a different logic from the one already presented in FIDIA application scenario, secondly, given the characteristics of the product, it represents a good test case for the development of the maintenance management module.

What characterises the chosen fridge is its on-board control system capable of detecting most of the possible faults including defrost resistors failure, environment and freezer temperature sensors failure, lamp failure and others. Considering that this kind of faults are already managed locally, and that they are not predictable in advance through the monitoring of any specific parameter, the diagnostic module of the predictive maintenance decision support system was focused on the thermodynamic circuit. In particular the ageing of the thermodynamic circuit is determined by micro-leaks which cause progressive decrease in the refrigerant level and hence lower heat absorption capability requiring a higher compressor working time in order to match the temperature set point. This phenomenon can be monitored using several parameters measured by the on-board control system and easily transferable over a network connection with devices already implemented by WRAP and ready to be installed on future products.

In order to avoid substantial mistakes in the ageing estimate process caused by some particular protection states that are triggered by some component faults and operate to simulate a proper behaviour as much as possible (with the side-effect of masking the real ageing level to the diagnostic system), the expert system has been structured in two separated modules. The first one uses defined variables to estimate the ageing of the thermodynamic circuit, while the second takes as inputs some particular measurements plus all the warning and fault signals generated by the on-board control system, and uses them to compute an estimate of the reliability of the ageing value. Operating this way, the expert system produces an ageing estimate and a measurement of its reliability, letting the user understand whether the ageing value is representative of the real condition of the thermodynamic circuit or rather induced by a specific operation mode triggered to protect the fridge from particular failures.

Apart from the development of a fuzzy expert system implementing a different inference philosophy, this application scenario was ideal for testing the development of the maintenance management module for several reasons. The first and most important is the interest WRAP showed in having a tool allowing to manage maintenance actions effectively according to the real products needs. During preliminary meetings WRAP proved to be a very dynamic company extremely technology-oriented and with a clear vision on how specific tools can affect the future business of the group.

This particular attitude guaranteed commitment in the development phase and gives positive expectations for a future test of the module. A second reason can be found in the kind of product WRAP is working on for PROMISE. While a milling machine, like the one that was considered in the previous application scenario, is an interesting test case for its complexity, the fridge under analysis in this case has completely different characteristics. First of all a fridge is a common product, with a wide and geographically distributed market. This is fundamental when testing a tool like the maintenance management module which is intended to aid the scheduling of the maintenance missions organised, for geographical area, in order to maximise the economic efficiency. Clearly such a module cannot be tested on a small number of installed products and neither on geographically concentrated markets since most of its potential would not emerge. Secondly, the fridge has an adequate number of components: not too few to make the maintenance management module useless, and not so many

to be excessively complicated as a test case. For these reasons WRAP was chosen as a partner in the development of the maintenance management module.

The first step in the design process of the maintenance management module was the identification of the features which had to be implemented. Even though the application partner for the development was WRAP, all the three scenarios were analysed in order to collect ideas coming from very different sectors and all the partners were asked to give feedback about what emerged as the most important module characteristics from the initial brainstorming. After the first review of the necessary features made by the three application partners, only WRAP was involved in the successive stages. A draft proposal was submitted to WRAP, whose feedback was considered to make appropriate corrections. A second draft was proposed and new feedback received. This exchange was looped several times and resulted in the final proposal which, once approved by WRAP, was passed to project partners for implementation. The module is structured in different interfaces, each giving a specific view on the database of the PROMISE PDKM (Product Data and Knowledge Management) system. The interface is organised in four linked main modules each specifically designed to match the necessity of a particular area of interest. These four modules are the Predictive Maintenance DSS, the Spare Parts Manager, the Maintenance Mission Manager and the DSS Settings module. The Predictive Maintenance DSS is structured in different masks accessible from the first which is called the General View. This mask allows the visualisation of the status of the installed products filtered with the desired keys. Once the key has been chosen (type of product, type of expected fault, geographical area, and others) the matching database entries are shown, reporting for each a visual indication of the product status, the type of impending fault, the expected failure date and the date of the last maintenance action taken on that product. The General view allows to access the Spare Parts Management module and the Maintenance Missions Management module with the two buttons provided, while it redirects to the Item view when clicking on the serial number of one of the shown entries. The Item view provides complete information about each single product: general data about the geographical location are given and data regarding the residual life of each component and past maintenance actions are presented to give a complete idea of the products conditions. Moreover form the Item view it is possible to manage the maintenance of the single product adding it to the planned maintenance missions.

Another view, called Sensors view, is available to visualise monitored variables in a convenient chart form, allowing the visualisation of multiple variables on the same chart.

Two more modules have been designed for the maintenance module: the Spare Parts Manager and the Maintenance Mission Manager. The first one allows to visualise the estimated number of components needed for a certain period of time defined by the user. The value is calculated starting from the expected failure dates of the monitored products. The second one is designed to obtain a better scheduling of the maintenance missions, optimising the number of maintenance actions in the same mission, either changing more than a component on the same product, or scheduling actions on products in the same area when the expected residual life does not economically justify another maintenance mission in the near future.

Finally a DSS Management module allows to change specific settings of the predictive maintenance diagnostic module.

2.7.7 Conclusion

In this paper a methodology for the development of predictive maintenance algorithms has been proposed, together with a methodology for the usage of the obtained aging data.

Three test cases have also been carried out, developing three predictive maintenance algorithms and the corresponding interfaces and usage strategies.

Form the test cases emerge that the methodology easily guides the user in all the steps necessary to build a predictive maintenance decision support system which ensures good performance while requiring relatively few resources, both during the development and for operation. Moreover the maintenance management module, which distinguishes the obtained system from many others, is extremely valuable for all the companies who want to make maintenance a better business.

Since the test cases gave positive results, they will be developed deeper, implementing completely the solution within the PROMISE environment.

Moreover other cases will be analyzed and developed in different business scenarios, showing the effectiveness and the business soundness of the proposed solution.

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2.8 Inferencing in Large Scale Sensor Networks

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Abstract. This paper presents a strategy for the optimal decomposition of large-scale sensor networks, and subsequent design of a sectioned Bayesian network for energy efficient sensing. A key issue in the design of Bayesian networks for monitoring engineering systems is to ensure that a reliable inference scheme about the health of the system can be made by combining information acquired from each sensor in the system into a single Bayesian network. However, as the size of the network rapidly grows, aggregating information made by all the sensors becomes computationally intractable. Hence, sectioning of the Bayesian network based on functional or logical constraints allows for improved computational efficiency in aggregating information while reducing the overall communication requirements. This approach ultimately leads to a reduction of the energy costs, which is critical to sustained and effective operation of the sensor network. Sectioning of the Bayesian network into a Multiply Sectioned Bayesian Network (MSBN), however, must follow both the physical constraints of the system and specific conditions that allow for valid inferential analysis of the system state. The goal of this paper is to provide guidelines that will yield an optimal network decomposition design while satisfying these physical and inferential constraints. The overall decomposition problem is formulated as a nonlinear network optimization problem, with the objective of minimizing the cumulative energy used by the sensor network while satisfying the structural and inferential constraints of the MSBN, as well as the physical requirements specified by the problem domain. Efficient heuristics for decomposing sensor networks into an optimal MSBN are proposed. The proposed method is then tested for a sample sensor network system and the computational results are presented.

2.8.1 Introduction

The rapid development in sensor technology over the past decade has led to the deployment of a large number of sensors and sensor networks in complex industrial systems and processes for more comprehensive, reliable, and timely gathering of characteristic data. Currently, such networks are limited in size and detection capability in real world applications due to energy limitations and communication bandwidth constraints.

An approach to alleviate the above mentioned problems in large-scale sensor networks is to segment the sensor network into smaller sub-networks and introduce local decision-making capability at the sub-network level. Data fusion and synthesis can be performed at the localized sensory nodes, or a small group of sensors, and only higher-level inferences are communicated between the groups. This approach has the advantage of significantly reducing the communication requirements and computational overhead on the central controller, thereby requiring less energy consumption. However, the process of distributed inferencing, local decision-making and network segmentation could potentially lead to incorrect or inaccurate assessment of the machine or process condition. This paper focuses on two critical issues related to decomposition of sensor networks: the ability to guarantee valid inferences about the whole system and the overall energy efficiency.

The general problem of aggregating information from decomposed sensor networks is essentially a problem of uncertain reasoning: to infer the state of a *complex, partially observable, non-deterministic* and *dynamic* environment from uncertain background knowledge and observations. The fundamental issues are how to represent the uncertain knowledge and beliefs, and how to update them in light of new observations. Arguably, so far the most successful approach is the one based on Bayesian probability theory. By incorporating graphical models, namely *Bayesian Networks* (BNs), the approach can express and update beliefs as probabilities effectively for applications, which require uncertain reasoning.

In the case of decomposed sensor networks, distributed BNs or *Multiply Sectioned Bayesian Networks* (MSBNs) provide a solid basis for knowledge representation. Extending the single decision-maker based BN, distributed BNs represent the knowledge and belief of each sub-network as a Bayesian subnet. The collection of subnets needs to satisfy a set of conditions that ensure correct, distributed probabilistic inference. In order to perform globally correct inferences in a BN context, a *hypertree* organization for sensors is needed. If a graph is used to depict each subdomain as a node and the non-empty intersection between two subdomains as a link, the result is a *hypergraph*. The hypertree organization requires that a subgraph of the hypergraph exists and it is a tree. This representation imposes a constraint on how the entire domain is partitioned into subdomains. While finding a feasible partition of the causal structure of a domain monitored by a sensor network, which satisfies the hyper-tree constraint, is relatively easy, identifying *good partitions* that are conceptually coherent and minimize energy usage is non-trivial. In this paper we present decomposition guidelines that can guide the subdomain partitioning process to produce energy efficient hyper-tree organizations effectively.

As the number of sensors deployed in a network grows, energy consumption becomes an increasingly critical issue, as it forms a prerequisite for both individual sensors and the entire sensor network to operate properly and reliably during the designed service life. Energy consumption in a sensor network can be viewed as consisting of two interrelated aspects: *computation* and *communication*. While localized on-sensor data processing reduces in-network traffic and thus the related energy consumption for communication, it increases the energy consumption at the individual sensor node level. Conversely, transmitting raw data to a central controller minimizes on-sensor computation energy and, maximizes the life span of individual sensors, however at the expense of increased data transmissions and communication energy consumption. In this paper, we further address the implications of energy proportion, with the goal to devise an optimized MSBN scheme for energy-efficient sensor network operation.

2.8.2 Sectioned Bayesian Networks

Bayesian networks (BNs) have often been used to model the propagation of uncertainty in causal networks. A BN is a graphical model of a domain where observations of the domain are represented as random variables on nodes. A causal relation between the variables is represented by arcs connecting the nodes. Since the inclusion of loops leads to intractability, the network structure is constrained to be a *directed acyclic graph* (DAG). The strength of the causal relations is expressed by a conditional probability distribution (e.g., $P(A|B,C)$, where B and C are the parents of A). Sensor agents may contain enough memory and processing capacity such that a small BN can be assigned to each agent. Such a *subnet* could receive evidence signals and confidence signals from several surrounding sensors. Together, with the observed inputs from the sensing element, the sensor agent could reason about the most probable state of a certain system variable. A reliable inference about the health of the entire system can be made by combining beliefs about all the system variables into a single BN.

As the size of the network grows, the process of aggregating inferences made by all the sensor agents becomes computationally intractable. Hence, sectioning of the overall BN, based on functional or logical constraints, will allow computational efficiency in aggregating inferences and reduces overall communication requirements, thus leading to significant energy savings. An MSBN allows for the partitioning of the overall BN into several sub-networks, and only communicates inferences between the sub-networks. The graph structure of an MSBN is a secondary structure, called a *hypertree*. The *hypernodes* of this hypertree are subDAGs of the underlying BN. Together the subDAGs result in a DAG for the MSBN. Intersections between two subDAGs are called *d-sepsets*.

The actual representation of MSBNs is based on some basic underlying assumptions and constructed in detail in the literature and briefly summarized here. First, it is assumed that each agent's belief is represented by probability; beliefs are represented by each agent using a probability distribution, and the belief updating is performed exactly. Second, an agent A_i can in general influence the belief of each other agent through direct or indirect communication, but can communicate directly to another agent A_j only with probability $P_i(V_i \cap V_j)$ where $V_i \cap V_j \neq \emptyset$. Thus, agent communication occurs using a concise message of the belief over the commonly shared variables. Third, a simpler agent organization is preferred in which agent communication by concise message passing is achievable; a tree-organization for agent communication should be adopted. Fourth, each agent represents its subdomain dependence as a DAG, thus yielding efficient encoding of an agent's belief over a subdomain. Finally, the *joint probability distribution* (JPD) must be consistent with each agent's belief over its subdomain. The JPD is the collective belief of all agents and is reflective of the expertise of each agent within its subdomain and supplements the agent's limited local knowledge outside its subdomain. Using these basic assumptions, a formal definition of an MSBN is derived, presented in the literature, and restated here as follows:

An MSBN is a triplet (V,G,P): $V = \cup_i V_i$ is the total universe where each V_i is a set of variables called subdomains. $G = \sqcup_i G_i$ (a hypertree MSDAG) is the structure where nodes of each subgraph G_i are labeled by elements of V_i. Let x be a variable and $\pi(x)$ be all parents of x in G. For each x, exactly one of its occurrences (in a G_i containing $\{x\}\cup\pi(x)$) is assigned $P(x|\pi(x))$, and each occurrence in other subgraphs is assigned a uniform potential. $P = \prod_i P_i$ is the JPD, where each P_i is the product of the potentials associated with nodes in G_i. Each triplet $S_i = (V_i,G_i,P_i)$ is called a subnet of the MSBN. Two subnets S_i and S_j are said to be adjacent if G_i and G_j are adjacent in the hypertree.

Although the segmentation of a large Bayesian network into an MSBN may improve computational efficiency and reduce energy costs, it is important to follow specific guidelines when sectioning the system into subnets monitored by each agent. Given the basic underlying assumptions and the formal MSBN definition and construction guidelines, it is important to adhere to the conditions necessary to construct a valid MSBN. A violation of any required condition will produce invalid inferences and prevent the agents from properly monitoring or controlling the physical system. For example, a partitioning scheme that does not create d-sepsets in the hyperlink between subnets will yield an invalid network as demonstrated in the literature. An example system using sensor output information is shown in Figure 2.7. For this system, sensor output information (nodes *a*, *b*, *c*, *h*, *m*, *r*, and *w* in Figure 2.7) is fed into select segment heads for computational analysis. The output from these segment heads either exits the system or is used as input for another segment head. For illustrative purposes, the sensor network and operations performed within each segment are based on a circuit example[2]. Using the valid sectioning guidelines of MSBNs, a properly sectioned BN consisting of four partitions and five subnets (i.e., D0, D1, D2, D3, and D4) is shown in Figure 2.8. Other sectioning schemes and a detailed discussion of invalid sectioning for this example are presented in the literature.

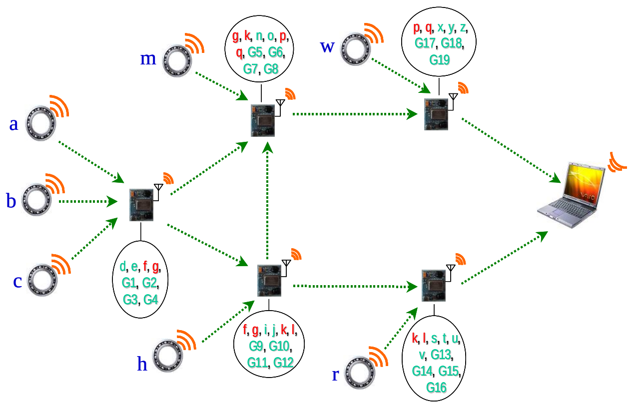

Figure 2.7 Sensor network configuration

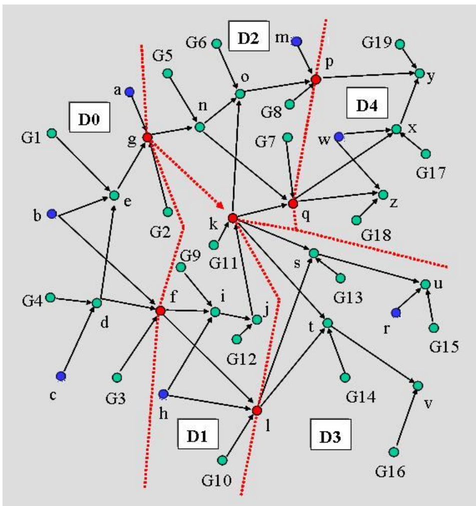

Figure 2.8 Valid MSBN (5 subnets)

In addition to satisfying the conditions for valid construction of MSBNs, proper sectioning of the overall BN should also consider any physical constraints of the system. For example, it may be required that certain nodes of the BN be grouped together in the MSBN for data fusion operations within a segment head to be properly performed. In this case, there may exist hard-wired operations within the segment that cannot be feasibly separated in a sectioned network (e.g., nodes *d*, *e*, *f*, *g*, *G1*, *G2*, G3, and *G4* in Figures 2.7 and 2.8). This requirement imposes a limitation on the possible sectioning schemes of the MSBN that provide valid inferences of the physical system. Prior to presenting the algorithm for determining the optimal sectioning scheme for an MSBN, an introduction of energy efficient sensing is provided in the next section.

2.8.3 Energy Efficient Sensing

This paper addresses problems encountered when attempting to achieve energy efficient sensing in large-scale sensor networks, and introduces a discussion on network decomposition utilizing the theory of MSBNs. This section presents the governing equations used to compute sensor network energy consumption for the sample system that will be used later in this paper (Section 5) to test the optimal decomposition scheme that is presented in the next section (Section 4).

Energy consumption in a sensor network can be viewed as consisting of two interrelated aspects: local data processing (*computation*) and data transmission (*communication*). Given a fixed sampling rate and data length, the power and energy cost for local data processing can be estimated as:

$$P_{comp} = C \cdot V_{dd}^2 \cdot f \tag{2.23}$$

$$E_{comp} = N \cdot C \cdot V_{dd}^2 \tag{2.24}$$

where N is the number of clock cycles needed for processing each task, C is the effective switching capacitance determined by the specific hardware, f is the operating frequency, and V_{dd} is the DSP core voltage supply. The operating frequency f can be expressed as a function of voltage supply V_{dd}:

$$f \le \frac{K(V_{dd} - V_T)}{V_{dd}} \approx K(V_{dd} - \varepsilon) \tag{2.25}$$

where ε is the threshold voltage and K is a technical constant dependent on the processor hardware.

In order for two sensor-agents to communicate, the energy consumption needed for data transmission can be expressed as:

$$E_{Tx} = e_{e\_tx} \cdot k + \varepsilon_{amp} \cdot d^{\alpha} \cdot k \tag{2.26}$$

where *k* is the number of transmitted data bits, *d* is the distance between two sensor-agents, α is a factor valued from 2 to 5, depending on the environment of wireless transmission, $\varepsilon_{amp}(J/b/m^2)$ is the amplification coefficient to satisfy a minimum signal-to-noise ratio to ensure reliable reception at the receiver, and e_{e_tx} (*J/b*) is the energy dissipated to operate the transceiver. The energy consumed for receiving a data stream can be expressed as:

$$E_{Rx} = e_{e\_rx} \cdot k \tag{2.27}$$

where e_{e_tx} (*J/b*) is the energy dissipated to operate the receiver.

Equation (2.26) shows that, for a fixed distance, the energy consumed is proportional to the length of the data bits. On the other hand, the longer the distance between two sensor-agents, the more the energy will be consumed. Previous research has identified the following energy efficient data gathering scheme:

Scheme: The *sensor-nodes* are sectioned into different *groups*. Each *sensor-node* performs *localized* data processing, and only the features extracted from the raw data from each *sensor-node* are transmitted to the corresponding *group-head*. After data fusion, the *group-head* transmits the fused information to the *central monitoring unit* (CMU). The energy consumption (denoted as E_{Total}) for this scheme is calculated as:

$$\begin{aligned} E_{Total} = \sum_{m=1}^{M} [\sum_{j}^{N_m - 1} (E_{e\_tx} + \varepsilon_{amp} \cdot \bar{d}_j^{\,2} + E_{e\_rx}) \cdot k_f \\ + N_m \cdot E_{cmp} + E_{cmpf} + (E_{e\_tx} + \varepsilon_{amp} \cdot \hat{d}_m^{\,2}) \cdot k_m] \end{aligned} \tag{2.28}$$

where *M* is the number of *groups*; N_m is the number of *sensor-nodes* in the corresponding *group*; $\bar{d}_j$ is the distance between a *sensor-node* and its corresponding *group-head*; k_f is the number of bits for extracted features; k_m is the number of bits for fused data; $\hat{d}_m$ is the distance between the *group-head* and the CMU; and E_{cmp} and E_{cmpf} is the energy cost for feature extraction procedure and data fusion operation, respectively, and can be calculated using Equation (2.28).

The equations for energy efficient sensing presented in this section are used to test the optimal sectioning strategy for an example sensor network system in Section 5. The next section introduces the algorithm used to determine the optimal network decomposition strategy for a multi-agent sensor network system using MSBNs.

2.8.4 Optimal Sectioning Strategy

The general theory of representing a system as a BN, guidelines for sectioning a network into an MSBN for multi-agent inferential analysis and improved energy efficiency, and an introduction to energy efficient sensing have been presented. Given the requirements that satisfy both the logical constraints for creating a valid causal network and the preservation of any physical system constraints, a protocol for identifying the optimal MSBN configuration is required from a system design perspective. This section presents an algorithm that provides optimal decomposition guidelines of the overall BN into an MSBN while satisfying both the validity and physical constraints of the system.

For a given sensor network, the goal is to identify the valid decomposition scheme that minimizes the cumulative energy consumption attributed to both on-sensor computational operations and communication within the network. The first step of the algorithm is to identify all of the nodes (or variables) in the system, where $\{V\} = \{v_i,\ldots,v_m\}$ is the set of all nodes and m is the total number of nodes. Given $\{V\}$ and the flow characteristics of the system, the BN for the system may then be constructed and defined as the triplet (V,E,P). E is the set of arcs such that $G = (V,E)$ is a DAG (i.e., the *structure* of the BN), and P is the probability distribution. (Note that, for an MSBN, $G_i = (V_i,E_i)$ is the DAG for each subnet i).

Given this network, the physical system constraints are then identified and structured as subsets that must not be separated in the MSBN. These physical limitations may be due to such factors as hard-wired data fusion operations or the distance between sensors or segment heads. Define $\{Q_k\}$ as a set of nodes that must be contained within the same subgraph due to physical constraints for any constraining unit k (e.g., a data fusion segment head), and let g_k be a subgraph containing these nodes. Then, the overall subgraph G_i for a subnet i contains ξ_i, where $\xi_i = \cup_k g_k \,|\, k \in i,\{Q_k\}$ (i.e., given that unit k is contained within subnet i; as well as the set of nodes in unit k) is the total collection of subgraphs contained within G_i due to physical constraints and $\xi_i \subseteq G_i$.

An MSBN is defined as a triplet (V,G,P), where: V is the total universe where each V_i is a set of variables called a *subdomain* (i.e., $\{V\} = \{V_i,\ldots,V_s\}$ and s is the total number of subnets); G is a *hypertree MSDAG* where the nodes of each subgraph G_i are labeled by elements of V_i; and P is the JPD, where each P is the product of the potentials associated with nodes in G_i. Finally, there may be a constraint due to the total number of partitions allowed in the MSBN. Let N_p be the constraining limit of allowable partitions, and n be the total number of partitions in the actual MSBN.

Given the physical constraints of the system, the optimal network decomposition strategy is then evaluated as the subgraph G_i constructions that produce the minimal total energy consumption for the sensor network system (i.e., E_{total}). This algorithm may be formulated as the following nonlinear optimization problem:

Identify the optimal subgraph G network decomposition scheme that satisfies the following objective function:

$$\text{Minimize } E_{total}$$

subject to:

(1) $n < N_p$, $n = N_p$, or $n > N_p$ (depending on system)
(2) *Physical constraints* (problem specific) such that $\xi_i = \cup_k g_k \,|\, k \in i, \{Q_k\} \; \forall i,k$
(3) *BN constraints*[1][2] such that $BN = (V,E,P)$, where $G = (V,E)$ is a DAG
(4) *MSBN influence constraints* (valid sectioning) [1][2]:

- $MSBN = (V,G,P)$;
- $G = \bigsqcup_i G_i$ (a hypertree MSDAG);
- $G_i = (V_i,E_i)$ is a DAG;
- G is a connected DAG such that:
  - $\exists$ hypertree ψ over *G;*
  - each hyperlink in ψ is a *d-sepset.*
- Let $G_i = (V_i,E_i)$ (for i = 1,2) be two DAGs such that $(V_1 \cup V_2, E_1 \cup E_2)$ is a DAG. Then, the intersection $I = V_1 \cap V_2$ is a *d-sepset* between G_1 and G_2 if:
  - $\forall\, v \in I$ and $\pi(v) \in G$;
  - $\pi(v) \subseteq V_1$ or $\pi(v) \subseteq V_2$, where $\pi(v)$ are all the parents of v in G.
- $P = \prod_i P_i$ is the JPD, where each P_i is the product of the potentials associated with nodes in G_i;
- $S_i = (V_i,G_i,P_i)$ is called a subnet of *MSBN.*

Solution of the above algorithm yields an MSBN configuration that dictates both the number of groupings as well as the partition design to minimize energy consumption within the sensor network. This algorithm is tested in the next section using a sample sensor network.

2.8.5 Numerical Example

To investigate the energy consumption and identify an optimal partitioning scenario, a sensor network layout was constructed, as illustrated in Figure 2.9. This network presents a generic layout of the sample system shown in Figure 2.7 and could be applied to that system. According to the physical constraints of a specific system being monitored, sensor nodes that measure physical information from the same part of the system are considered as one subgroup (e.g., subgroup g1, g2, g3, g4, and g5 in Figure 2.9), and network partitioning can only be performed between one or more of these subgroups. Although a large-scale sensor network may contain a larger number of sensor nodes (>10^2), the sensor network layout (12 sensor nodes in total) investigated in this paper is illustrative for investigating energy efficiency through network partitioning based on MSBNs, and could be expanded with increased computational complexity to include more sensor nodes. Table 2.3 lists 10 valid network partitioning scenarios when the entire network is sectioned into only two groups (i.e., s = 2 and $n = N_p = 1$) based on the MSBN approach.

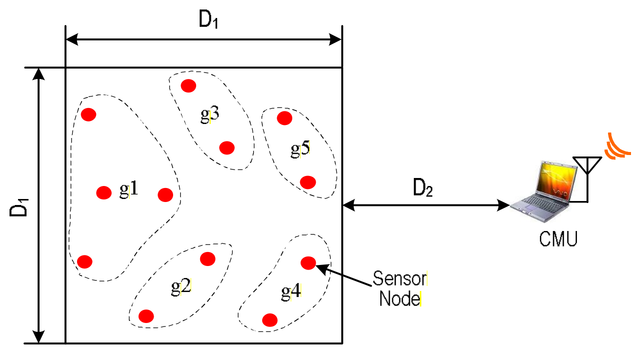

Figure 2.9 Sensor network configuration

Given that the distance between the *sensor-nodes* and the *group-head*, as well as between the *group-heads* and the CMU, affect the energy calculation (as illustrated in Eqs. (2.24) and (2.26)), the perimeter, D_1, of the sensor network and the distance, D_2, between the CMU and the sensor network can be used as a measure for the overall energy consumption of the sensor network. Parameters used for the energy calculation are listed in Tables 2.4 and 2.5, respectively, in which a commercially available DSP (model Blackfin BF532) is used as the platform for realizing the *sensor-agent*. The DSP features a maximum operating frequency of 400 MHz. The machine cycle N_{LP} needed for energy calculation, as listed in Table 2.4, is based on a "Discrete Harmonic Wavelet Packet Transforms (DHWPT) algorithm. This algorithm performs joint time-frequency vibration data decomposition at the sensor node level, from which specific "features", such as the energy content of the vibration signal at each sub-frequency band, are extracted from the raw vibration data. The time T_{DF} used for data fusion was found as 0.5 s.

Table 2.4 Valid sensor network partitioning scenarios

Scenario	Group A	Group B
1	{g1}	{g3, g5, g4, g2}
2	{g1, g3}	{g5, g4, g2}
3	{g1, g3, g5}	{g4, g2}
4	{g1, g3, g5, g4}	{ g2}
5	{g3}	{g5, g4, g2, g1}
6	{g3, g5}	{g4, g2, g1}
7	{g3, g5, g4}	{g2, g1}
8	{g5}	{g4, g2, g1, g3}
9	{g5, g4}	{g2, g1, g3}
10	{g4}	{g2, g1, g3, g5}

Table 2.5 Parameters for calculating computation energy

Parameter	V_C (V)	C (nF)	f (MHz)	N_{LP}
Value	1.2	0.5	400	110 x 10^6

Table 2.6 Parameters for calculating communication energy

Parameter	e_{e_tx} (nJ/b)	ε_{amp} (pJ/b/m^2)	α
Value	6,535	8,934	2

Figure 2.10 illustrates the energy consumption for each of the 10 valid network partitioning scenarios listed in Table 2.3, without including the energy consumption of the CMU. As shown in Figure 2.10, for a fixed distance between the CMU and the sensor network (D_2), the energy consumption increases as the perimeter D_1 increases for each network partitioning scenario. This is due to the fact that a greater amount of energy is needed to amplify the signal as the transmission distance increases to ensure reliable signal reception. Next, the energy dissipated by each partitioning scenario varies under a fixed perimeter D_1. For example, the energy consumption for *Scenario 5* (denoted as Seg5) is the highest while the energy consumption for *Scenario 3* (denoted as Seg3) is the lowest in the constructed sensor network layout. The difference for the energy consumption between *Scenario 5* (the worst one) and *Scenario 3* (the best one) becomes more and more significant as the perimeter D_1 increases, from approximately 0.7% to 18.3%, when the perimeter D_1 increases from 10 m to 100 m (Table 2.6). Based on these results and the restriction that the sensor network is to be segmented into

only two subnets, the optimal decomposition scheme yields subgraphs $G_A = \xi_A = \{g1,g3,g5\}$ and $G_B = \xi_B = \{g4,g2\}$.

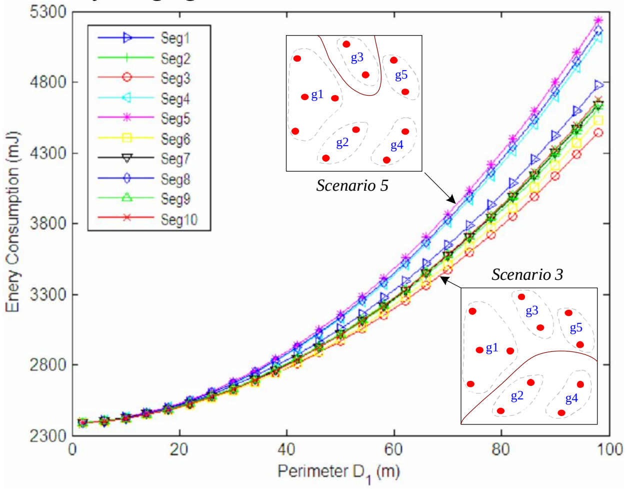

Figure 2.10 Energy consumption of the sectioned sensor network with fixed D2 (D2 = 100 m)

Table 2.7 Difference of the energy consumption between scenario 5 and scenario 3

Perimeter (*m*)	Energy Consumption (*mJ*)		
	Scenario 5	Scenario 3	Percentage of Increase
10	2,429	2,412	0.7%
20	2,526	2,502	1.0%
30	2,681	2,619	2.4%
40	2,893	2,774	4.3%
50	3,161	2,968	6.5%
60	3,486	3,201	8.9%
70	3,867	3,473	11.3%
80	4,306	3,785	13.8%
90	4,801	4,135	16.1%
100	5,353	4,524	18.3%

2.8.6 Conclusion

The energy efficiency of large-scale sensor networks can be effectively improved by segmenting them into “Multiply Sectioned Bayesian Networks” (MSBNs). Both the nature of the physical system to be monitored and the inferential constraints for valid system monitoring present challenges to the proper design of an energy efficient MSBN. This paper presented decomposition guidelines that satisfy both the functional and logical constraints of the system being analyzed, while providing an optimal design for energy efficient sensing. The algorithm was then demonstrated to show the optimal sectioning scheme for a sample sensor network. As the size of the network or the number of allowable partitions increases, however, the computational complexity also increases. Research is being continued to refine the proposed sensor network study and develop computationally efficient decomposition schemes to quantitatively evaluate larger and less constrained systems.

Acknowledgements

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2.9 Optimizing Maintenance Processes with RFID

Gerhard Müller, Klaus Richter, Cathrin Plate, Johannes Mandelartz

Abstract. Radio frequency identification (RFID) technology is entering more and more domains of logistics and engineering. The specific features of this technologiy are also opening significant potentials to improve performance and rationalize processes in the maintenance industry too. Various sectors of industry are already using RFID technology in diverse maintenance (pilot) projects in closed and proprietary information systems. This paper presents the state of the adoption of RFID technology in the German maintenance industry as exemplified by different pilot projects and describes the fields of RFID applications in maintenance processes. Along with the issuing technical standards for RFID technologies, another focus is managing the collaboration of plant operators and component and equipment suppliers in this field. Apart from their efforts to standardize IT, the goal of these cross-industry working groups is to identify potential cross-company benefits and RFID value added in maintenance. In the future, this will make it possible to devise completely new maintenance processes in companies as well as with component suppliers and maintenance service providers.

2.9.1 Introduction

Radio technologies are widely used in society not only to communicate but also to identify, localize and track all and any objects. RFID (radio frequency identification) systems are a further development of static identification technologies ranging from linear or matrix barcode and direct part marking (DPM) to dynamic data management.

Many companies use information and communication technologies in maintenance. The spectrum ranges from simple Microsoft Office products to stand-alone applications for maintenance (e.g. computerized maintenance planning and control systems or CMMS) through maintenance modules integrated in enterprise resource planning (ERP) systems such as SAP Plant Maintenance (SAP PM). Many maintenance units view the inability of many company IT systems exchange data with one another as problematic. Thus, many diagnostic systems for monitoring complex equipment still do not provide standard interfaces to maintenance systems (CMMS). In large, complex plants with, for instance, many identical maintenance assets in the plant structure or many measuring and diagnostic points, the identification of assets causes problems. Under certain circumstances, maintenance activities are performed on the "wrong" component. Furthermore, important information that can only be retrieved on a (physically remote) CMMS terminal may be lacking when equipment malfunctions.

2.9.2 Drivers behind the Adoption of RF Systems in Maintenance

Two key aspects can be identified as factors driving the adoption of RFID in maintenance:

- Drivers from the perspective of maintenance (e.g. intransparency of maintenance processes, costs of maintenance); and
- Technical innovations in information technology (e.g. mobile terminals, tablet computers, wireless communication, component miniaturization, embedded systems with sensors).

Drivers from the Perspective of Maintenance

A look at pilot projects in Germany reveals some key drivers behind maintenance organizations' adoption of distributed information carriers such as RFID (frequently in conjunction with mobile work order management):

- insufficient capabilities to identify assets or measuring and diagnostic points in a plant;
- paper-based order processing with long feedback times and errors because data is transferred into CMMS manually;
- problems rapidly determining an asset's current configuration or order numbers for replacement parts in the case of a breakdown;
- insufficient automated IT support for cross-company processes (e.g. automated transfer of technical data and configuration into an operator's CMMS when an asset is delivered and commissioned);
- security requirements such as legally unassailable documentation;
- etc.

Technical Innovations in Information Technology

The trend toward miniaturizing equipment as costs keep falling is opening a new market for autonomous logistics assets outfitted with sensor systems and communication modules to optimize company processes. At present, the coupling of RFID systems for object identification with telematic modules is producing new products also called "smart objects" or "smart devices".

The following developments are advancing the creation of smart devices (cf. Hansmann 2001):

- mobile terminals for various target groups and situations;
- integrated peripherals/modules for identification (barcode, RFID), position finding (GPS, indoor WLAN) and communication (WLAN, GSM, UMTS) in terminals; and
- devices optimized for mobility (integrated circuits, air interfaces for communication, energy / power management, component miniaturization).

The use of distributed information carriers and mobile terminals is rationalizing maintenance work in companies. Leaps in technical performance in technologies, mobility and online communication are enhancing quality in organizing maintenance.

2.9.3 Basic Principles of RF Systems

In contrast to barcode's optical code recognition, RFID operates with radio waves that do not require any direct visual contact and enable detecting coding in spherical space zones. Hence, an RFID tag – even when the tag is arbitrarily aligned – is easier to detect and read than a barcode label.

Moreover, RFID permits mechanical covering without reducing read quality. As a pure radio solution, RFID is resistant to contamination and mechanical stresses. What is more, RFID can keep variable data on an asset up-to-date since the content of the data is not only readable but also writeable and upgradeable within the memory limits when being processed.

RFID is frequently employed as a generic term for the complete technical infrastructure. A radio frequency (RF) or radio frequency identification (RFID) system includes:

- a transponder (a word combining transmit and respond; also called an RFID tag or label);
- a transceiver unit (a read-write device with integrated antenna); and
- integration with servers and service and enterprise resource planning systems (middleware).

A transponder has a chip (integrated circuit to store data) that is connected with an antenna. The chip either extracts its operating power from the radio frequency signal emitted by the reader (passive transponder) or a self-contained power source in the form of a battery (active transponder).

Other distinctive features of RFID technology are:

- the transponder's memory capacity (128 bits to 2,000 bytes);
- the transponder's design (as a paper label, cast in glass or synthetic resin, as a screw, etc.);
- the transponder's rewriteability (RO read only, WORM write once read many, RW read write);
- the transponder's form of mounting (bonded or bolted on a surface, glued in a borehole, affixed to an object, concealed attachment, etc.); and

- the frequency range that determines the read-write range and is tuned (i.e. its radio signal) to the transponder and reader.

Systems based on 125-135 kHz, 13.56 MHz (worldwide), 868 MHz (Europe) and 2.45 GHz are particularly interesting for maintenance.

Table 2.8 summarizes the characteristics of RF systems.

Table 2.8 Characteristics of RF systems

Frequency Range	Wave-length	Operating Mode	Key Functions for Logistics Applications
< 135 kHz	low frequency (LF)	passive	Identification, communication (0 - 0.5 m)
13.56 MHz	high frequency (HF)	passive	Identification, communication (0 - 0.6 m)
433 MHz	ultra high frequency (UHF)	passive	Identification, communication (6 - 8 m)
868 MHz	ultra high frequency (UHF)	passive, active	Identification, communication (2 - 4 m)
2.45 GHz	Microwave (MW)	active	Identification, localization, communication (50 - 200 m)
5.8 GHz	Microwave (MW)	active	Identification, localization, communication (50 - 200 m)

Databases can be used to visualize identification, position and status data and integrate it in company IT systems.

2.9.4 Variants of RFID Use in Maintenance

A wide variety of demands is made on technical concepts for transponder use in maintenance. These stem from:

- the operating conditions to which manufacturing equipment can be subjected (e.g. dirt, dust, extreme temperatures, aggressive media, metallic environments);
- the logistical conditions (e.g. a large mix of subcontracted suppliers; the construction site character of larger maintenance measures);
- the types of assets (mobile maintenance assets or stationary components; complex or standardized parts, etc.); and

- the company operations and information flows being supported.

RF technologies provide the following functionalities upon which application scenarios can be based:

- identification of maintenance assets or components;
- storage of static or dynamic information on the maintenance assets;
- localization of mobile assets; and
- determination of the condition of maintenance assets over time and throughout processes.

Table 2.9 outlines RFID functionalities, associated technologies and their application in maintenance.

Table 2.9 Variants of RFID use in maintenance

Description	Technology	Example in Maintenance	Central System/ Database
a) Pure identification			
An asset has only one distinct identification number	1-D barcode or RO/ WORM transponder (passive)	Identification of a measuring or diagnostic point, of a spare part	Central system contains all relevant data on an asset
b) Storage of static information on asset			
An asset has one distinct identification (e.g. machine type and serial number) and other static data	2-D barcode or WORM/ RW transponder (passive)	Electronic nameplate of motors, identification of a spare part	Central system contains all relevant data on an asset
c) Storage of dynamic information on asset			
Like b) but any other data can be stored or edited	RW transponder (passive)	Asset transponder containing all master and current motion data on an asset; Synchronization of data over mobile terminals; mobile order management	Data is in part redundant on the transponder and in the central system
d) Localization			

Tracking of mobile assets (people, equipment, tools, etc.) through room and time	WORM/ RW transponder (passive) and gates or active transponder (MW)	Localization of ground conveyors, containers and people on the plant premises	Internal middleware and interfaces to central system
e) Condition monitoring			
Monitoring of assets' motion and condition (temperature, shock pulse, vibration, humidity, etc.)	RW transponder (passive) with sensors; active transponder (MW) with sensors	Operating conditions on assets without internal monitoring control; determination of data for condition-based monitoring	Internal middleware and interfaces to central system

2.9.5 Example: Mobile Work Order Management with RFID

In mobile order management, a central system (e.g. CMMS) electronically transmits maintenance job orders to mobile terminals. The mobile terminals temporarily store the orders and retransmit them to the central system after execution. The data transmitted by the CMMS can be confirmed, modified or supplemented.

Order management can involve using RFID to identify maintenance assets. The automatic identification of maintenance assets or spare components helps internal and external employees when they are executing orders. RFID identification can ensure that the "right" activity has been performed on the "right" asset. This reduces time consuming asset searches and identification and eliminates installation errors.

The advantages of mobile order management in conjunction with RFID are:

- maintenance assets are distinctly identified (and potentially even linked with individual work steps on a mobile terminal);
- maintenance staff productivity is boosted;
- the information flow is expedited;
- feedback on orders is near real-time and paperless; and
- manual notes are virtually eliminated.

Furthermore, disassembly, industrial safety or maintenance instructions can be transmitted together with electronic orders. This reduces time researching information. Figure 2.11 illustrates the principle.

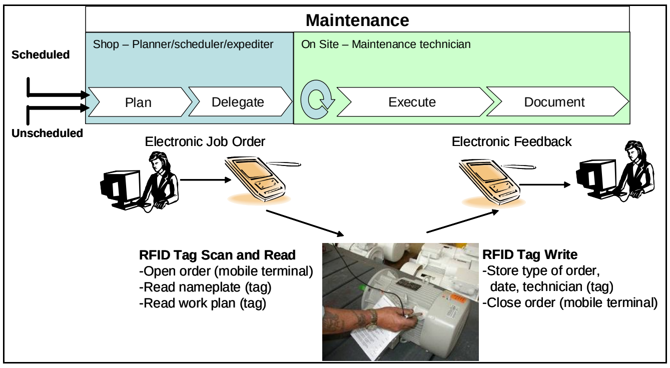

Figure 2.11 Mobile order management with RFID

Linking RFID technology and mobile terminals is also supported by the current commercial market. Ever more handheld and PDA manufacturers are offering RFID readers in various frequency ranges for their products. Mobil telephone manufacturers are also beginning to integrate RFID components (e.g. Nokia Field Force Solution).

Concepts for sales order processing supported with mobile terminals are already well known from the after sales service business where service technicians receive GSM/GPRS order data from expeditors and likewise wirelessly reply with replacement part orders and feedback on orders.

2.9.6 RFID Pilot Project in Maintenance in Germany

The first pilot projects in Germany to utilize passive transponders in maintenance were already underway in the mid 1990s. One of the first to adopt such an approach and technology, AIRBUS Hamburg started its first project to track aircraft tools in 1999. The objective of the project was to globally track tools for aircraft maintenance, which AIRBUS lends to airlines and must be recalibrated after every use.

AIRBUS continued this project in 2003 with another project to identify spare parts with the stated objective (Airbus 2003) "to simplify component repair management, where the repair and flight history of the component will be available electronically. The passive transponder assures the availability and accuracy of vital information and documentation and also allows a comprehensive tracking system. The airlines will further benefit by time saved on trouble shooting, parts inspection, repairs administration and on the whole logistics cycle."

Another outstanding RFID project in maintenance involves mounting transponders on maintenance assets at Frankfurt Airport. Aware that the quality of its facility management processes is crucial to guaranteeing smooth operations, maximum security and convenience for travelers, the airport's operating company FRAPORT AG decided to test the benefits of RFID in this area and initiated a pilot project in 2003 (Legner and Thiesse 2006). The facility managers are particularly interested in applying RFID to such tasks as easy identification, distributed data storage, fraud prevention, structured documentation and paperless information management by using mobile applications for maintenance processes. In the past, the inspection of 22,000 fire shutters generated 88,000 pages of paper documentation that had to be archived for several years. A mobile solution using RFID has eliminated this work completely. FRAPORT AG is now extending this solution to other applications such as fire doors, smoke detectors and conveyor flaps.

Small and medium-sized enterprises are increasingly discovering the advantages of RFID for themselves. Enterprises from virtually every industry are represented here, including:

- an electric motor manufacturer in 2004: This company is using transponders in its manufacturing for milestone controlling and in after sales service for maintenance history. (Müller 2005);
- a paper manufacturer in 2006: This company is using RFID technology in conjunction with mobile terminals for paperless order management and real-time order feedback (Rauch 2006);
- an aluminum rolling mill in 2006: This company is also using mobile terminals and RFID technology to track reparable components that are installed in different places during their service life (Pampel 2006);
- other RFID pilot projects in maintenance in Germany currently come from the automotive industry and their suppliers of robots (Ehleiter 2007), the energy industry and hospital management.

Another group dealing with RFID consists of providers of measuring, diagnostic and lubricating systems and manufacturers of tools and spare parts.

2.9.7 Benefits of RFID in Maintenance

The chief advantages of using RFID in maintenance processes are the precise identification of maintenance assets when required maintenance work is being done, the storage of data relevant for maintenance (e.g. servicing and inspection data) directly on a particular object, the elimination of previously necessary paper documents (cf. FRAPORT AG) and the acceleration of information flows (Richter and Plate 2006).

The following examples provide an overview of the benefits attainable by using RFID in maintenance:

1. Increased maintenance staff productivity (efficiency increase)

- reduction of unproductive and administrative times (travel times, information search times, reporting, etc.);

- qualification of the execution of maintenance activities by means of identification technology (the “right” activity in the “right” place); and
- current information on an asset directly on site (current configuration, order numbers for replacement parts, etc.).

2 Reduced manual (multiple/repeated) data acquisition activities and the associated error sources, e.g. when

- receiving, issuing, installing and returning spare parts; and
- identifying maintenance assets and measuring and diagnostic points.

3 Reduced error sources in processes, e.g. mix-ups of similarly designed assets.

4 Elimination of paper documents (material orders, transportation orders, maintenance job orders, etc.), printing costs and format changes.

5 Option of integrating third parties, e.g. refurbishing shops, equipment vendors or external maintenance and data exchange with these third parties.

The monetary benefits were determined in the pilot projects by means of cost-benefit analyses, however turn out differently in each case depending on the maintenance process and the company analyzed. Benefit analyses described each of the nonmonetarily evaluable aspects of utility.

2.9.8 Current Development

RF technologies are on the threshold of entering the mass market. Various sectors such as commerce and parcel service are making great efforts to create a stable, standardized environment for the introduction of RFID technology in the overall value added chain. To this end, users are forming strategic partnerships in order to establish a close relationship between the developers and users of hardware and software. Both sectors are endeavoring to standardize both RFID based applications and technologies and products to make it easier for companies to start using the new technology and to clearly communicate its advantages.

Current activities in these fields are having and will have an impact on other sectors such as mechanical and plant engineering or the maintenance industry (Müller *et al.*, 2007).

For example, in industrial plant construction the physical processes on a construction site are fields of application that, both from the perspective of logistics and construction, provide great potential for improving productivity by using RFID (Richter *et al*., 2006) (Figure 2.12).

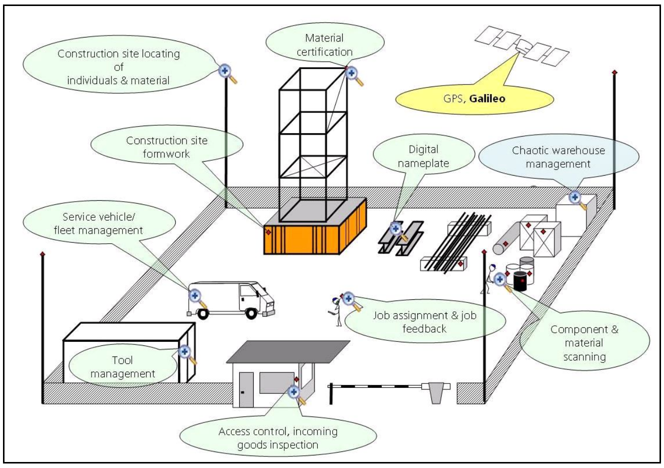

Figure 2.12 Application of RF based methods in construction site logistics (Schenk *et al*. 2006)

So far, pilot projects have characteristically been undertaken by individual plant operators independently planning and carrying out the implementation of RFID with the goal of improving the effectiveness and efficiency of their maintenance processes. On the other hand, certain machinery manufacturers have also already integrated transponders in their products and sell these to customers. Since there is no mandatory technical or IT standards at present for cross-company use of RFID technology in maintenance, interest groups need to be formed around this issue. Such associations of RFID manufacturers, RFID users and services providers are already established in the consumer good's distribution industry (e.g. METRO FUTURE STORE, EPC Global). The continued use of tags already installed by suppliers (Müller 2005) for various processes (e.g. warehouse management, assembly and disassembly, maintenance, shutdown) is giving the plant construction and maintenance sector as well as manufacturers a competitive edge too.

The multitude of different logistics and maintenance processes in an industrial asset's life cycle involving different companies makes it difficult to apply a standardized approach to integrate RF technologies today. A classification based on the field of application and the asset being analyzed can provide a foundation for making RF based processes standardizable and certifiable in the future (Figure 2.13).

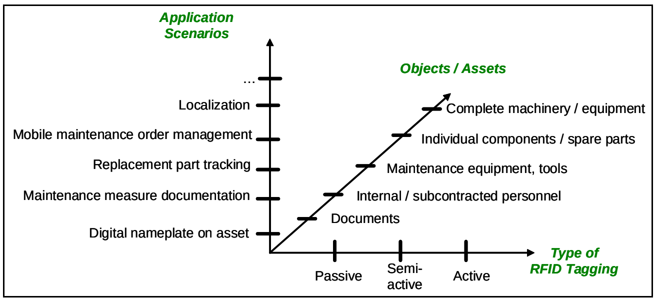

Figure 2.13 Classification of RF based scenarios

Cross-company working groups are forming around life cycle-based process analyses to work on the standardization and certification of RFID systems for the processes of asset manufacturing, construction, installation and commissioning and maintenance. Both manufactures of complex components and equipment and later users such as plant operators, subcontracted maintenance firms or transportation service providers have recognized the benefits of RFID.

The following partners are national pioneers in RFID in the maintenance industry:

- the Association of German Engineers (VDI), Expert Committee for Maintenance;
- the Forum Vision Instandhaltung e.V. (FVI) – Forum Vision Maintenance;
- the Fraunhofer-Institute for Factory Operation and Automation (IFF) as one partner for applied research;

Among other things, their collective efforts are aimed at:

- establishing guidelines for the placement of transponders on (initially) selected maintenance components, e.g. engines, transmissions;
- specifying reference processes in maintenance that RFID can support;
- in conjunction with the reference processes, formulating recommendations on the selection of RFID technology as well as useable, commercially available products (RFID transponders, readers, mobile terminals);
- defining the respective data models and interfaces to CMMS for the reference processes;
- addressing other issues such as data security and integrity and process reliability with RFID.

Future developments will go beyond single company applications to standardized cross-company applications. The results of this collaborative work are continuously being published. This is intended to raise awareness in the whole industry of potentials for improvement with RFID and to disseminate the requisite technological know-how.

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2.10 Structural Reliability Assessment in Maintenance Management Systems

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Abstract. The paper deals with a procedure for the evaluation of reinforced concrete deteriorating bridge reliability, to be incorporated in the safety level determination module of a Bridge Management System (BMS). The reliability index is evaluated both at single component level and at system level thanks to a FORM like procedure that utilizes design data as input parameters. The input parameters are treated as random variable that may be modeled by different distributions. The proposed procedure, implemented in the code EVAS, permits to conduct time-variant reliability analyses for both single component and series/parallel systems. Two deterioration models, due to reinforcement corrosion, have been implemented in the code. The deck of Belvedere bridge at L'Aquila is analyzed to illustrate the method. The reliability index profiles for the bridge are evaluated considering the beams, constituting the main deck, both as a series system or parallel system. The reliability profiles obtained using the two different deterioration models are compared and discussed.

2.10.1 Introduction

During the last years, the development of Bridge Management Systems (BMSs) has become a matter of great importance for the agencies and authorities in charge of the road and railway infrastructure management (Godart and Vassie, 1999). Usually, BMSs are realized according to a modular structure, which includes a computerized database and a module for the determination of the security level. In addition, they include a series of modules delegated to the processes of optimization of the resources for maintenance/repairing interventions, both at the level of a singular bridge as well as of the entire network.

Furthermore, very recent studies concerning the new design of BMSs are looking to base these systems on lifetime reliability and whole-life costing. A reliability-based system permits the use of reliability index that is theoretically well-founded indicator of safety and serviceability. Combining reliability of different failure modes with deterioration model, a reliability profile for the observed bridge can be obtained.

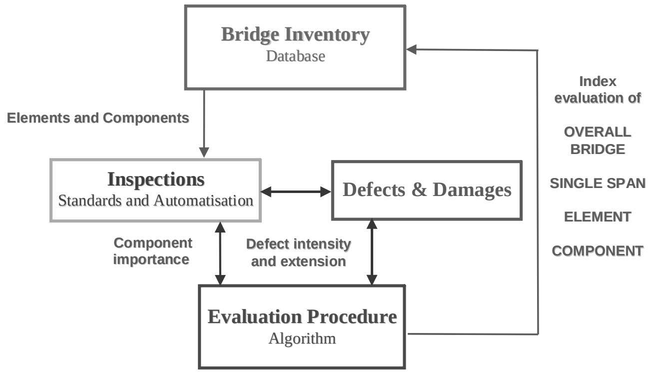

Figure 2.14 Sketch diagram of DOMUS BMS modules

Based on a prescribed target reliability level, the probability distribution of the expected time of intervention (i.e. maintenance, repair) can be evaluated (de Brito *et al.*, 1997; Kong and Frangopol, 2002; Frangopol and Maute, 2003).

The aim of the present paper is to illustrate the features of a new numerical integrated code which implement a classical procedure to determine time-variant structural reliability. The developed numerical procedure may be used to provide time-dependent safety indicators to a BMS which can be integrated with visual inspection based bridge condition evaluations (see Figure 2.14 and Gattulli and Chiaramonte, 2005) or in structural health monitoring systems (Täljsten and Hejll, 2003).

In particular time-dependent reliability analysis requires a number of assumptions about loading, resistance and deterioration models. Therefore, these model should be updated over time to predict the actual behavior of structures. On this respect the best sources of data to update the models may come from nondestructive evaluations (NDE) such for example modal testing. However NDE are often very expensive and cannot be carried out for a large number of structures belonging to a same owner. Although visual inspections are regularly conducted and the data recorded and readily available, these results are generally not used for reliability-profile updating (Estes and Frangopol, 2003).

The present research is devoted, firstly in developing a time-dependent reliability procedure for bridge-type structures and then in integrating such procedure through updating of the reliability profiles with data coming from visual inspections. The research objectives are the development of an integrated methodology for reliable decision making in inspection time intervals (see Figure 2.15) and maintenance optimal strategies.

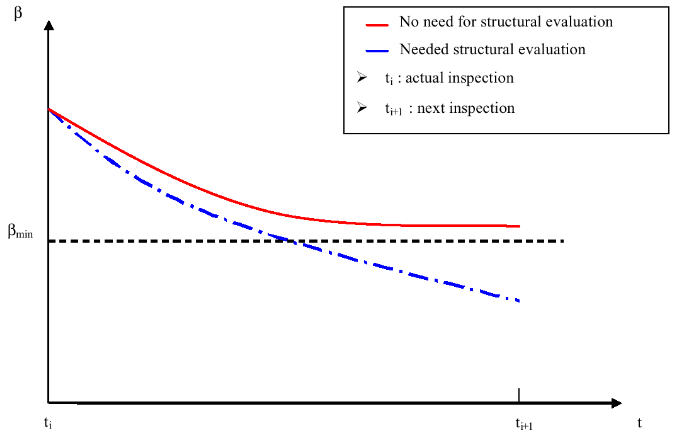

Figure 2.15 Use of reliability profile in decision-making

The procedure, here, considered permits to calculate the evolution in time of a selected indicator of the structural reliability (reliability index) (Ditlevsen 1996, Melchers 1999), considering the processes of deterioration typical of structural elements made in reinforced and pre-stressed reinforced concrete.

In particular different patterns, already presented in literature, have been considered in order to face the study of deterioration with a special reference to the problem of reinforcement corrosion (Stewart 2000, Val 1998, Frangopol 1998).

Furthermore, the presented study has been conducted, with the aim of implementing in a single integrated code the numeric evaluation of structural reliability at the component and system level together with its evolution in time in order to have a tested procedure usable in BMS-systems under development (Godart and Vassie, 1999).

The research has conducted to the development of a code denominated EVAS (EVoluzione dell'Affidabilità Strutturale). With the code EVAS it is possible to determine time-variant structural reliability for both singular components and series/parallel systems. The number of components in series are unlimited while a limited number of components (N=30) could be considered for parallel systems. The time-variation of structural reliability is determined thanks to two deterioration models which simulate the corrosion in steel bars of reinforced concrete components.

The code EVAS implements a FORM like procedure and it has been subjected to a series of tests with the reference to known results present in literature of resolved problems with FORM or SORM methodologies or through Monte Carlo simulations. Results achieved with EVAS are well in accordance with those samples, both relatively to singular limit state functions (linear or not), as well as for complex systems.

The program has then been utilized to determine the evolution of the reliability index associated to the pre-stressed reinforced concrete bridge Belvedere in L'Aquila. In particular, both reliability index and failure probability have been considered, with the reference to limit state for moment, shear and in combination of both. Finally, the bridge reliability has been evaluated considering the single beam behaves at the system level both as a system of series or parallel elements. The reliability time-evolutions of the series/parallel systems have been compared in order to furnish an insight on the structural behavior of the entire system.

2.10.2 Reliability of Reinforced Concrete Bridges in EVAS

The EVAS program allows the evaluation of the reliability index, β, and of the failure probability, P_f, of structural systems. The implemented algorithm permits also the description of initial values of β and P_f, and their evolution in time. Evolution is caused by deterioration process affecting the materials constituting structural system.

Reliability of a single component

The reliability of a single component, single limit state function, is evaluated in EVAS using a FORM like algorithm (Melchers 1999). The main steps of the procedure are described in the following:

1. selection of a starting point $\mathbf{x}^i$;
2. use of the Nataf transformation to get the normal standard r.v. $\mathbf{u}^i$:

$$f_X(\mathbf{x}) = \phi_n(\mathbf{y}, \mathbf{R})|\mathbf{J}| \tag{2.29}$$

where **J** is the Jacobian of the transformation that can be expressed as:

$$\mathbf{J} = \mathbf{L}_0^{-1} \cdot \left\langle \frac{f_X(x_i)}{\phi(u_i)} \right\rangle \tag{2.30}$$

and $\mathbf{L}_0$ is the lower triangular decomposition of **R**.

3. compute the gradient of the limit state function in the standard normal space:

$$\nabla_{\mathbf{u}} g(\mathbf{u}) = \mathbf{J}^{-1} \nabla_{\mathbf{x}} G(\mathbf{x}) \tag{2.31}$$

4. compute the directions ($\cos\alpha$):

$$\boldsymbol{\alpha}^i = \frac{-\nabla_{\mathbf{u}} g(\mathbf{u}^i)}{\|\nabla_{\mathbf{u}} g(\mathbf{u}^i)\|} \tag{2.32}$$

5. evaluate $\beta = -(\mathbf{u}^i)^T \alpha^i$ at the i^{th} step;
6. use of the HL-RF algorithm to estimate the next approximation point:

$$\mathbf{u}^{i+1} = \frac{\nabla_{\mathbf{u}} g(\mathbf{u}^i)^T \cdot \mathbf{u}^i - g(\mathbf{u}^i)}{\|\nabla_{\mathbf{u}} g(\mathbf{u}^i)\|} \frac{\nabla_{\mathbf{u}} g(\mathbf{u}^i}{\|\nabla_{\mathbf{u}} g(\mathbf{u}^i} \tag{2.33}$$

7. determine the new $\mathbf{x}^{i+1}$ coordinates using the inverse Nataf transform;
8. iterate the procedure until the actual value of the reliability index minus the value evaluated at the previous step is less than a fixed tolerance (e.g. t=0.001).

System Reliability

System-reliability analysis concerns the formulation of the limit state and calculation of the failure probability when the structure has more ways of failing. Systems can be modeled as series, parallel or general ones.

A series system is one which fails if anyone or more of its components fail. If F_i denotes the i^{th} failure event, then the combined system failure probability can be written as:

$$P(F_S) = P\left(\bigcup_i F_i\right) \tag{2.34}$$

A parallel system is one which fails only if all of its components fail. The combined system failure probability can then be written:

$$P(F_P) = P\left(\bigcap_i F_i\right) \tag{2.35}$$

A general system consists of a combination of series and parallel subsystems.

In EVAS it is possible to evaluate the reliability either considering the system as a series one or considering it as a parallel one.

Series System

Once β and P_f have been calculated for every limit state function, it is possible, using EVAS, to evaluate a system reliability index and a system failure probability considering these limit states function as a series system.

The used approach to get the system indicator values makes use of Ditlevsen's limit for a series system. The subroutine called LB evaluates a lower β limit, while the subroutine called UB evaluates an upper limit for it.

The subroutine LB implements the following formula (Ditlevsen 1996):

$$P(F_S) \geq P(F_1) + \sum_{i=2}^{k} \max\left\{\left[P(F_i) - \sum_{j=1}^{i-1} P(F_i \cap \right.\right. \tag{2.36}$$

The subroutine UB implements the following formula (Ditlevsen 1996):

$$P(F_S) \leq \sum_{i=1}^{k} P(F_i) - \sum_{i=2}^{k} \max_{j<i} P(F_i \cap F_j) \tag{2.37}$$

$$\text{where } P_{fij} = P(F_i \cap F_j) = \Phi_2(-\beta_i, -\beta_j, \rho_{ij}). \tag{2.38}$$

$\Phi_2(-\beta_i, -\beta_j, \rho_{ij})$ is the distribution function of the two-dimensional normal distribution with mean values (0,0), variances (1,1); (β_i, β_j) represent the reliability indexes of the i^{th} and j^{th} events, while ρ_{ij} is their correlation coefficient. The evaluation of the term $\Phi_2(-\beta_i, -\beta_j, \rho_{ij})$ can be simplified considering the following relations:

$$\Phi_2(-\beta_i, -\beta_j, \rho_{ij}) \begin{cases} \geq \max\{\Phi(-\beta_i)\Phi(-\beta_{j|i}), \Phi(-\beta_j)\Phi(- \\ \leq \Phi(-\beta_i)\Phi(-\beta_{j|i}) + \Phi(-\beta_j)\Phi(-\beta \end{cases} \tag{2.39}$$

if $\rho_{ij} > 0$, while

$$\Phi_2(-\beta_i, -\beta_j, \rho_{ij}) \leq \min\{\Phi(-\beta_i)\Phi(-\beta_{j|i}), \Phi(-\beta_j)\Phi(\tag{2.40}$$

if $\rho_{ij} < 0$.

The conditional reliability index $\beta_{i|j}$ can be so evaluated:

$$\beta_{i|j} = \frac{\beta_i - \rho_{ij}}{\sqrt{1-\rho^2_{ij}}} \tag{2.41}$$

Parallel System

With EVAS it is possible to evaluate reliability index profiles considering the system of limit state functions as a parallel one. Failure probability has been defined in terms of a multinormal integral that in turn has been effectively approximated by a product of one dimensional normal integrals (Pandey 1998) :

$$P_{fp} = P\left[\bigcap_{k=1}^{m} X_k \leq -\beta_k\right] = \Phi_m\left(-\boldsymbol{\beta}, \mathbf{R}\right) \tag{2.42}$$

where β_k is the reliability index of the k^{th} limit state function, **R** is the correlation matrix and P_{fp} the failure probability of the system composed of *m* limit state functions.

The right hand side of equation (2.42) can be approximated as:

$$\Phi_m(\mathbf{c}, \mathbf{R}) \cong \prod_{k=1}^{m} \Phi\left(c_{k|k-1}\right) \tag{2.43}$$

where $\mathbf{c} = -\beta$.

The general expression for evaluating $c_{k|k-1}$, used in the implemented procedure, can be written as:

$$c_{m|k} = \frac{c_{m|(k-1)} + r_{mk|(k-1)} A_{k|(k-1)}}{\sqrt{1 - r^2_{mk|(k-1)} B_{k|(k-1)}}} \tag{2.44}$$

where $A_{i|q} = \phi(c_{i|q}) / \Phi(c_{i|q})$, $B_{i|q} = A_{i|q}\left(c_{i|q} + A_{i|q}\right)$ and the conditional correlation has been expressed as:

$$r_{mk|(k-1)} = \frac{r_{mk|(k-2)} - r_{k(k-1)|(k-2)} r_{m(k-1)|(k-2)} B}{\sqrt{1 - r^2_{k(k-1)|(k-2)} B_{(k-1)|(k-2)}} \sqrt{1 - r^2_{m(k-1)|}}} \tag{2.45}$$

2.10.3 Time Variant Reliability

The corrosion of steel has been identified as one of the main causes of bridge structure deterioration process (BRIME D5 1999). The corrosion process causes a cross section reduction of structural steel elements. Moreover, there is a lost in the cross sectional area in those bars and wires that are used in reinforced and pre-stressed reinforced concrete bridge members.

In particular, the corrosion of bars and wires which are embedded in concrete elements, rather than in structural steel elements, is not an easy process to detect and measure. In EVAS the problem of bridge structural deterioration has been analyzed focusing on the corrosion due to chloride penetration and two different models have been introduced.

Deterioration model for steel bars

A quantitative description of corrosion propagation is usually given in terms of the so called “corrosion rate”, which is defined as the steel area reduction per unit of surface and per unit of time (Stewart 2000).

The model implemented in EVAS for evaluating the bars cross section reduction in time is the one developed by Val *et al.* 1998. In this model, named DV (Diameter Variation), the chloride contamination is considered as the main cause of corrosion and corrosion is considered to be uniform.

In this model, applying Faraday’s law, we get a uniform corrosion penetration of $11.6\mu m / yr$ corresponding to a corrosion current density $i_{CORR} = \mu A / cm^2$. We can then estimate the cross sectional bars diameter reduction at time t:

$$\Delta D(t) = 0.0232 \int_{t_i}^{t} i_{corr}(t) dt \tag{2.46}$$

where t_i =corrosion initiation time expressed in years. Assuming a constant annual corrosion rate, equation (2.46) can be written:

$$\Delta D(t) = 0.0232(t - t_i)i_{corr} \tag{2.47}$$

The net cross sectional area of steel bar at time t can be written:

$$As(t) = \begin{cases} \dfrac{\pi D_0^2}{4} & t \le t_i \\ \dfrac{\pi [D_0 - \Delta D(t)]^2}{4} & t > t_i \end{cases} \tag{2.48}$$

where D_0 =initial diameter of reinforcing bar (mm).

The value of the corrosion rate, i_{CORR}, can be found in literature depending on the environment condition and on the exposure class of the structure.

Figure 2.16 Gerber-type system of Belvedere bridge in L'Aquila.

Resistance Deterioration Function

The structural deterioration can also be modeled in EVAS using a resistance deterioration function (named RD), that is, introducing a time variant decreasing function which reduces the initial resistance in time.

The time variant resistance of an element can be expressed as:

$$R(t) = R_0 g(t) \tag{2.49}$$

where $R(t)$ = resistance as a function of time; R_0 = initial resistance; $g(t)$ = resistance deterioration function.

The deterioration function can be expressed as (Frangopol 1998):

$$g(t) = \begin{cases} 1 & 0 \le t \le T_i \\ \left[1 - k(t - T_i)^{\alpha_1}\right]^{\alpha_2} & t \ge T_i \end{cases} \tag{2.50}$$

where T_i =corrosion initiation time; k, α_1 and α_2 =random variables that depend on the corrosion mechanism, on the material properties and on the environment condition.

Considering the cases where $g(t)$ is linear or quadratic in t:

$$g(t) = 1 - k_1(t - T_i) \tag{2.51}$$

$$g(t) = 1 - k_1(t - T_i) + k_2(t - T_i)^2 \tag{2.52}$$

Inside EVAS there are two different resistance deterioration functions: CORRM(t) and CORRV(t); the first describes the moment resistance degradation and is expressed as (Frangopol 1999):

$$CORRM(t) = 1 - 0.005(t - T_i) \tag{2.53}$$

while the latter describes the shear resistance degradation (Frangopol 1999):

$$CORRV(t) = 1 - 0.0075(t - T_i) \tag{2.54}$$

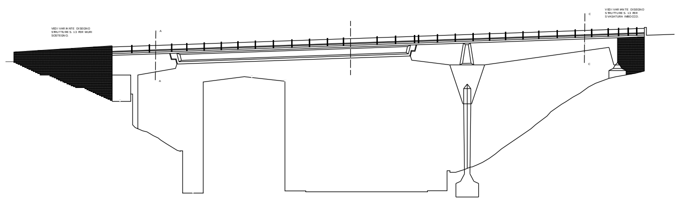

Figure 2.17 Section view of the bridge

2.10.4 The Belvedere Bridge

The Belvedere Bridge is a pre-stressed reinforced concrete bridge situated in L'Aquila. The bridge is 80 m long and has a maximum height of about 20 m (Figures 2.16 and 2.17). The structural system is composed by two approaching frames on which lays a main deck supported by a Gerber-type system. The central deck consists of 6 transverse elements and of four longitudinal I-beams; each of these beams has a constant cross section and the length of 34 m. The external beams have 17 wires $12\Phi7$, while the internal beams have 14 wires $12\Phi7$ (Figures 2.18 and 2.19).

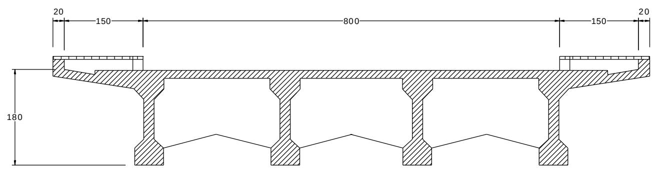

Figure 2.18 Belvedere bridge cross section of the central span.

The load model utilized in the study is the DM90 prescribed by the Italian bridge code. Dead loads include structure's and super-structure's self weight, while live loads include a) two columns of a conventional three axels truck (600 KN), b) a uniform load (30 KN/m) disposed along the middle lane line and c) a uniform load (4 KN/mq) due to crowd (Figure 2.20).

For taking into account dynamic effects, live loads have been amplified. Moreover, loads have been reduced in order to consider the fact that the bridge is a second category bridge, according to Italian classification.

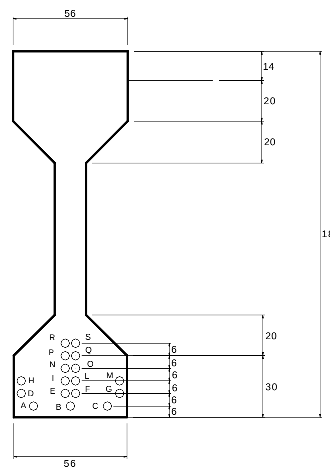

Figure 2.19 Girder cross section (cm)

All load effects have been computed by means of a finite elements model of the bridge's central span. This model consists of frame elements representing longitudinal beams and transverse members, and of shell elements representing the slab.

In the evaluation of the load effect (both for moment, at middle span, and for shear; near supports) loads have been combined for getting the worse situation possible. These evaluated load effects and their statistical properties are shown in Tables 2.9 and 2.10.

Table 2.10 Initial moment load effect

	Beam	Moment	B.F.	COV	Distribution	Mean
	#	[KNm]				[KNm]
DL	1	3880.8	1.05	0.10	Normal	3696.0
	2	3896.3	1.05	0.10	Normal	3710.8
	3	3896.3	1.05	0.10	Normal	3710.8
	4	3880.8	1.05	0.10	Normal	3696.0
LL	1	2223.1	1.30	0.19	Normal	1710.1
	2	2159.4	1.30	0.19	Normal	1661.1
	3	1949.8	1.30	0.19	Normal	1499.8
	4	1659.8	1.30	0.19	Normal	1276.8

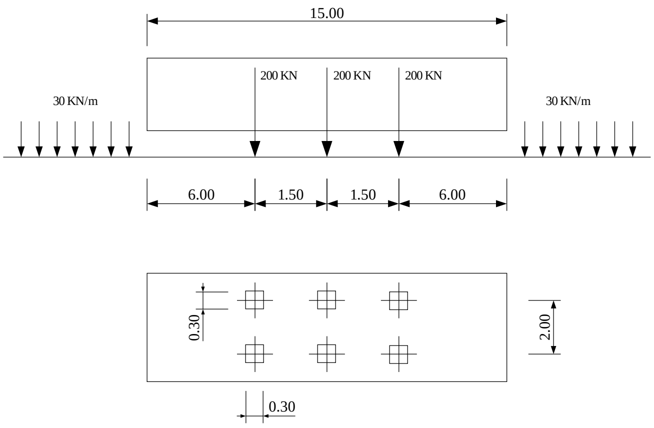

Figure 2.20 Position of truck loads

Table 2.11 Initial shear load effect

	Beam	Moment	B.F.	COV	Distribution	Mean
	#	[KN]				[KN]
DL	1	478.5	1.05	0.10	Normal	455.7
	2	447.8	1.05	0.10	Normal	426.5
	3	447.7	1.05	0.10	Normal	426.4

	4	478.5	1.05	0.10	Normal	455.7
LL	1	156.9	1.25	0.23	Normal	125.5
	2	324.6	1.25	0.23	Normal	259.7
	3	248.6	1.25	0.23	Normal	198.9
	4	129.2	1.25	0.23	Normal	103.4

Both the deterioration models implemented in EVAS have been used in the case study of Belvedere bridge for the determination of the reliability profiles. In the first deterioration model which describes the steel bar diameter variation (DV, Sect. 3.1) the dependence of the moment and shear resistance on the diameter variation have been calculated through the relations furnished in Eurocode 2. In particular, the assumed material properties and their statistical descriptions are shown in table 2.11 while in Tables 2.12 and 2.13 the corresponding evaluated resistances and their statistical properties are summarized.

Table 2.12 Material properties

Variable	COV	Distribution	Mean
			[Mpa]
f_{psy}	0.12	Log-Normal	1860
f_{sy}	0.15	Log-Normal	440
f_c	0.20	Log-Normal	42

Table 2.13 Initial moment resistance

Beam	Moment	B.F.	COV	Distribution	Mean
#	[KNm]				[KNm]
1	12692.1	1.00	0.12	Log-Normal	12692.1
2	11593.7	1.00	0.12	Log-Normal	11593.7
3	11593.7	1.00	0.12	Log-Normal	11593.7
4	12692.1	1.00	0.12	Log-Normal	12692.1

Table 2.14 Initial shear resistance

Beam	Moment	B.F.	COV	Distribution	Mean
#	[KN]				[KN]
1	1298.0	1.00	0.10	Log-Normal	1298.0
2	1298.0	1.00	0.10	Log-Normal	1298.0
3	1298.0	1.00	0.10	Log-Normal	1298.0
4	1298.0	1.00	0.10	Log-Normal	1298.0

The statistical description of the variables have been assumed following well established literature (Frangopol 1999, MacGregor 1983, Nowak 1994).

In the second deterioration model (RD, Sect. 3.2) resistance characteristics have been implemented in EVAS through the deterioration function (Equation 2.50).

The analyses with the DV model has been conducted considering different environmental conditions (different corrosion rates) (Table 2.14). In Table 2.15 the examined cases are summarized.

Table 2.15 Model 1 sub-analysis cases

Case	Degradation rate	I_{CORR}
1	Low	1.0
2	Medium	2.0
3	High	3.0

Table 2.16 Analysis cases summary

Model description	Model name	
Deterioration function	RD	
Cross sectional steel reduction	DV1	I_{CORR}=1.0
	DV2	I_{CORR}=2.0
	DV3	I_{CORR}=3.0

In the following a selected set of results obtained through a series of reliability analyses are summarized. The analyses have been firstly conducted considering the four longitudinal I-beams belonging to the main span of the bridge deck as single components.

In Figure 2.21 the reliability index profiles are shown for the single component for a selected limit states (limit shear - LS). The used degradation model used for each component, is CORRV (see Equation 2.53).

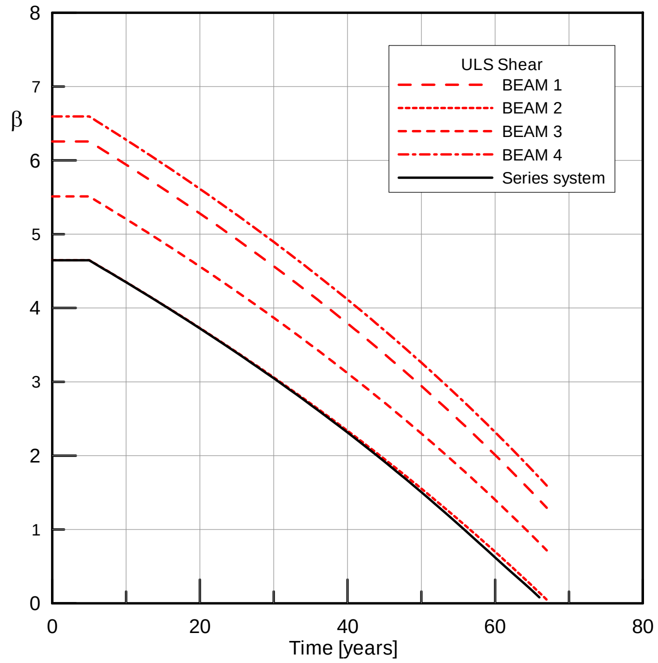

Figure 2.21 Reliability index profiles for the 4 beams and series system –LS Shear

The entire main deck have been evaluated modeling the four beam components as a series system. The obtained results put into evidence how the beams 2 and 3, which are in the middle part of the deck are less reliable. The worst case (beam 2) determines the reliability index profile of the whole system modeled as a series one.

Moreover for the single beam component a campaign of analyses have been also conducted considering the two limit state functions representing the shear at the supports with the state function of the moment at the middle span. These limits state functions have been combined as a series system for each beam evidencing how the shear represent always the worst case.

A campaign of simulations has been devoted to analyze the influence of the deterioration model on the reliability profile. In particular the results obtained considering the deterioration model describing the steel bar diameter variation (DV) are compared with those obtained using the resistance deterioration model (RD).

The DV model is implemented describing as r.v., the resistance characteristics, the materials strength properties and varying the diameter of the steel bars. The RD model is implemented using a deterioration function applied directly to the resistance characteristics, moment and shear.

Besides that the results obtained with the DV model and with models RD model are very similar - as expected – when the deterioration is not yet started (*t*=0) both for moment and for shear.

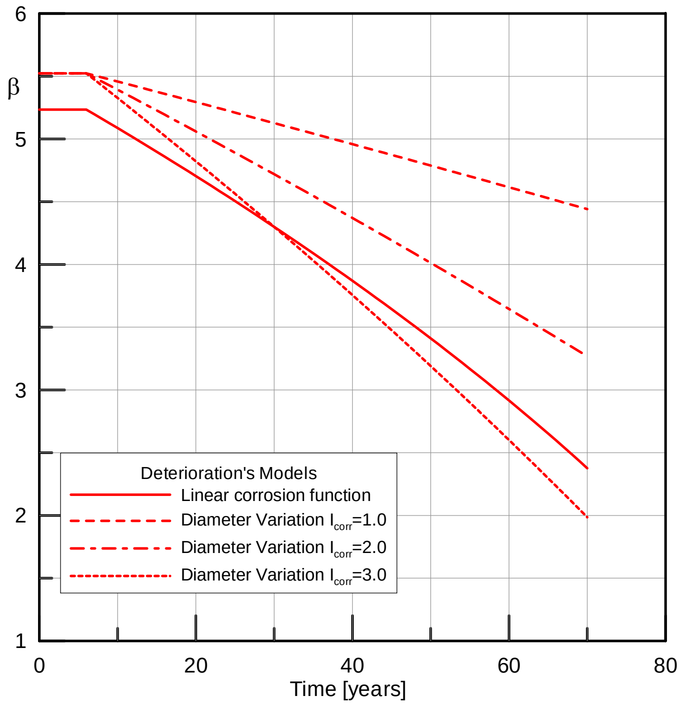

Figure 2.22 Reliability index profiles: LS moment

However, considering a target value for the reliability index β, $\beta_{TARGET} = 3{,}72$, which corresponds to probability of failure $P_{F,TARGET} = 10^{-4}$ it is possible to notice a few differences between the results produced through different deterioration models. In particular, considering the reliability index profile associated to the moment limit state as depicted on Figure 2.21, the worst condition is reached with the RD model and with the DV for which it has been set the parameter I_{corr}=3.0. For both of these models the time necessary to get the target value is almost 40 years. Furthermore, when the moment limit state is combined, as a series system, with the shear limit states, the last one prevails. Thus, the time needed to reach the target reliability value strongly decreases and only almost 20 years are necessary to reach the selected probability of failure (see Figure 2.23).

The above results are in good accordance with the hypothesis about DV model, since increasing the parameter I_{corr} the deterioration rate also increases. The comparison with the RD model shows also that the use of a linear degradation function, less penalizing than a quadratic one, leads to a valid and efficient indicator of reliability variation in time.

Furthermore, it is possible to observe both looking at the reliability profile (Figures 2.22 and 2.23) or at the probability failure profile (Figures 2.24 and 2.25) that the dominant failure mechanism of the Belvedere bridge is related to the shear.

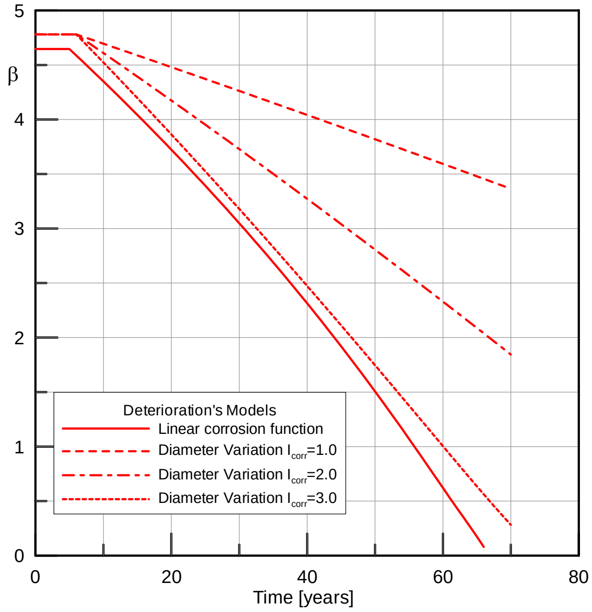

Figure 2.23 Reliability index profiles: LS shear

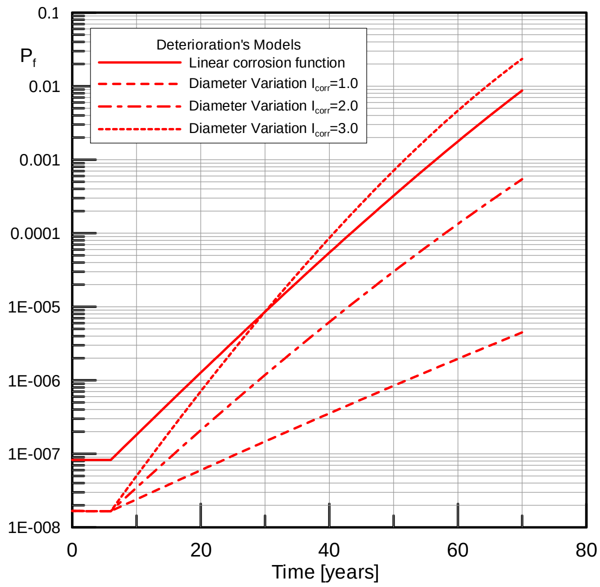

Figure 2.24 Failure probability profiles: LS moment

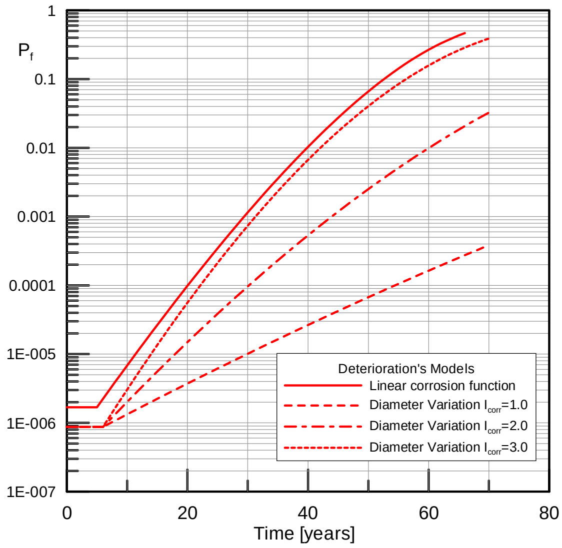

Figure 2.25 Failure probability profiles: LS shear

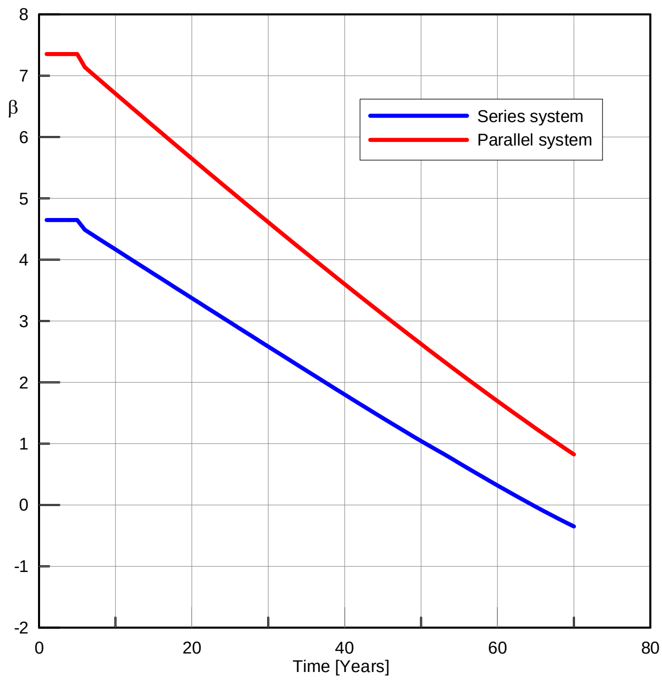

Figure 2.26 Reliability index profiles for the series and parallel systems: LS shear

Finally, the main deck of the Belvedere Bridge has been modeled as a system composed by four parallel components. The obtained results are compared in Fig. 2.26, with the previous ones. Both cases have been elaborated considering the shear limit state and a linear corrosion function (Equation 2.53). The comparison evidences that, in the parallel case, the time necessary to reach the lower limit for a reliable functioning of the bridge (β_{TARGET}) is about 42 years and hence more than the twice time the values obtained considering the deck composed by a series of beam components.

2.10.5 Conclusion

The present paper describes a procedure implemented in the code EVAS for the numerical evaluation of both the reliability index and the structural systems' failure probability for single components as well as series and parallel systems.

The procedure considers also two different deterioration models of reinforcement in RC and pre-stressed RC structural systems.

The main features of the presented research is the implementation in a unique integrated code through a FORM-like algorithm of different deterioration models and different way of analyzing the structural system complexity.

The entire procedure has been tested in the evaluation of the reliability index and its time evolution in the case of the pre-stressed reinforced concrete bridge Belvedere in L'Aquila. The application of the procedure to the studied case has permitted to evaluate the reliability index and the probability of failure, with the reference to moment and shear limit states, and in combination of them. The obtained results are prone to be utilized in a BMS either to compare those indicators with others directly related to visual inspections, or to select the optimal time of intervention for inspections and maintenance.

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3. Modeling and Metrics

Abhijit Deshmukh

3.1 Introduction

Selection of appropriate maintenance actions and strategies for preventive maintenance depends on our ability to accurately predict component deterioration, and its impact on overall system performance. The ability to predict component and system behavior under uncertainty depends on the selection of appropriate modeling methodologies that allow decision-makers to represent the complex system interactions at required fidelity and capture the impact of component deterioration or failure on overall system performance. Another important factor affecting the selection of an appropriate modeling framework is the performance metric or objective function used to monitor the performance of maintenance plans. In most cases, selection of appropriate modeling tools and metrics is key to developing successful predictive maintenance systems.

This section presents a collection of four papers that cover a range of modeling methodologies and metrics used to quantify maintenance management performance. The modeling approaches presented in this section range from analytical to computational, and the performance metrics considered range from myopic or local to long-term and global. The first two papers (Dubi, and Borgia *et al*.) present the use of novel analytical modeling methodologies for maintenance management optimization. The second set of papers (Zille *et al*., and Caputo *et al.*) use state-of-the-art computational modeling frameworks to capture the interactions between components in complex systems and assess the performance of various maintenance strategies and consider performance metrics that are quite different from the standard criteria used to evaluate maintenance management systems. Contributions of each of the papers are highlighted in the following paragraphs.

The first paper (Dubi) presents the use of Monte Carlo methods for solving complex maintenance optimization problems. The author describes the maintenance problem in a logistics and service part delivery setting, where not only the field service operations are modeled but also the logistic envelope that is necessary to support the maintenance operations in the field is modeled. Various objective functions and constraints are considered, ranging from spare part levels, waiting time, to repair resource limits This paper highlights the efficacy of Monte Carlo methods for solving the joint spares and maintenance optimization problem, which would be extremely difficult to solve using traditional methods.

The second paper (Borgia, De Carlo, Peccianti, Tucci) presents the use of Dynamic Object Oriented Bayesian Networks (DOOBN) for modeling reliability of complex systems where the conditional probabilities of success/failure of system components are time dependent. The object oriented formalism allows one to encapsulate sections of the causal network into single nodes, thereby simplifying the complex graph into a series of small ones. Borgia and colleagues demonstrate the capabilities of the DOOBN modeling approach using the case study of a compressed air production system. The case study clearly shows the advantages of modeling time dependent probabilities in estimating the reliability of the compressed air system during summer and winter months.

The third paper (Zille, Berenguer, Grall, Despujols, Lonchampt) uses Stochastic Synchronized Perti Nets (SSPN) coupled with Monte Carlo simulation to develop a computational framework to accurately capture component deterioration, system operation, system dysfunction, and maintenance actions. The component level model and the three system level models are developed and validated independently. They are then coupled by means of interactions in order to simulate the complete system behavior in presence of specific maintenance actions. The strength of this approach lies in the ability to create models of detailed component behavior separately from the maintenance actions.

The final paper (Caputo, Pelagagge) presents a quantitative approach that integrates risk and cost-benefit analyses in order to select cost effective maintenance policies that have acceptable levels of risk. The methodology presented by Caputo and Pelagagge is based on quantifying top level events using fault trees, then conducting sensitivity analysis on the occurrence of these events, and finally using this information to compare corrective measures based on cost and effectiveness criteria. They present the application of this methodology that explicitly incorporates risk in the selection of maintenance policies using a case study of a chemical processing plant that uses highly toxic and flammable materials. This case study highlights the need to consider risk as a performance criteria in addition to overall cost when selecting maintenance policies.

3.2 Maintenance Resources Modeling and Optimization; Analytic Aspects and Monte Carlo Applications

Arie Dubi

Abstract. In this paper we wish to present a novel new approach to the optimization problem. Consider a plant or an airbase or a refinery or any other large realistic system. The system itself contains a large number of LRUs (line replaceable components) working together The LRUs in the system have a number of distinct features. They have failure and repair distributions, these distributions may imply that the components age and deteriorate with time. They are not statistically independent; an event (failure or repair) of one of the LRUs may result in a change of state in many other LRUs. The components are correlated in many other ways. Bad maintenance of one component may result that less spare parts are needed for other LRUs, because the availability of the system is low and components are not functioning for large periods of time. Furthermore, in a realistic system there is a large set of "contingency rules". For example: if pump number 3 fails activate pump number 4 and set subsystem 7 passive" or "if the air-condition fails the failure rates of a given subsystem increase".

As will be shown the analysis of such systems, namely, the prediction of their future availability as function of time is a prohibitively difficult problem. It has already been demonstrated that this problem can be successfully addressed only using the Monte Carlo method.

The system/s is "surrounded" by a logistic envelope intended to supply the necessary support for the system to operate. The logistic envelope may contain the following items: There may be local repair teams at each location. There can be several locations in which parts of the system are situated- with certain repair capacity. The local repair teams may also apply preventative maintenance when required. There may be local spare parts storages (say one in each location); failed units may be repaired locally, or may be discarded or may be shipped to a higher echelon for repair. Thus, the logistic envelope may contain a number of repair depots. In each depots failed unit arrive and are either discarded or repaired locally or again shipped to a higher repair level. The repair depots contain spare parts storages and they ship spare parts in return to a unit that arrived in for repair.

Indeed, the prediction of the performance of the system should include the whole logistic environment.

What are the elements that can be optimized?

The type and period of preventative maintenance for each LRU in the system.

The number of spare parts, of each type, to be held at any storage, at each location.

The number of resources: specified repair teams, work benches and other repair and maintenance resources to be held at each location.

The main point is that if we perform maintenance optimization for a single type of component, we make a mistake, because maintenance (like everything else) is not standing alone. It affects other elements of the system for example, good maintenance will reduce the number of failures and hence will affect the number of required spares and working hours (repair resources).

Again, the above problem of prediction and optimization is of enormous magnitude and is almost never addressed in its entirety. Two common simplifying assumptions prevail and enable the "solution" of the problem.

The first assumption is "statistical independence", that is each LRU "lives" as if no other units exist in the system. This enables the analysis to be done in one dimension considering a single LRU at a time and then constructing the system and its future from the results obtains for each unit in the system.

The second assumption is a constant failure rate of components i.e. exponential failure and repair distributions. This enables mathematical treatment of the components, for example, the time dependent availability is trivially obtained, but with this distribution there is no aging and no preventative maintenance.

Another assumption of less usage is that the repair time is negligible. This is often used when non exponential distributions are used and maintenance is considered.

These above assumptions are used not because there is any realistic or engineering justification. They are used because otherwise the problem is prohibitively difficult to solve. They have been used so intensively in system engineering and reliability work and for so long that they have become a corner stone of the discipline and there is a great reluctance to abandon them.

The purpose of this work is to show that the above problem of prediction and optimization can be solved in its entirety.

3.2.1 The Transport Problem

In this section we will briefly describe the mathematical elements of predicting systems performance in general to support the statement that the Monte Carlo method is the only viable method for this purpose.

Let the vector $\vec{B} = (b_1, b_2, ..., b_n)$ denote the state of the system where b_i is the state of component i and n is the number of components in the system. Let its respective state. That is, $H_i(b_i, t - \tau_i)$ is the probability that a component that entered state b_i at time τ_i, will exit this state up to time t. Also denote the Hazard function by $z_i(b_i; t - \tau_i)$. We define the "Free flight Kernel", namely the probability density for a system that entered into state $\vec{B}'$ at time t' to exit that state at time t. This kernel is denoted by $T(\vec{B}'; t' \to t)$ and is given by the expression:

$$T(\vec{B}';t' \to t) = \left\{ \prod_{i=1}^{k} \frac{1 - H_i(b'_i, t - \tau'_i)}{1 - H_i(b'_i, t - t')} \right\} x \sum_{i=1}^{k} z_i(b'_i, t - \tau'_i) \quad (3.1)$$

The free flight kernel controls the "time of residence in any given state". An additional kernel is required to define the process of transferring from a given state to another. This kernel is called the event kernel (or collisions kernel) and is denoted by $C(t;\vec{B}' \to \vec{B})$. It is given by:

$$C(t;\vec{B}' \to \vec{B}) = \frac{z_j(b'_j \to b_j; t - \tau'_j)}{\sum_{i=1}^{k} z_i(b'_i \to b_i; t - \tau'_i)} x \left[\prod_{G_1} \delta(\tau_j - \tau'_j) \prod_{G_2} \delta(\tau_j - t) \right] \quad (3.2)$$

This expression contains the ratio of the hazard of the "trigger component" to the total system's hazard function. Note also the dirac delta function products. They express the fact that for a group G_1 of components the time of entry into the state remains as it was. These components have not changed their state as a result of the event. A second group of components G_2 changed their state such that the time of entry equals the current time. This is not the most general case and one may consider the case in which the component enters its state with a given age.

With the above definitions it is easy to show that the number density function fulfils the equation:

$$\psi(\vec{B}, \vec{\tau}, t) = \sum_{B'} \int_0^t \int_{\tau'} \psi(\vec{B}', \vec{\tau}', t') T(\vec{B}', t' \to t) \, x C(t; \vec{B}' \to \vec{B}) d\vec{\tau}' dt' \quad (3.3)$$

It is to be noted that the number density function depends not only on the state vector and time but also on the times of entry into the respective states of the components.

Equation 3.3 is the "transport equation" of systems. Everything related to the model is introduced into the free flight and event kernels and the solution of the equation enables an exact prediction of all aspect of the system future behavior.

That is, if the model created describes correctly the reality of the system then the solution will provide any required quantity related to the time behavior of the system. However, the dimensionality of the equation grows exponentially times factorial with the number of components, hence a system of; say 22 components will result in a set of millions of simultaneous integral equations, far from our current ability to solve. Hence, although the equation is known, it can be solved only for the trivial case of a single components. Indeed, this equation is reduced to the simple first order differential Markov equation if exponential distributions are assumed for both failure and repair. Still, a system with n components each having three possible states (say, operational, failed and passive) would result 3^n states and a simple energy production system with 11 components would mean about 177.000 states. The dimension of the problem is the number of components – Here comes the relief of the second approximating assumption. If we assume that the components are statistically independent then the problem is reduced to eleven one dimensional trivial problems. Hence we move from a single 11 dimensional problem to eleven, one dimensional problems. Equation 3.3 explains why these uncontrolled and damaging approximations are required. Yet, it has been shown that the above equation is easily addressed by the Monte-Carlo Method and it is possible to solve any model with any level of realistic complexity and dimension. We will therefore assume in the following that we have the ability to construct a model of every realistic system and obtain its future time dependent properties (availability, production etc.).

Although the Monte Carlo Method is a viable tool for the solution of complex realistic models, it poses a serious difficulty when optimization is considered. This because Monte Carlo calculations require large amount of computer time and if an optimization requires marginal analysis with hundreds of calculations it becomes rather impractical. We will present a solution to this problem in the form of a hybrid optimization method in which a parametric performance surface of the system as function of resources is postulated and a small number of Monte Carlo calculations are performed to "learn" the parameters of the surface. The optimization is then performed analytically and is controlled by a small number of Monte Carlo calculations aimed at improving the parameters of the surface. This method will be presented in the following sections.

3.2.2 The Optimization Problem

In the following we describe the general problem with the aid of an example that can be easily generalized. The first part is the logistic environment and the second is the description of the system and the maintenance applied to it.

The Logistic Envelope

Consider a set of locations and depots as shown in the following figure.

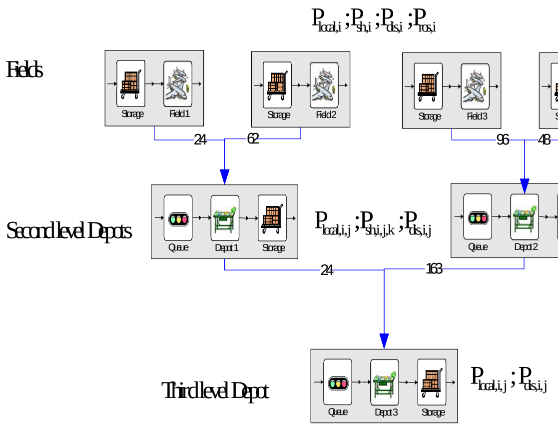

Figure 3.1 Basic logistic structure of four fields and three hierarchical depots

Four fields are presented and in each field a given number of systems reside. Each field contains a storage of spare LRUs. Upon a failure of an LRU the following steps are taken:

1. the location in the system in which this LRU resides is repaired (restored): this can be done in one of the two following ways:
- repairing the LRU on site, that is repairing the failed LRU, and restore the system, this process is called "repair on site (ROS)"; no spare LRU is required;
- replacement: the failed LRU is removed and a spare is obtained from the local storage and replaces the failed LRU.

It is assumed that each failed type of LRU has a probability denoted by $P_{ros,i}$ (i is the index of the LRU type) to be repaired on site. If the failed LRU is replaced then the following routes are available for its treatment.

2. the failed LRU may be repaired locally in a depot residing at the field. After repair the LRU is returned into the local storage. The probability for this is $P_{Loc,i}$;
3. with probability $P_{sh,i}$ the failed LRU is shipped to a higher depot (as indicated by the arrows in Figure 3.1);
4. the LRU may be discarded with probability $P_{Dis,i}$ at the local depot. In this case a new LRU will be ordered, from the vendor, with Lead time $T_{Lead,i}$

Note that the sum of probabilities: $P_{Dis,i} + P_{Sh,i} + P_{Loc,i} + P_{Ros,i} = 1$

It is clear from the above that an LRU will arrive for repair at the Depot as a result of shipment from the field.

At every high depot there are again three options, with probabilities dependent upon the type and the depot. The probabilities are respectively:

$P_{Dis,i,j}$ - The probability that the LRU of type i will be discarded at Depot j. In this case a new LRU will be ordered by this depot with lead time $T_{Lead,i,j}$

$P_{Loc,i,j}$ - The probability that the LRU will be repaired locally and sent, after repair, to the local depot storage.

$P_{Sh,i,j,k}$ - The probability that the LRU will be shipped to a higher Echelon depot k for repair.

In the current example the second Echelon contains a single depot (Number 3). The highest echelon has the same probabilities except that: $P_{Sh,i,k,m} = 0$ - This depot(s) can not send the LRUs to higher levels. They either repair them or discard them and purchase or manufacture new ones.

Another relevant Data item is the repair time of each type at each depot –denoted by $T_{r,i,j}$.

Two additional rules complete the logistic envelope description:

1. the repaired LRU is stored in the storage of the level at which it was repaired (or purchased);
2. each location provides a spare LRU upon request. Once it provides such an LRU it makes an immediate request for a replacement LRU from the agent to which the Failed LRU (that started the chain of events) was sent for repair.

For example: if the LRU is repaired locally in the field, the field storage will ask for an LRU from itself: that is the repaired LRU will be put into this storage. If the LRU is shipped to a higher level the local storage will request an LRU from the higher level. If a higher level depot obtains a request for a spare it means that the corresponding failed LRU was sent for repair in that depot. If the LRU is repaired locally (in the higher depot) or is discarded, the depot will request a spare from itself. If it sends that LRU to still higher level it will request it from the higher level. Note that the highest level can request replacements only from itself.

The System and its Maintenance

An example of a system is shown in Figure 3.2. In principle the system can hold hundreds or thousands of LRUs and there is no limitation to its structure. It may contain any types of connection and/or any types of logical contingency rules such as Stand-by units and subsystems of any type. Along with complex conditions, such as: if subsystem 1 is failed and subsystem 3 is operational and the year period is "Summer". The time dependent failure rate of each component in Subsystem 4 is increased by a time dependent factor. The failure and repair data concerning the system is shown in Table 3.1. We bring a very simple example inhere as the goal is to explain the principles of the method of optimization.

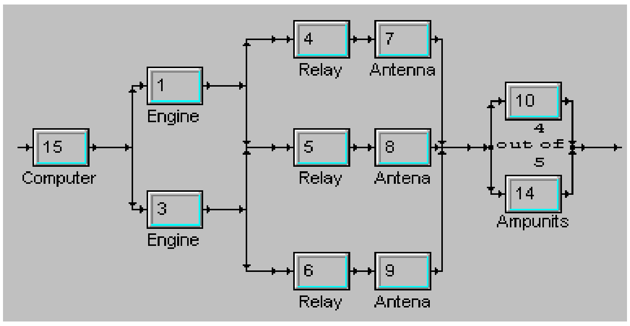

Figure 3.2 a system with 14 LRUs of 5 types

This table is presented in order to stress the "aging" distributions of components that require maintenance. Note that the repair data in the table is related to the repair of the system, this means either the time of replacement, if a spare LRU is used or the time to repair an LRU on site. The times of repair of the LRUs in the depots are part of the logistic envelope data.

We assume that preventative maintenance is an operation that reduces the age of the maintained component back to zero. Obviously, if a component has an exponential failure distribution there is no point in such maintenance. In the above some components have Weibull failure distributions (η and β the shape factor) are given in the table. The non-parametric distribution implies that the component has 10% probability to fail up to 2000 hours and 90% , uniformly, between 2000 hours and 9000 hours.

We now have the complete general scenario. We have the systems, they are distributed amongst several fields with three echelons of repair and depots. It is very easy to generalize this scenario in terms of number of fields, repair levels (Echelons) and even with the logical conditions within the systems and within the logistic envelope.

The optimization question is: how many spare parts should be procured within each level and each storage and for each type of LRU and how many maintenance operations should be performed, given, of course, the cost of maintenance, cost of failure of each LRU, cost of spare parts, and cost of system down time, so as to obtain a required average availability over a given period of time at minimal cost.

Indeed, the above is not the most general "optimization question". One may ask the same question for a given budget where the target is to maximize availability. One may perform several Maintenance operations on several LRU groups so that the system continues operating during maintenance.

Table 3.1 Failure and repair data for the system in figure 3.2

	Type	Failure PDF.	η	β	MTTR
1	engine	Weibull	2700	1.65	62
2	Relay	Weibull	8200	2.1	48
3	Ant.	Exp.	4500		72
4	Amp.	Weibull	4200	1.4	4
5	Comp.	Non Parametric	10% - 2000 90%- 9000		24

Yet, we present here the basic question in order to describe the principles of the optimization. It is to be noted that optimizing spare parts and maintenance are not two independent questions! Maintenance reduces the number of component failures hence results in a smaller need for spare parts. At the same time it takes part of the budget hence less spares may be bought for the same total "life time cycle" budget. Thus the question is not only the optimization of each process, which in itself is a very serious problem, but the joint optimization of both.

Furthermore, two other elements for optimization are "repair resources", such as specified repair teams, work benches and repair equipment. These are also costly and are distributed amongst the depots. What type of resources and how many? is also part of the problem. It is also possible to consider the structure of LRUs by SRUs (shops repairable units) and ask how many SRUs should be stocked at any storage. In the following we will address these problems and indicate the theory and algorithms that solve it.

3.2.3 Optimization Theory

Inhere we describe the basic theoretical considerations that lead to the hybrid optimization solution. We first bring a number of important concepts and then show how they are used in the theory.

The Sensitivity

The first concept to be introduced is that of the sensitivity of a given type of component, s_j. The sensitivity is obtained during the Monte Carlo calculation where upon the failure of the system the component type(s) responsible for that failure are identified. This is done by scanning through all the failed components and identifying those that *upon repair would repair the system*. Namely, if a component is failed at the moment of a system failure it is held responsible for the system failure only if its (*ad hoc*) repair repairs the system. The downtime of the system is then added to a counter for all the component types that are found responsible for the system failure. Denote by $T_{d,i,j}$ the j^{th} downtime stored for the i^{th} type throughout the Monte Carlo calculation. Then $T_{d,i} = \sum_j T_{d,i,j}$ is the total (system) downtime accumulated throughout the calculation for this type. The sensitivity is then derived as the ratio:

$$s_i = \frac{T_{d,i}}{\sum_{j=1}^{m} T_{d,j}} \tag{3.4}$$

The numerator accounts for the downtime resulting from failures of this type while the denominator is a measure of the total downtime of the system. Hence the sensitivity can be viewed as the relative unavailability resulting from any given type. With this notion we define:

$$U_i = U \cdot s_i \tag{3.5}$$

as the partial unavailability of the system resulting from failures of type i. It is easily seen that:

$$U = \sum_{i=1}^{m} U_i \tag{3.6}$$

Thus the average unavailability of the system is presented as a sum of the partial unavailability's

The Waiting Time

The next concept central to the optimization is the "waiting time": it is the average time one needs to wait from the moment a spare was asked for until it is available. It is essential to understand that the whole logistic environment, with all its depots, repair facilities, storages etc. is expressed, as far as the field is concerned in this single concept. If one has, for example, an infinite number of spares on location then there is no need in any recycling or repair depots of spare parts.

The average waiting time is given by:

$$T_{w,i} = \Im(T_{c,i}, q_i, \lambda_{d,i}) \\ = T_{c,i}\left[D_{q_i}(\lambda_{d,i}, T_{c,i}) - \frac{q_i}{X_i} D_{q_i+1}(\lambda_{d,i}, T_{c,i})\right] \tag{3.7}$$

where $\lambda_{d,i}$ is the rate of demands for spares of type i, $T_{c,i}$ is the recycling time of a failed unit of this type, q_i is the number of spares of type j in the storage and $X = \lambda_d \cdot T_c$. $D_q(X)$ is the cumulative Gamma distribution:

$$G_q(X,t) = \frac{\lambda_d(\lambda_d \cdot T)^{q-1}}{\Gamma(q)} e^{-\lambda_d \cdot T} \tag{3.8}$$

Hence

$$D_q(\lambda_d, T_c) = \int_0^{T_c} \frac{\lambda_d(\lambda_d \cdot t)^{q-1}}{\Gamma(q)} e^{-\lambda_d \cdot t} dt \tag{3.9}$$

Equation 3.7 assumes that a failed spare is recycled and returns to the storage after time $T_{c,i}$. Note that with this formulation discarding a unit is the same as recycling it as long as a new unit is purchased with lead time $T_{c,i}$ -so there is no need to separate Recycled LRUs from Discarded LRUs.

The Waiting Time in a Multi-Echelon/ Multi-Field Scenario

As will be seen, the waiting time is the most critical element of the optimization. Equation (3.7) provides its basic form in a single filed, single depot scenario. It is now necessary to generalize it for the general scenario such as the one depicted in Figure 3.1.

Consider first the local field storage. We generalize the recycling time – to be the time elapsing since the request is made by a storage for a spare until that spare arrives. Consider the situation for a "field storage". With probability $P_{Dis,i}$ the failed LRU is discarded and the local storage orders a spare from the vendor. This spare will arrive after $T_{Lead,i}$ hours hence the recycling time is exactly $T_{Lead,i}$. With probability- $P_{Loc,i}$ the failed spare will be repaired at the local depot this will require $T_{r,Loc,i}$ hours after which the repaired unit will be sent to the storage.

Hence the recycling time is $T_{r,Loc,i}$. With probability $P_{sh,i,j,k}$ the unit of type i at field j will be shipped to be repaired at depot k. In this case a request will be made from that depot to send a replacement. This will require time: $T_{sh,i,j,k} + T_{wait}(i,k)$ that is the shipment time from depot k to field j plus the necessary "Waiting time" at depot k for a spare of type i. hence the overall recycling time is the weighted average of the form:

$$T_{c,j,i} = P_{Dis,i,j} x T_{lead,i,j} + P_{Loc,i,j} x T_{r,loc,i,j} + \sum_k P_{sh,i,j,k} x T_{wait,i,k} \tag{3.10}$$

Note that in expression (3.4) the possibility that a failed LRU may be sent to several different depots is allowed and the summation over k is an averaging over all the depots into which the failed spare may be shipped. we may write the waiting time at field j for type I as:

$$T_{w,i,j} = \Im(T_{c,i,j}, q_{i,j}, \lambda_{d,i,j}) = T_{c,i,j} x \left[D_{q_{i,j}}(\lambda_{d,i,j}, T_{c,i,j}) - \frac{q_{i,j}}{X_{i,j}} D_{q_{i,j}+1}(\lambda_{d,i,j}, T_{c,i,j}) \right] \tag{3.11}$$

Where $T_{c,j,i}$ is calculated from equation (3.4). All the quantities in expression (3.4) are known except the waiting time at the depot. Our next step is to look at this waiting time. But, this waiting time is exactly the same as that of the field except that now the index j is the depot number and the index k is a higher depot into which depot j may ship failed units that it can not repair. Equation (3.11) then applies to all fields and all depots. In the highest depots the "Shipment" term is excluded since these depots do not ship failed spares to any higher level. They either repair them locally of purchase new ones (In case of discard) or produce new ones if the are the manufacturer. Also note that in expression (3.11), $\lambda_{d,i,j}$ is the total number of demands for a spare of type i, made from depot j, by all the lower sites that are sending spares for repair. This concludes the algorithm because as we go backward from the highest depots level we can calculate each waiting time (As the highest depots do not contain a waiting time for a still higher level) until we obtain the waiting time at each field for each LRU.

For the scenario shown in Figure 3.1, the equations for the fields are:

$$T_{w,i,j} = \Im(T_{c,i,j}, q_{i,j}, \lambda_{d,i,j}) = T_{c,i,j} x \left[D_{q_{i,j}}(\lambda_{d,i,j}, T_{c,i,j}) - \frac{q_{i,j}}{X_{i,j}} D_{q_{i,j}+1}(\lambda_{d,i,j}, T_{c,i,j}) \right] \tag{3.12}$$

Where i is the type of the LRU and j is the "Field number". $\lambda_{d,i,j}$ is the rate of demand for spares of type i at field j, $q_{i,j}$ is the number of spares of type i stored in the local storage of the field and field and $T_{c,i,j}$ is given by equation (3.4)

$$T_{c,j,i} = P_{Dis,i,j} x T_{lead,i,j} + P_{Loc,i,j} x T_{r,loc,i,j} + \sum_k P_{sh,i,j,k} x T_{wait,i,k} \tag{3.13}$$

Where k is 1 for $j = 1,2$ and k=2 for $j = 3,4$ - The waiting time for Depot number 1 is given by

$$T_{d,w,i,1} = \Im(T_{c,d,i,1}, q_{d,i,1}, \lambda_{d,i,1}) = T_{d,c,i,1} x \left[D_{d,q_{i,1}}(\lambda_{d,i,1}, T_{d,c,i,1}) - \frac{q_{d,i,1}}{X_{d,i,1}} D_{q_{d,i,1}+1}(\lambda_{d,i,1}, T_{d,c,i,1}) \right] \tag{3.14}$$

Where the demand rate, spares stored and recycling time are all related to Depot number 1. A similar equation holds for depot number 2. The recycling time of depot number 1 is again given by

$$T_{D,c,1,i} = P_{Dis,i,1} x T_{lead,i,1} + P_{Loc,i,1} x T_{r,loc,i,1} + P_{sh,i,1,3} x T_{wait,i,3} \tag{3.15}$$

Obtained from equation (3.4) with the only depot into which failed LRUs may be shipped is depot 3. Finally, the waiting time at depot 3 is, again:

$$T_{d,w,i,3} = \Im(T_{c,d,i,3}, q_{d,i,3}, \lambda_{d,i,3}) \tag{3.16}$$

The recycling time in this depot is:

$$T_{c,j,i} = P_{Dis,i,j} x T_{lead,i,j} + P_{Loc,i,j} x T_{r,loc,i,j} \tag{3.17}$$

Hence the average of discarding and repairing only (no shipment to higher echelons).

Expression 3.17 can be easily calculated, then substituted into equation 3.16, thereby obtaining the waiting time at depot 3m then Equation 3.16 is inserted into Equation 3.15 to obtain the recycling time in depots 1 and 2, then backward in Equation 3.14 yielding the waiting times in these depots, from this we obtain the recycling time at each field, by substituting into Equation 3.13 and the Substituting Equation 3.13 into 3.12 the waiting time for each type of LRU in each field is obtained as function of the complete logistic chain. With this process the waiting time at the field can be derived for any complex logistic envelope.

In the next section we see how the waiting time is used in the optimization process.

The Optimization of Spare Parts

We have already seen that the unavailability of a system can be defined as the sum of the partial unavailability's that in turn can be obtained from the sensitivities of the component types. We, next define an approximate dependence of the partial unavailability, U_j, on the waiting time. The steady state unavailability of a component is given by: $\frac{T_{r,i}+T_{w,i}}{T_{f,i}+T_{r,i}+T_{w,i}}$, $T_{r,i}$ is the nominal repair time (MTTR), $T_{w,i}$ is the waiting time that must be added to the repair time and $T_{f,i}$ is the MTTF. Assuming now that the MTTF is much larger than the total repair time, the steady state unavailability becomes a linear function of the waiting time. Hence we suggest that the partial unavailability, U_i, is a linear function of the waiting time in the form:

$$U_{i,j} = A_{i,j} T_{w,i,j} + B_{i,j} \tag{3.18}$$

This is the partial unavailability of type i in field j. The bulk parameters can e derived from two independent Monte Carlo calculations. –for example one calculation with infinite spare parts ($T_{w,i,j} \equiv 0$)and one with zero spares $T_{w,i,j} \equiv T_{c,i,j}$. In the first case the waiting time is zero and in the other it is the recycling time. Hence we obtain two equations with two unknowns for the bulk parameters of each type from which $A_{i,j}$ and $B_{i,j}$ are easily derived. Once the bulk parameters are known the unavailability in each field can be calculated analytically, using Equations 3.6 and 3.18 for any given spare parts strategy: $\vec{q} = (q_{1,j}, \ldots\ldots\ldots, q_{m,j})$. Where $q_{i,j}$ is the number of spares of type i in storage j, namely:

$$U_j(\vec{q}) = \sum_{i=1}^{m} U_{i,j}(\vec{q}) = \sum_{i=1}^{m} \left(A_{i,j} T_{w,i,j}(q_{i,j}) + B_{i,j} \right) \tag{3.19}$$

This can be done because for each spare parts strategy we can calculate the waiting time for each type at each field (using Equations 3.15 and 3.16) and as the bulk parameters are known expression 3.18 can readily be calculated.

At this point marginal analysis can be performed. In this process a single step is composed of adding a single spare part. When a spare is added to type i, the ratio:

$$\beta_i = \frac{U(q_1,..,q_i,..,q_m) - U(q_1,...,(q_i+1),..,q_m)}{c_{s,i}} \tag{3.20}$$

($c_{s,i}$ being the cost of a single spare of type i) is calculated. β_i is in fact the added performance expected per one dollar invested in a spare of type i. The type of spare for which β_i is highest is chosen and a spare is added to this type in the chosen depot. This process goes on until the desired level of performance is reached or until the given budget is exploited. It must be noted that adding a single spare to any storage for any type at any echelon affects the waiting time in one or more fields (The higher the echelon more fields are affected). Thus we cover all the options of adding spares and account for every possible type and level. This process is done analytically using the algorithm for calculating the waiting time for each storages strategy and Equation 3.19 for calculating the unavailability at each field. An additional extremely important element is added to the process in that after a given number of analytic steps an additional Monte Carlo calculation is performed with the spare parts strategy reached so far. This guarantees that the process is controlled in that the analytically derived performance at that stage is *compared* and *corrected* with the exact result obtained from the Monte Carlo calculation. Also the values of A_j are recalculated resulting in a "learning process" of the bulk parameters.

Optimization of Maintenance

We bring Inhere only the very basic elements of this theory. We assume that the total cost considered for preventative maintenance is comprised of three items. The cost of maintenance: this is given by the number of times maintenance is performed multiplied by the cost of each operation, namely: $N_m x C_m = \left[\frac{T_{max}}{T_p}\right] x C_m$ -

T_p -is the time interval between consecutive maintenance operations and T_{max} is the service time considered. The second term is the cost of failures: this concerns only the direct cost involved in a failure. Denoting the cost and number of failures of components of type i by $C_{f,i}$ and $N_{f,i}$ respectively, this term yields: $\sum_{i-All\,Types} N_{f,i} x C_{f,i}$. The last term is the cost of down time of the system. This term takes the form: $\left[\frac{T_{max}}{T_p}\right]\Delta T_p x C_d + N_{s,f} x < T_{d,s} > x C_d$ - The first term is the down time resulting from the maintenance itself –this is the number of maintenance operations multiplied by the duration of maintenance, ΔT_p. The second term contains the number of system failures multiplied by the average down time of the system per failure, $< T_{d,s} >$. The sum of the above three terms is the overall cost of maintenance that should be minimized. This can, of course be done by a series of MC parametric calculation but we wish to replace it with an analytic approximation. The first term presents no problem as all its quantities are known. For the second term we run a single MC calculation with no maintenance and record the number of failures of each component type as function of time: $n_{f,i}(t)$ with this function known we know the number of failures each type will have with any number of maintenance operations as:

$$N_{f,i}(T_p) = \left(\left[\frac{T_{max}}{T_p}\right] + 1\right) x n_{f,i}(T_p) \,. \tag{3.21}$$

In the third term the average down time of the system per failure is readily known from the single MC calculation performed and the number of system failures (For a general non serial system) is obtained by recording, in the MC calculation the quantity - $P_{f,s,i}$ being the probability that a failure of component of type i will result a system failure. Assuming that this probability is a constant, independent of maintenance we may write: $N_{s,f} = \sum_{i-All\,Types} P_{f,s,i} x N_{f,i}$ hence the total cost can be written as:

$$\begin{aligned} C_{Total}(T_p) &= \left\lceil \frac{T_{max}}{T_p} \right\rceil xC_m + \\ &\left\lceil \frac{T_{max}}{T_p} \right\rceil \Delta T_p xC_d + \\ &\sum_{i-AllTypes} \left\{ \left(\left\lceil \frac{T_{max}}{T_p} \right\rceil + 1 \right) n_{f,i}(T_p) xC_{f,i} \right\} + \\ &\sum_{i-AllTypes} \left(\left\lceil \frac{T_{max}}{T_p} \right\rceil + 1 \right) n_{f,i}(T_p) xP_{s,f,i} x < T_{d,s} > xC_d \end{aligned} \tag{3.22}$$

This total cost is a function of a single parameter, the time interval between maintenance. Thus it can be evaluated analytically as function of T_p and the value that minimizes this cost is selected.

Repair Resources Considerations

We have so far described the basic features of optimization of spare parts and maintenance as separate issues. We expand the spare parts optimization now to include repair resources. In the next section the extension to higher indentures is discussed. We assume that at every repair shop (depot) a given number of resources is available. Lack of a necessary resource will cause a queue to be formed and as a result the "repair time" of a component at that depot will be increased. Thus an additional time decrement $T_{w,que}$ must be added to the nominal repair time, $T_{r,Loc,i}$. Hence all we have to do is to evaluate $T_{w,que}$ and use, in the waiting time algorithms (Equations 3.10 and 3.11) the quantity: $(T_{r,Loc,i} + T_{w,que,i})$. We denote the rate of arrival of repair demands into the depot by $\lambda(t)$ (Ignoring indices for the time being and discussing a single type of LRU and a single depot). The demand rate, which was considered a constant in the discussion of spare parts *can not be considered constant any more* since if the resources are not sufficient the demand rate will decrease until it fits the repair rate of the depot. Note that in such a case LRUs will be queued into an increasing size of queue. This will mean, in reality, that the number of LRUs in the systems will be reduced and thus the rate of failures will also be reduced. One may easily note that keeping the number of LRUs in the fields constant (by supplying an unlimited number of spares) will cause an unbounded increase of the queue and an infinite delay and infinite repair time. Hence, the logistic environment will become obsolete. Denote the number of units (LRUs) actually in the field by $M(t)$ then the rate of change of the number of LRUs in the field is given by:

$$\frac{dM(t)}{dt} = -[\lambda(t) - \lambda_r] \tag{3.23}$$

Where λ_r is the repair rate in the depot and $\lambda_r \leq \lambda(t)$. Note also that if failure rate of a single LRU is λ_0 then the demand rate is given by $\lambda(t) = \lambda_0 x M(t)$. Substituting this into the above equation yields:

$$\frac{d\lambda(t)}{dt} = -\lambda_0 [\lambda(t) - \lambda_r] \tag{3.24}$$

with the obvious solution: $\lambda(t) = [\lambda_0 x M_0 - \lambda_r] x e^{-\lambda_0 t} + \lambda_r$ where M_0 is the initial number of LRUs in the field. The size of the repair queue is then given by: $Q(t) = \int_0^t [\lambda(t) - \lambda_r] dt = \frac{\lambda_0 M_0 - \lambda_r}{\lambda_0}\left[1 - e^{-\lambda_0 t}\right]$ and the queue size in steady state will thus be:

$$Q_\infty = \frac{\lambda_0 M_0 - \lambda_r}{\lambda_0} \tag{3.25}$$

The average waiting time resulting from this queue size will be:

$$T_{w,que} = \frac{\lambda_0 M_0 - \lambda_r}{\lambda_0 \lambda_r} \tag{3.26}$$

Equations 3.25 and 3.26 will be used to calculate the increase of the repair time due to queuing in the following general scenario.

We assume that there are m different types of repair men or repair resources. We also assume that there is any number of "combined repair teams": each repair team may include one or more of any of the repair resources. A repair team is denoted by: $\left[k_1^1, k_2^1, k_3^1, ..., k_m^1\right]$ -where k_J^s is the number of repair resources of type j in repair team s. For example, if the types of repair men/resources are : mechanic, electrician, crane, toolkit and engineer, respectively, then if for a particular repair one needs two engineers, one crane and a mechanic the repair team will be denoted by $[1,0,1,0,2]$

The matrix: $\{k_L^s\}_{L=1,\dots,m}^{s=1,\dots,n}$ uniquely describes the available combinations of repair teams needed in the logistic scenario as it describes all the types of repair teams required in any repair process.

We also assume that the repair of an LRU may require a specific repair group with probability: $P_{i,s}$. This is the probability that for a failure in an LRU of type i, repair group s will be required. Let $t_{r,i,j.s}$ denote the time requires for repair group s at depot j to complete work on LRU of type i. Then the average time group s is occupied in repair is given by:

$$t_{r,s,j} = \frac{\sum_{i-\text{All types}} \lambda_{i,j,s} t_{r,i,j.s}}{\lambda_{j,s}} \tag{3.27}$$

Where $\lambda_{i,j,s}$ is the rate of demands from group s at depot j by LRUs of type i (Note that this quantity can be learned from a single MC calculation) Also $\lambda_{j,s} = \sum_i \lambda_{i,j,s}$ where the summation includes all the LRU types repaired by group s, hence $\lambda_{j,s}$ is the rate of demands from group s in depot j. The next step is to look at a repair resource of type m. The demand rate from this resource is the sum of the demand rates of all the groups to which such a source belongs. Hence

$$\lambda_{j,m} = \sum_{\substack{s=\text{All Groups}\\ \text{That Use type m}}} \lambda_{j,s} \ . \tag{3.28}$$

In each group s at depot j, the resource is occupied by each group for an average time $t_{r,s,j}$, hence the average time in which this resource is occupied, per demand is given by:

$$< t_{r,j,m} >= \frac{\sum_{s} \lambda_{j,s} t_{r,s,j}}{\lambda_{j,m}}. \tag{3.29}$$

Noting that the number of repair resources of type m required in each group s is k_m^S we may conclude that the average number of repair resources of type m required per repair operation is:

$$< k_{m,j} >= \frac{\sum_{s-\text{All repair groups of m}} \lambda_{j,s} k_m^S}{\lambda_{j,m}} - \tag{3.30}$$

In general the rate of repair is given by the ratio of the number of available resources to the occupation time of the resource in the repair. In our case the average repair time is the product of the average number of resources required for repair $< k_{m,j} >$ by the average repair time $< t_{r,j,m} >$ hence the repair rate of a resource of type m in depot j is given by: $\langle \lambda_{r,j,m} \rangle = \frac{N_{m,j}}{\langle t_{r,j,m} \rangle \langle k_{j,m} \rangle}$ where $N_{m,j}$ is the actual number of repair resources of type m situated at depot j. The repair rate of any given group s is then defined as the minimal repair rate amongst all its members hence: $\langle \lambda_{r,j,s} \rangle = \underset{m-\text{All Repair types of groups}}{\text{Min}} \{ \langle \lambda_{r,j,m} \rangle \}$. We denote the type m for which the rate is minimal by m_{min} and thus $\langle \lambda_{r,j,s} \rangle = \langle \lambda_{r,j,m_{min}} \rangle$ with these considerations we may conclude that the steady state size of queue that will be formed as a result of group s will be (see Equation 3.32):

$$Q_{j,s,\infty}(m_{min}) = \frac{\lambda^0{}_{j,s} M_{j,s} - \langle \lambda_{r,j,s} \rangle}{\lambda^0{}_{j,s}} = \frac{\lambda^0{}_{j,s} M_{j,s} - \langle \lambda_{r,j,m_{min}} \rangle}{\lambda^0{}_{j,s}} \tag{3.31}$$

$M_{j,s}$ is the sum of all the LRUs that contribute over all the fields to demands from group s in depot j. This quantity can be obtained from a single MC calculation or even from input data analysis. $\lambda^0_{j,s}$ is the nominal average demand rate of a single LRU that contributes demands to this group. This is given simply by $\lambda_{j,s} = \sum_i \lambda_{i,j,s}$ (See above) divided by $M_{j,s}$. Equation 3.31 yields the size of the queue that will be formed as a result of a single repair group s. But, the size of the queue will be the sum of all the groups that share the same m_{min} as all the LRUs in that queue are waiting for this type. Thus, for each type of repair resource we check if it is a minimal type (m_{min}) for any repair group. If it is then the queue related to it is given by: $Q_j(m_{min}) = \sum_s Q_{j,s,\infty}(m_{min})$ this is the steady state queue waiting for type m_{min} in the depot. The average repair rate of all these groups is:

$$\lambda_{r,j}(m_{min}) = \frac{\sum_{\in\Gamma(m_{min})} \lambda_{j,s}(m_{min})\langle\lambda_{r,j,s}\rangle}{\sum_{s\in\Gamma(m_{min})} \lambda_{j,s}} \tag{3.32}$$

And finally the waiting time for an LRU that requires group s, belonging to a known m_{min} is given by

$$T_{w,que,j}(s) = \frac{Q_{j,\infty}(m_{min})}{\lambda_j(m_{min})} \tag{3.33}$$

Equation 3.33 is used in the following form. As we calculate the recycling time of equation 10 we have to introduce $T_{r,loc,i,j}$ - This is the nominal repair time of type i at depot j. We identify the group s repairing that type and add $T_{r,loc,i,j} + T_{w,que,j}(s)$ thereby including the effect of adding repair resources into the optimization process.

Optimization of SRUs:

We now add the possibility that each LRU is composed of L(i) internal units called SRUs (Shop repaired units) and a failure of an LRU is resulting from a failure of a single SRU (The possibility that a group of failed SRUs result an LRU failure can be easily added to the model). We denote by $p_{i,n}$ the probability that in a failed LRU it is SRU of type n that is failed. The repair process involves the identification of the failed SRU and its replacement by a spare SRU taken from the local storage. We further assume that the failed SRU of type n is recycled with a known recycling time $T_{c,SRU,n}$ .This enable the use Equation 3.12 for the waiting time for an SRU in the form

$$T_{w,SRU,n,j} = \Im(T_{c,SRU,n,j}, q_{SRU,n,j}, \lambda_{d,SRU,n,j}) = T_{c,sru,n,j}\begin{bmatrix} D_{q_{SRU,n,j}}(\lambda_{d,SRU,n,j}, T_{c,sru,n,j}) - \\ \dfrac{q_{SRU,n,j}}{X_{SRU,n,j}} D_{q_{SRU,n,j}+1}(\lambda_{d,SRU,n,j}, T_{c,SRU,n,j}) \end{bmatrix} \tag{3.34}$$

The waiting time of an LRU at the depot will be given by the average waiting time for its replacement SRUs, hence:

$$T_{w,LRU,i,j} = \sum_{n=1}^{L(i)} p_{i,n} \Im(T_{c,SRU,n,j}, q_{SRU,n,j}, \lambda_{d,SRU,n,j}) \tag{3.35}$$

Where the summation is done over all the SRUs comprising LRU of type i. Finally the repair time of the LRU, used in Equation 3.15 in the determination of the waiting time of an LRU in the field in the optimization process is given by:

$$T_{r,loc,i,j} = T^0_{r,loc,i,j} + T_{w,que,j}(s) + T_{w,LRU,i,j}(sru's) \tag{3.36}$$

Where $T^0_{r,loc,i,j}$ is the nominal repair time (When a spare SRU is available and the LRU is out of the repair queue). $T_{w,que,j}(s)$ (Equation 3.33) is the waiting time in the repair queue due to lack of repair resources and $T_{w,LRU,i,j}(sru's)$ (Equation 3.35) is the waiting time for a spare SRU required in the repair.

Note that the optimization process and the derivation of the LRU waiting time is not directly affected by SRUs or queuing for repair resources. These elements affect only the local repair time of an LRU.

3.2.4 Combining the Spares and Maintenance Optimization

We have shown above the basic theory of spare parts optimization and preventative maintenance optimization. However, performing these optimization separately is not appropriate since there is an obvious interaction between the two elements. In order to combine them we first perform the preventative maintenance optimization with the assumption of unlimited spare parts of all types and repair resources. Preventative maintenance reduces the number of failures so its optimum is indeed the starting point for the spare parts optimization. That is, since with increasing maintenance (decreasing time between maintenance) the number of failure decreases it is obvious that as we increase the number of maintenance operation up to the optimum –both the combined cost of maintenance (Equation 3.22) and the cost of spare parts and repair resources is decreasing. Hence, ones the optimal point of maintenance is obtained, this point is used for the optimization of spare parts as a reference point. Yet, it is possible that with increased maintenance, although the cost of maintenance will increase, the further decrease in the number of failures may improve the overall cost (maintenance and resources). But, as we already have the spare and resources strategy obtained in the optimization we can assume that the number of required spare parts will follow the reduction of number of failures obtained with "excessive" maintenance- Hence we can analytically evaluate the "combined" optimization point for both maintenance and spare parts.

3.2.5 Combined Optimization Example

We consider the system shown in Figure 3.2 and assume a field that contains 6 such systems. Some additional logical conditions are applied: The Engines and Amplifiers are repaired "As bad as old" (units 1,3,10,11,12,13,14). The units of type "relay" (units 4,5,6) are repaired twice on site and upon the third failure must be replaced and recycled. Maintenance is performed on all the system units – except 2 (which is a clock that defines when maintenance is done) and the Antenna's (Units -7,8,9) that have an exponential failure distribution. In maintenance the age of the unit is restored to zero (made as good as new) and if the unit is under repair during maintenance it is repaired "as good as new". In table 3.1 some initial data concerning the optimization is presented.

Above costs are in Dollars.

Cm –is the cost of maintenance for each type per system.

Cf – is the direct cost of repair of each type per failure.

$P_{f,s,i}$ - Is the probability that a failure in a unt of type i will result a system failure.

Table 3.2 Data related to maintenance

Type	Cm	Cf	$P_{f,s,i}$	$T_{c,i}$
1.Engine	100.	33.6	0.067	168
3.Relay	42.	17.6	0.0027	740
4.Antt.	Na	35.	0.014	4200
5.Amp	13.5	13.5	0.0058	740
6.Comp	34	38.3	0.96	740

The first step is the estimation of the expected number of failures for each LRU type as explained in section. In Figure 3.3 the results are shown for the type "Computer" where the number of failures as function of number of maintenance operations is shown in comparison with the actual Monte-Carlo calculation. A very good agreement is obtained for all types.

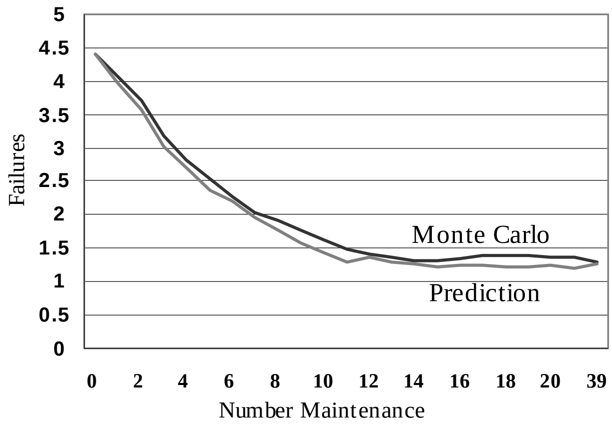

Figure 3.3 Number of failures, computer, prediction compared to MC calculation.

In Figure 3.4 the various down times are shown as function of the number of maintenance operations. The town time caused by system failures, as it decreases with maintenance, the down time resulting from maintenance as it increases linearly with maintenance operations and the sum of both as predicted by the theory compared to the down time calculated by MC.

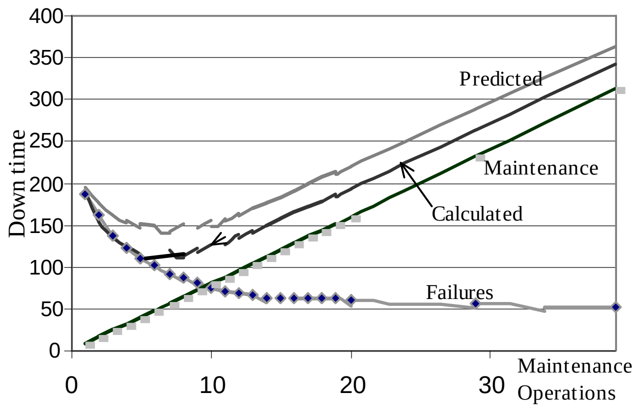

Figure 3.4 System down time analysis as function of maintenance operations

The down time is obtained using the equation $\left[\frac{T_{max}}{T_p}\right]\Delta T_p + N_{s,f}x < T_{d,s} >$ where $N_{s,f}$ is derived from the equation $N_{s,f} = \sum_{i-All\,Types} P_{f,s,i}xN_{f,i}$ .In Figure 3.5 the results obtained with Equation 3.22 are compared to those of a detailed MC calculation.

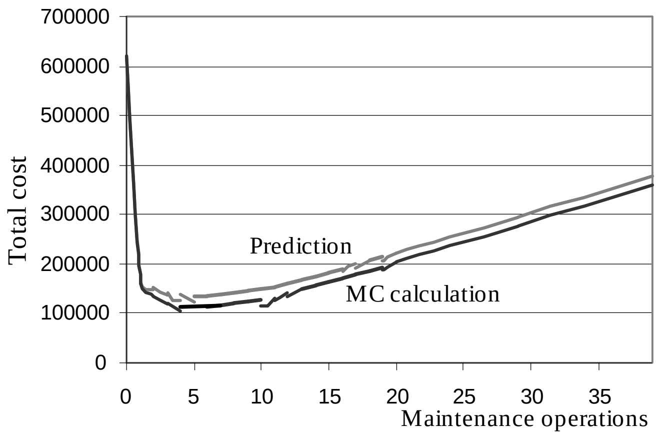

Figure 3.5 Total cost –prediction VS MC calculation

It is seen that although there is a certain (10%) difference between the results the analytic method captures the location of the optimum and provides a reasonable estimate of the total cost at the optimum. It should be noted that one should not expect an exact estimate of the total cost from the analytic approximation. We have the MC method for that. What we wish to obtain is indeed the location of the optimum. The minimal cost predicted is $135.306 with 4 maintenance operations while that obtained by the calculation is $112.900.

Once the optimum maintenance location is known (5 operations every 4000 hours for a service time of 24.000 hours, the spare parts optimization is performed. This was done with the SPARTM software in which this automatic optimization is embedded. The recycling times of the types are shown in table 2 above and the cost of each spare is 6.400; 2.800; 12.000; 9.200 and 1.780 respectively (with the order of types of Table 2). In Figure 3.6 the optimization process is displayed.

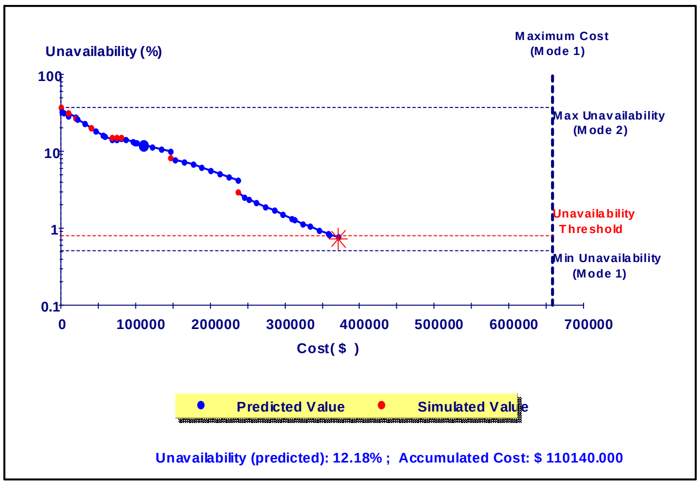

Figure 3.6 The optimization process

The optimization process indicates that an average availability of 0.73% can be obtained with an expenditure of $371000 – This in comparison with an expenditure of $658000 that will yield an unavailability of 0.515%. The last figure is that of an "Infinite storage". The storage strategy is shown in Table 3.3:

Table 3.3 Optimal storage with 5 maintenance operations

Type	Spares
1.Engine	7
3.Relay	4
4.Antt.	18
5.Amp	10
6.Comp	4

At this point however, we know how the number of failures will be decreased with additional maintenance. Assuming that the optimal storage will follow the same reduction we can predict the curve of total cost, namely that of maintenance + spare parts as function of increased maintenance: this curve is shown in Figure 3.7.

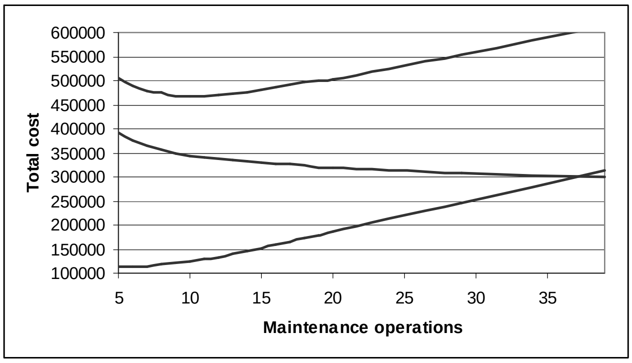

Figure 3.7 Predicted total optimum (spares + maintenance) beyond the optimal maintenance

It is seen that whereas the total Life cycle cost at the optimal maintenance is $484.000 it may be reduced to about $453.000 with 10 maintenance operations. This is a small effect and we actually see that we already have a good idea about the "Optimal range" of both maintenance and spare parts. At this point we execute again the spare parts optimization with 10 maintenance operations and obtain that an unavailability of 0.7% (even better than the 0.73% obtained before) at a cost of $332.000 (compare to the prediction of $329.000 and the total life time cost is then $457.000). Obtaining such accuracy of the prediction is quite encouraging.

3.2.6 Conclusion

In the above we have outlined a new hybrid optimization theory for a complex general logistic model. Apart from the optimization of multiple echelons, repair teams, SRUs a method for joint optimization of resources and maintenance was outlined and demonstrated.

This is an enormous problem and was classically treated by separating each process with simplifications mentioned in the first chapter. We, thus claim, that with the availability of advanced MC methods that enable the modeling of such complex scenarios it is now feasible to apply full whole scenario optimization taking all the above elements and *the interaction between them* into account. This by an hybrid approach in which an approximate analytic expression for the performance of the systems in the field as function of every elements of the logistic envelope is derived. This model is based either on data extracted from the model input or from a small number of MC calculations. The optimization is then carried out analytically, but, and this is a critical point, the analytic optimization, unlike existing classical spares optimization methods, does not go uncontrollably. Following a number of optimization steps a Monte-Carlo (exact) calculation is performed; at this point, the results of the analytic optimization are verified and corrected and the parameters of the optimization "learned".

The method was already tested on many practical cases; inhere we brought a single example.

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3.3 Modelling and Simulation of Complex Maintenance Strategies for Multi-Component Systems

Valérie Zille, Christophe Bérenguer, Antoine Grall, Antoine Despujols, Jérôme Lonchampt

Abstract. When maintenance managers work out preventive maintenance programs of critical systems such as power plants, they usually make choices between various alternatives on the basis of qualitative information provided by experts opinion. However, it would be useful to make it possible to estimate and to compare various maintenance programs on quantitative criteria such as system availability and maintenance costs. The present work proposes a two-stages modelling framework which aims at representing both a complex maintenance policy and the functional and dysfunctional behaviour of a complex multi-component system. A first stage consists in representing a system of several components and simulating its behaviour when given operating profile and maintenance strategy are applied, so as to estimate the maintenance costs and the system availability. At the second stage, a generic model of component is developed to describe the component failure and maintenance processes. A particular aspect is the representation of both the degradation mechanisms that lead to failure modes and the relative symptoms that can appear, in order to get a precise description of the effects of the various maintenance tasks carried out.

3.3.1 Introduction

Industrial Context

The opening of the electricity market forces producers to be more competitive and to react quickly to the market changes. They must manage their plants as well as possible and more particularly the maintenance process, which includes together current maintenance, unexpected maintenance and restorations, and have a large impact on plant performances. However, optimisation of this process is complex because various, and sometimes antagonistic, criteria like availability, safety, and costs must be simultaneously taken into account. Thus Maintenance managers must establish a strategy considering various possible options among the nature of maintenance (corrective, preventive), the type of tasks (overhaul, monitoring, scheduled replacements...), their frequency, the maintenance line (repair on site or in workshop), etc. These choices are frequently based on qualitative information :

experts opinion, good sense and intuition which could be helpfully complemented by quantitative information resulting from deterministic and/or probabilistic calculations. In order to work out the preventive maintenance programs in nuclear and fossil fired plants, EDF applies on critical systems a dedicated Reliability Centered Maintenance method (RCM) which makes it possible to determine the critical failure modes and to help the experts to propose applicable, effective, and economic preventive maintenance tasks.

However, due to the probabilistic nature of the failures, it is not easy to compare different options on quantified bases. It is difficult to evaluate the results of the application of a maintenance program over several years, in terms of availability, safety level, and costs, and decisions are generally based on qualitative information. For this reason it appears convenient to develop methods to assess the effects of the maintenance actions and to quantify the strategies.

Thus it would be possible to answer questions often met in the field of electricity production, regarding :

- the impact of a preventive maintenance program;
- how to assess quantitatively the impact of preventive maintenance program in terms of availability and costs? How to make a rational choice among various options of preventive maintenance tasks? ;
- the impact of operating conditions;
- how to calculate the impact of operating conditions on equipment reliability, system availability and maintenance costs ? How much are the expenditures generated by a given plant operating profile?;
- a maintenance tasks ranking;
- in order to comply with budgetary constraints for example, how to identify the preventive maintenance tasks which could be differed or removed, without unacceptable consequences on performances?;
- the actual state measurement of an equipment;
- how to diagnose the degradation state of complex equipment so as to estimate its probable life expectation before restoration and the foreseeable expenditure?

Scientific Context

The assessment of complex maintenance program performances, resulting for example from implementation of RCM, encounters several methodological difficulties, which the resolution constitutes the scientific challenge of this work. These difficulties are due first to the complexity of the systems on which the maintenance programmes are implemented (systems constituted of several dependent components, with several degradation mechanisms and several failures modes possibly in competition to produce a system failure) and secondly to the complexity of the maintenance programmes (diversity of maintenance tasks).

In the past several decades, maintenance policies have been extensively studied in the literature and numerous performances and costs models for maintenance strategies have been developed, see e.g. (Valdez-Flores and Feldman 1989). However, most of them are devoted to simple maintenance strategies (periodic maintenance, condition-based maintenance, age-based maintenance, …) with a finite number of actions and defined effects (perfect inspections, perfect replacements, minimal repair, …) and applied on single-unit systems, see e.g. (Dekker 1996; Mooustafa *et al.*, 2004). Obviously, the framework for maintenance modelling of a system cannot result of a simple juxtaposition of elementary maintenance models of its components.

Some approaches based on stochastic simulation allow taking into account more complex maintenance strategies but they generally aim at developing simulation techniques such as Monte Carlo simulation, or optimization procedures, see e.g. (Doyle 2004; Marseguerra and Zio 2000).

Finally, only a few part of maintenance simulation works give an interest to components degradation and failure phenomena and to the effects of maintenance actions, which are described by classical modelling tool (lifetime distribution for components failure process, single degradation phenomenon, perfect replacement or minimal repair, …).

3.3.2 Overall Model Presentation

Overall Model

Equipment failure modes analysis are often carried out by using a FMECA matrix which contains, if complete, the necessary information to represent the complexity of the problem :

- the equipment failure modes, i.e. according to standard EN13306, manner in which the inability of an item to perform a required function occurs;
- the degradation mechanisms which lead these failure modes to occur;
- the influencing factors which possibly affect the degradation mechanisms by starting them or by affecting their kinetics;
- the possible symptoms which make it possible to characterize the degradation level;
- the failures modes effects on the system and on the installation.

The maintenance tasks which make it possible to detect and/or repair the equipment and which applies to degradations can be added in this FMECA matrix.

To model reality as accurately as possible it is convenient to represent these various characteristics and these observations have resulted in working out an overall model, shown on figure 1, divided into four parts sharing information :

- "System dysfunction" modelling;
- "System operation" modelling;
- "System maintenance" modelling;
- Components modelling.

The four modelling levels can be validated independently and then associated by mean of interactions in order to simulate complete systems.

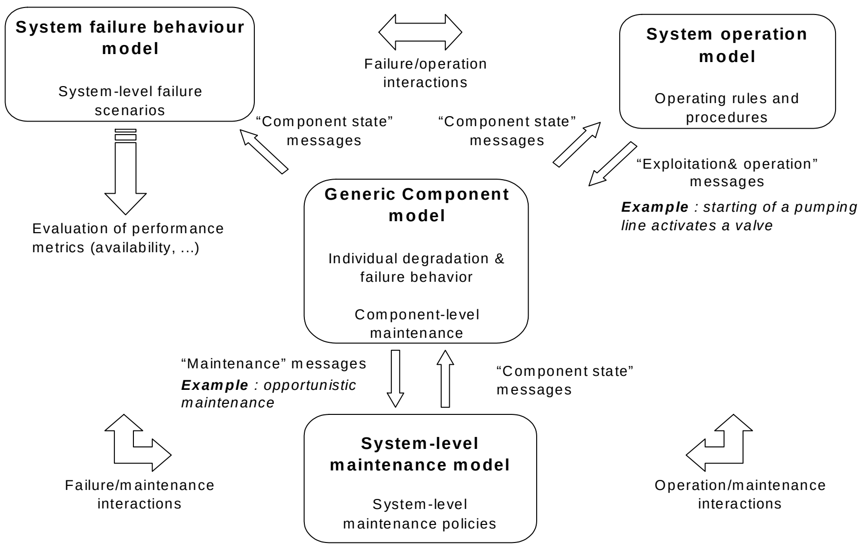

Figure 3.8 Overall structure for maintenance modelling

3.3.3 Three Models to Describe the System Behaviour

The system dysfunction model describes all the degradation/failure scenarios of the system. It gives out the global performance indicators of the maintained system. Indeed, it allows the evaluation of the system unavailability, due either to a failure either to some maintenance actions, and also the associated maintenance costs.

The system operation model aims at describing the nominal behaviour and the operating rules of the system, defined as input data of the complete framework. This model interacts with the component model and evolves according to the operating profile and to the needs of the system : activating of a required component, stopping of a superfluous component, etc.… Obviously the operating behaviour of the system cannot be described by the simple juxtaposition of the component-level models and it is necessary to take into account all the possible interactions and dependences between components. At this level one can model spare equipments, activating of defence systems in case of an equipment failure, stopping of a line in case of maintenance of one of its component.

In the system maintenance model, one can define the system maintenance strategy applied, whereas individual maintenance procedures will be considered only at the component modelling level. It allows describing grouping procedures that are used to take advantage of economics of scale due to economic or technical dependences between components in the case of opportunistic maintenance. This model might also include resources sharing and availability problems due to a limited number of repair teams or specific tools and spare parts stocks.

Since all the models can be validated independently, one can decide to use different kinds of modelling tools as some are more appropriate to some cases than other. Thus, a possible representation of the system operation model can be made by using Petri Nets methodology to model the system operating rules, whereas a fault tree can describe the different scenarios leading to the system unavailability, either for dysfunctioning or for maintenance. Finally, one can model the system maintenance simply by iterating the maintenance rules.

3.3.4 Interactions between the Different Models

The three system-level models and the component-level model interact together in order to represent completely the system behaviour, its unavailability and expenditures, knowing the behaviour of its components and the maintenance tasks are carried out.

Component-level model gives information on components states (failure, unavailability for maintenance) and on maintenance costs to the three other system-level models which evolve according to this input data and possibility sent feedback data.

For example, as shown on Figure 3.8, the system operation model sends information to the component-level model to require the activating of a stand-by component or the stopping of an auxiliary component that has become useless after the repair of the main component.

The system maintenance model can send data to the component-level model to force the maintenance of a component coupled together with a component already in maintenance.

Generic Modelling of a Maintained Component

Industrial complex systems are made of numerous components whose availability is submitted to the failure mode occurrences and the maintenance tasks carried out.

Thus, the above-described system-level model is completed by a second level devoted to the system components and a basic model is developed for each component.

It is a generic model which takes into account both the physical states (sound state, degraded, hidden or obvious failure, failure) and the functional states (in maintenance, stand-by, operating) of a component.

At this level, all the maintenance tasks defined for a component are represented: predetermined maintenance tasks (scheduled replacement), condition-based maintenance tasks (external inspection, condition monitoring, test, overhaul) and corrective maintenance (repair). Other maintenance policies such as opportunistic maintenance are defined at the system level model and their activation are made with help of information between the component-level model and the system maintenance model.

Degradation process is also modelled to describe the degradation mechanisms evolution, which may lead to the components failure modes occurrence, and the relative states of degradation of the component. This way of representing components degradation through different states of degradation allows getting a more precise description of the component behaviour and of the preventive maintenance tasks which are carried out and which allow a possible return to a lower level of degradation, depending on their efficiency.

In addition, the model let us represent, for each degradation mechanism, the related symptoms or observations that appear and characterize its evolution. In fact, the detection of a symptom, using a condition-based maintenance task such as external inspection, condition monitoring or overhaul, gives information about the component degradation level and makes it possible to decide to carry out a preventive repair. So preventive maintenance tasks impact on the component's state, the symptom occurrence and the degradation level. Moreover, at each component degradation level, a component failure mode may occur, with an increasing occurrence probability, impacting on the system operation, and a corrective maintenance action would be then performed.

In real multi-component systems, relations between degradation mechanisms, failure modes, symptoms and maintenance actions increase in complexity due to their possible dependences, at both component and system level. Indeed, a single component has more than one failure mode, each of them occurring due to the evolution of various degradation mechanisms that may interact together. Different maintenance actions can be carried out on the component in order to avoid different degradations and a symptom can characterized different degradation mechanisms. Other complex dependences can be induced by the system structure.

Figure 3.9 describes the various possible relations that have to be taken into account to represent precisely components degradation/failure processes and maintenance, assuming that more than one degradation mechanisms, failure modes, symptoms and maintenance actions interact. The figure describes how the component degradation state, due to influencing factors, can be characterized by a symptom, which, if detected by a preventive maintenance task such as external inspection, overhaul, condition monitoring, will lead to the activation of a preventive maintenance repair or replacement in order to impact on the component degradation state.

One of the difficulties encountered for the development of a generic representation of the degradation mechanism evolution is that these mechanisms are influenced by many environmental and operational factors. For example, some mechanisms would evolve according to operating time, age, number of duty cycles, environmental conditions, degradation of an other component, etc.…

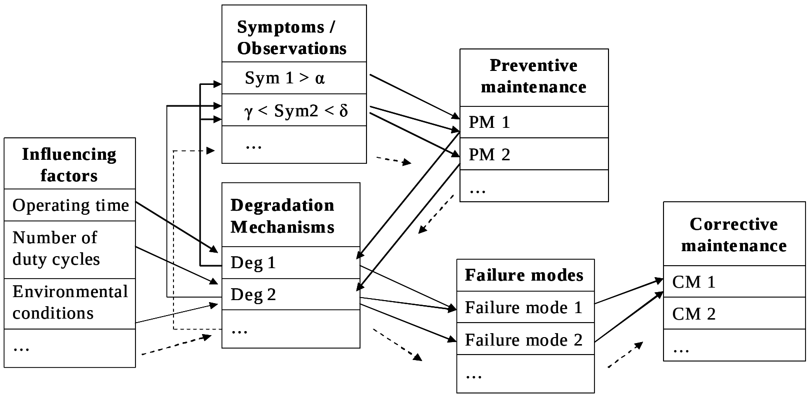

Figure 3.9 Various possible relations that must be modelled for a precise representation of component degradation and maintenance. Broken arrows represent other possible relations

Use of Petri Nets and Monte Carlo Simulation

The proposed generic methodology has been developed using the Stochastic Synchronized Petri nets (SSPN) and it has been coupled with the Monte Carlo simulation to compute the performances assessment of industrial systems, see e.g. (Bérenguer *et al*., 2004).

For systems dependability studies, SSPN offer a powerful and versatile modelling tool that can be used jointly with Monte Carlo simulation, which is widely used in this kind of work, see e.g. (Barata *et al*., 2002; Simeu-Abazi and Sassine 1999). The SSPN use classical properties of Petri nets to treat the sequential and parallel processes, with stochastic and deterministic behaviours and flows of information called “messages” which are very useful in the proposed approach to characterize the interaction between the four level models.

The application of the previous overall model on simplified real complex systems has given interesting results and led to further developments of representing. Simulations have been made to study the effects of parameters variation, such as maintenance tasks period, on the system behaviour.

Then, further developments were carried out to get a precise representation of components degradation and failure processes and the relative impact of maintenance tasks.

3.3.5 Focus: a Petri Nets Modelling to Compare Various Maintenance Programs

We propose here a representation of the relations between degradation mechanisms and maintenance tasks by using Petri Nets to describe equipment behaviour and more especially what can be the benefit of symptom representation to compare different kinds of maintenance programs.

In the following, we consider an equipment that can be degraded by two different degradation mechanisms, mechanism A and mechanism B, whose evolutions can lead to two different failure mode occurrences, respectively failure mode A and failure mode B.

A Petri Net is built for each degradation mechanism to represent its evolution through three degradation levels and the respective risk of failure mode occurrence as simplified in Figure 3.10 in the case of mechanism A.

Transitions between two successive levels of degradation are fired according to probability laws taking into account the various influencing factors that can impact on the mechanism evolution.

Failure modes can occur at each degradation level, with a corresponding failure rate, represented by the firing of the corresponding transition. The more the degradation level is important, the more the risk of failure mode occurrence is high.

Return to a lower degradation level is due to maintenance task performance and depends of its effectiveness.

In the particular case described in Figure 3.10, the return in the lowest degradation level for mechanism A is either due to a corrective repair, performed after the failure mode occurrence, either to the performance of a specific preventive task.

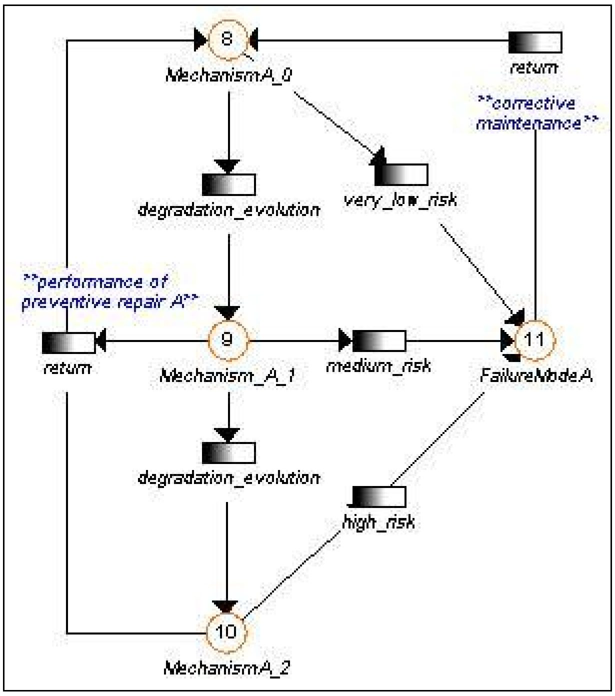

Figure 3.10 Simplified Petri Net modelling of degradation mechanism A evolution. A comparable net will represent mechanism B evolution.

We also assume that two symptoms, symptom 1 and symptom 2, appear and evolve according to the degradation evolutions they characterize. Again, symptoms evolution is represented through various symptom levels, corresponding of intervals between thresholds.

Symptoms and degradations evolutions can be different, depending on their nature and the various influencing factors that impact on them. However in the proposed example each level of symptom is linked to a given level of degradation. Thus, relations such as those described in Tables 3.2 and 3.3 inform on the level of symptom knowing the level of degradation for each mechanism, and Figure 3.11 gives a simplified Petri Net representation of the evolution of symptom 2.

Table 3.4 Symptom 1 level knowing mechanisms A and B levels. Symptom 1 is specific to the degradation A.

Symp. 1 Levels	Mechanism A - Levels			Mechanism B - Levels		
	0	1	2	0	1	2
0	X			X		
1		X		X		
2			X	X		

Table 3.5 Symptom 2 level knowing mechanisms A and B levels. Symptom 2 can appear due to the evolution of both the mechanisms

Symp. 2 Levels	Mechanism A - Levels			Mechanism B - Levels		
	0	1	2	0	1	2
0	X			X		
1	X				X	
2		X				X

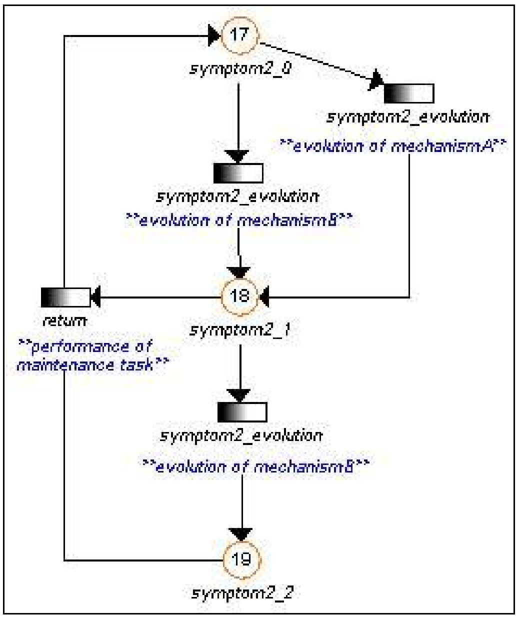

Figure 3.11 Simplified Petri Net modelling of symptom 2 evolution through various level. Transitions between successive levels are fired correspondingly to degradation mechanisms evolutions.

Both corrective and preventive maintenance tasks are considered. Figure 3.12 gives a simplified Petri Net modelling of corrective maintenance, performed when a failure mode occurs (condition for transition firing).

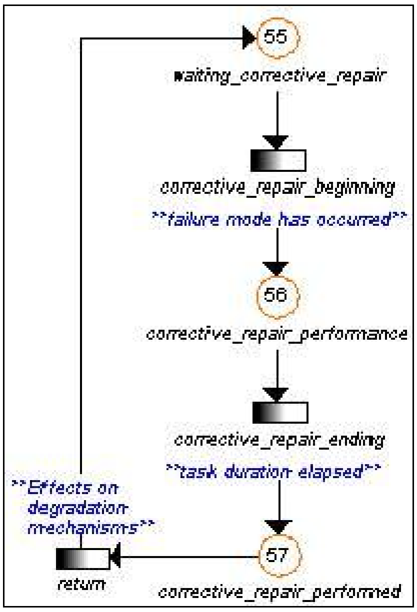

Figure 3.12 Simplified Petri Net modeling of corrective repair performed after a failure mode occurrence

Concerning the preventive maintenance tasks, a distinction is made between the detection tasks, modelled as shown in Figure 3.13, and the preventive repairs, modelled as shown in Figure 3.14.

Detection tasks are performed in order to characterize the component degradation state by observing a level of degradation or the relative levels of symptoms (measurements of degradation or symptoms are compared with given thresholds). Typically, these tasks are external inspections, condition-monitoring, tests or overhauls, and they are scheduled so they are performed after the corresponding period time is elapsed.

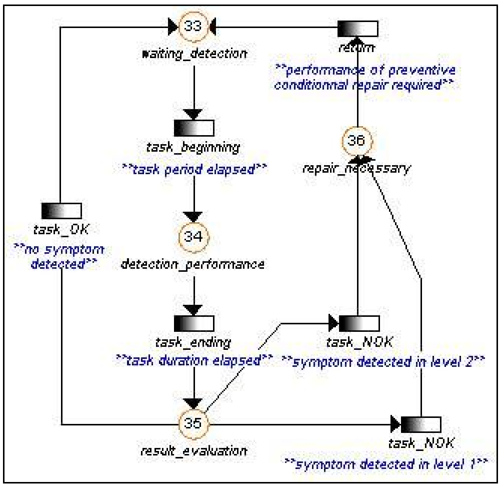

Figure 3.13 Simplified Petri Net modeling of detection task

The task modelled in Figure 3.13 aims at observing Symptom 1.

Then, a preventive repair can be carried out conditionally to the detection tasks result, that is if a degradation has been notified, as shown on Figure 3.14 regarding the repair of mechanism A.

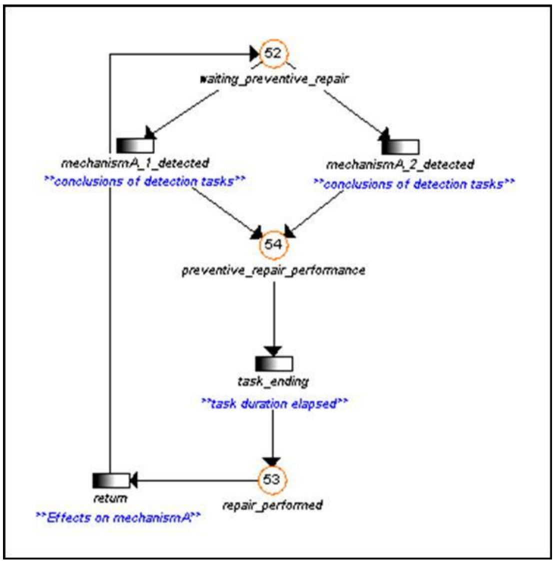

Figure 3.14 Simplified Petri Net modelling of preventive repair

All the different maintenance tasks have effects on the component state and by the way, on the degradations and symptoms levels.

This way of modelling a maintained component allows a detailed representation of how various maintenance tasks applied within a complex maintenance program can impact on the program performances in terms of costs and system unavailability.

Indeed, it makes it possible to model and simulate preventive maintenance programs composed of various type of tasks (external inspections, overhaul, condition-monitoring, test, scheduled replacement) so as to compute their performances and compare them on the basis of the effects of variations of parameters such as frequency or task type.

Moreover, the representation of symptom and degradation make it possible to take into account the distinction between the various detection type tasks. In particular, preventive maintenance tasks such as overhaul are expensive and induce unavailability of the component but give a good information about component degradation state. Whereas other preventive tasks such as external inspections or condition-monitoring are less expensive and does not require the component to be stopped but are often based on some symptoms observations that can be different from the degradation mechanism really undergoing.

3.3.6 Conclusion

The objective of the work presented here is to model and to simulate the maintenance programs in order to provide quantitative results that could support choices between different maintenance tasks and frequencies. This is done by a modelling framework that represents both a complex maintenance policy and the functional and dysfunctional behaviour of a complex multi-component system. Further developments are carried out to build the complete model and more especially to improve the generic component model (by taking into account degradation mechanisms, maintenance tasks effectiveness and all the complex relations between influencing factors, degradation mechanisms, symptoms, failure mode, preventive and corrective maintenance) and the interactions between all the different model (possibly by using different modelling techniques). The approach consisting in representing how failure modes can occur due to degradation mechanisms that can be characterized by the observation of symptoms give a possible comparison of different types of maintenance programs.

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3.4 A Risk–Based Maintenance Planning Methodology

Antonio C. Caputo, Pacifico M. Pelagagge

Abstract. Risk-based maintenance integrates reliability and risk concepts in the maintenance planning process, thus minimizing consequences and probability of system failure. This paper presents a methodological approach of general applicability utilizing quantitative risk analysis and cost-benefits evaluation in order to select the most cost effective maintenance policies in industrial plants, even in comparison with other risk reduction options. The methodology is based on quantification of top events resorting to fault trees, a sensitivity analysis of the probability of occurrence of top events and a comparison of corrective measures based on cost and effectiveness criteria. A case study describing the application of the methodology is also presented.

3.4.1 Introduction

Maintenance contributes to increase productivity and minimize the life-cycle cost of plants by maximizing the reliability and availability of equipments and consequently the long term profitability of industrial enterprises. (Campbell, 1995; Duffuaa *et al*., 1999; Niebel, 1994). However, maintenance practices impact heavily also on plant safety levels. It is unquestionable, in fact, that the availability and reliability of plants, of components and of control and protection systems, which are largely determined by the effectiveness of the adopted inspection and maintenance practices, have a direct impact on the probability of occurrence and magnitude of accidents and therefore on the risk level of the entire system (Smith, 1993, Lees, 1996). Thus maintenance planning may significantly contribute to risk minimization and becomes a strategic lever for safety management, especially when accidents with relevant consequences are involved. This is a critical issue, as nowadays plant managers are forced to increasingly burdensome risk assessment and reduction activities, owing to the growing public concerns about industrial accidents, but still rely on limited budgets and scarcity of resources.

Nevertheless, only a few approaches have been proposed aimed at defining maintenance policies based on system's risk or the criticality of failures. Existing methods are often based only on qualitative or subjective estimates, while the available Computerized Maintenance Management Systems are lacking in the analysis of maintenance policies implications on system safety. Thus maintenance management activities are usually poorly integrated with safety management in spite of the opportunity for significant synergy, and a need for establishing effective and generally applicable risk-based maintenance strategies arises.

3.4.2 Literature Review

Reliability Centered Maintenance (RCM) is a fairly recent approach aimed at defining maintenance policies based on safety, operational and economic criticality of failures (Moubray 1997). However, risk is quantified in coarse classes and the method relies on qualitative or subjective estimates. In fact, simple FMECA (Failure Model Effects and Criticality Analysis) based approaches are usually utilized. Such techniques, however, fully showed their limits in the practical applications (Ben-Daya *et al*., 1996; Gilchrist, 1993; Kmenta *et al*., 2000; Teng *et al*., 1996) owing for example to the utilization of judgements expressed according to arbitrary scales, or based on a limited number of factors without the possibility of weighing their influence. Even if several advanced FMECA techniques have been proposed by a number of authors, for example to include cost of failures (Gilchrist, 1993; Rhee *et al*., 2002), or adopting Monte Carlo techniques to account for safety issues (Bevilacqua *et al.,* 2000), or considering the scenarios following failures (Kmenta *et al*., 2000), or attempting a better linguistic characterization of judgements resorting to Fuzzy theory (Palaez *et al*., 1994), such qualitative approaches still result poorly suited for an in-depth risk assessment. An evolution of RCM is the Risk-Based Maintenence (RBM) paradigm, which instead explicitly includes risk by considering separate classes for probability and consequence of failure. This leads to a “risk matrix” formulation which, assigning numerical values to both probability and magnitude parameters enables to individually rank failure modes from low to high risk thus yielding a priority ranking for choosing maintenance tasks. RBM by integrating risk information into the decision-making process enables improved maintenance decisions by focusing resources on highest-risk equipment and providing objective means to evaluate alternative inspection and test strategies, thus prioritizing corrective maintenance activities and enabling reduced costs (Kihara and Fuji 2000).

A number of industries show interest in this kind of approach which has been also endorsed by the American Society of Mechanical Engineers and American Petroleum Institute. In Europe a consortium named Risk-Based Inspection and Maintenance Procedures for the European Industry (RIMAP Consortium, 2004) is active to develop standards of practice for RBM application (Sheperd 2005).

However, RBM even if successfully demonstrated in several engineering field remains a rather qualitative approach. Application examples may be found in civil engineering (Yam *et al*., 2003), ship management (Ayyub, 2004), material handling systems (Yatomi *et al*., 2004), fossil power plants (Kihara and Fuji 2002), cement plants (Takahashi *et al*., 2002), process equipment maintenance (Montgomery and Satterfield 2002; Hagemeijer and Kerkveld 1998), cross country pipelines inspection (Dey 2001). A reduced number of authors attempted also a quantitative approach to RBM although with different methodologies. Jiang *et al.* (2002) applied RBM to electricity transmission, including outage effects on overload and voltage security besides failure probability of equipment. Others demonstrated a fault tree based application to maintenance of fire protection systems (Farquharson *et al.*, 2003), or pipe line management (Nessim and Stephens 1998).

Nevertheless, while there is a steadily growing trend in utilizing risk as a criterion to plan maintenance, many efforts are still devoted to analysing specific equipments or fields of application therefore lacking in generality. Khan and Haddara (2003), however, propose methodological approach for quantitative risk-based maintenance and inspection scheduling and planning which has a general applicability. It includes a risk identification and estimation phase, a risk evaluation step resorting to fault tree analysis, and a maintenance planning procedure which determines the time intervals between maintenance tasks according to the desired values of probability of failure of the base events in the examined fault trees. Nevertheless, in this model no cost-effectiveness of the maintenance policy is assessed nor alternative risk reducing policies are considered. As a result, a need arises for a general purpose RBM methodology enabling also to select the most cost effective strategy in order to optimize risk reduction efforts.

3.4.3 Problem Statement

In the previous section the limits of qualitative approaches to risk based maintenance have been discussed and the presence of only a few quantitative approaches has been observed. On the other side, the currently adopted risk assessment techniques utilized in industrial plants (Khan and Abbasi 1998; Tixier et al. 2002) explicitly include a direct evaluation of the probability of occurrence of an accident resorting to quantitative techniques (CCPS, 2000; Henley and Kumamoto 1992).

Among them the most frequently adopted are those based on logic trees (Greenberg and Slater 1992). Fault trees enable to estimate the probability of occurrence of a given top event on the basis of reliability data of equipment and the probability of the base events which compose the tree. It follows that the reliability of a complex system may be increased either adopting structural measures, i.e. by increasing the inherent reliability of the single components and/or changing their interaction logic or, according to a management approach, acting on the maintenance activities. In this latter case, since repairable and/or monitorable systems are often involved (Ascher and Feingold 1984), it is effective to implement proper periodic inspection policies (Ben-Daya and hariga 1998; Banerjee and Chuiv 1996) and preventive maintenance practices (Barlow and Hunter 1960; Canfield 1986; Gertsbakh 1977; Hariga 1996; Kobbacy *et al.*, 1995; Makis and Jardine 1992; Malik, 1979; Nakagawa, 1977, 1980, 1986; Nguyen and Murthy 1981; Percy and Kobbacy 2000). Therefore, a correct maintenance policy may effectively contribute to risk reduction as much as other structural choices or other operational and managerial activities. In fact, for monitorable and maintainable systems, the availability and reliability of single components or of the entire plant, may be strongly influenced by the adopted maintenance policy, thus positively affecting the probability of occurrence of accidents and their magnitude or the capability of loss minimization. On the contrary, it often happens that proper preventive and condition-based maintenance strategies, applied to components of the safety and trip systems, together with their redesign from the functional and logic point of view, are economically advantageous respect the simple substitution of critical components with more reliable ones.

Therefore, risk-reducing strategies may be effectively based on the proper choice of maintenance activities.

Under this perspective the suggested approach is that of extending existing maintenance methods, such as the RCM and RBM, which try to select maintenance policies basing on qualitative FMECA-like analyses, by including the quantitative techniques typical of risk assessment and hazard evaluation methods.

3.4.4 The Proposed Methodology

In order to contribute toward the solution of this problem in the paper a methodology is proposed to assess the impact of maintenance on plants safety as well as to evaluate risk-reducing strategies based on the proper choice of maintenance activities and to identify the most effective policies under the technical-economic point of view. The method is based on the integration of reliability estimation techniques, quantitative risk assessment, maintenance planning techniques, and cost-benefits analysis in the framework of a life-cycle based cost-effectiveness analysis.

In greater detail the methodology includes the following steps, which are described in greater detail below:

1. system characterization;
2. definition of accident scenarios;
3. quantitative risk assessment through computation of accident probability of occurrence;
4. sensitivity analysis and ranking of base events;
5. identification of alternative risk reduction strategies;
6. strategies planning and cost estimation;
7. assessment of risk reduction potential of the proposed strategies;
8. cost-benefits ranking of considered strategies;
9. identification of optimal strategy.

System characterization. The system is described in terms of its functional requirements, working logic and physical structure. Process data, drawings and component information are collected. Acquisition of maintenance related data and failure information is carried out. This preliminary information retrieval phase aims at making available all the data required for subsequent reliability, availability and maintainability performance estimation.

Definition of accident scenarios. A preliminary and qualitative risk assessment is performed focusing on the relevant safety-related consequences of possible accidents in order to define credible loss scenarios and select among the many possible top events those requiring an in depth analysis owing to their loss potential. This may be carried out by experienced judgement, historical records, qualitative analysis techniques (i.e. HAZOP or FMECA) or resorting to rough-cut consequence modelling and semiquantitative ranking indices (Khan and Haddara 2003).

Quantitative risk assessment through computation of accident probability of occurrence. Fault tree analysis is utilized to evaluate system's reliability performances and assess the probability of occurrence of any investigated top event. This parameter is assumed in the following as the risk level indicator.

Sensitivity analysis and ranking of base events. The criticality of each base event is assessed resorting to fault tree sensitivity analysis in order to pinpoint the components or events which mainly affect the top event probability of occurrence (Elsayed, 1996). This enables to identify existing problem solving alternatives and effectively deploy corrective measures. In this case the Fussel-Vesely index is adopted which defines the top event frequency variation according to changes in the probability of occurrence of the base events. It is defined as

$$\text{Fussel Vesely Index (A)} = \Sigma_i \, MCS(A)_i \,/\, P_{TE} \qquad (3.37)$$

where P_{TE} is the probability of the top event, $MCS(A)_i$ is the probability of the *i-th* Minimal Cut Set containing base event A. However, other similar parameters such as the Birnbaum or the Criticality index may be utilized as well.

Identification of alternative risk reduction strategies. The possible strategies which could improve the reliability of the system and reduce risk by acting on the critical base events are identified. Actually these strategies relate to three distinct categories.

Type 1 strategy (S1): substitution of critical components with more reliable ones.

Type 2 strategy (S2): structural modifications to the system or changes to the safety systems logic.

Type 3 strategy (S3): adoption of proper maintenance policies (usually different kinds of breakdown repair, inspection policies and preventive maintenance may be feasible according to system characteristics).

Such measures may be applied either singularly or in a combined manner.

Strategies planning and cost estimation. Each of the identified alternative strategies is planned in detail and optimized. Required resources are assessed and their cost is estimated over the plant life cycle.

Assessment of risk reduction potential of the proposed strategies. For each of the single alternative strategies the revised probability of occurrence of the top event is computed, again resorting to fault tree analysis. Thus the global effects of the considered strategies in terms of system's reliability performances and risk reduction may be objectively assessed.

Cost-benefits ranking of considered strategies. An economic analysis and cost-benefits ranking is carried out to compare the effectiveness of the competing options for risk reduction based on a multicriteria technoeconomic performance index.

A Ranking Index RI_i for the generic *i-th* strategy has been defined as

$$RI_i = \frac{\Delta p_i \dfrac{p_i}{p_{max}}}{\sqrt{\dfrac{C_i}{C_{max}}}} \quad (3.38)$$

where Δp_i is the percent reduction in the probability of occurrence of the *i-th* top event after the strategy has been adopted, p_i is the initial top event probability, p_{max} is the probability of occurrence of most probable top event, C_i is the cost of the adopted strategy and C_{max} is the cost of the most costly strategy.

Identification of optimal strategy. Based on the ranking results and the managerial judgement the most cost effective improvement strategy is selected.

According to the adopted RI formulation the ranking is proportional to the percentual amount or risk reduction obtained, weighted by the relevance of the analysed event in respect to the most probable one and by the relative cost of the adopted strategy. However, the risk reduction aspect is given a prioritary role respect the cost minimization issue. Nevertheless different ranking criteria may be adopted to suit specific needs or different analysis perspectives.

After the risk reduction potential and the life-cycle cost of each strategy has been computed, the ranking index thus enables a comparative evaluation in relative terms of their cost effectiveness, in order to point out the option which shows the better trade off between relative risk level associated to each top event, the risk reduction potential of each strategy and the relative cost of each strategy. This comparison can be carried out at the single top event level to evaluate if a maintenance strategy is to be preferred to a system redesign strategy or which kind of maintenance strategy is to be preferred among several competing maintenance option. In this manner the best way to reduce the risk of a given top event may be assessed. At the system level, instead, the rating comparison may help in deciding which is the top event which can be acted upon with the higher cost effectiveness.

The described approach enables to focus maintenance planners attention on the components and failures which are most likely causes of relevant accidents and to identify the most cost-effective mix of plant modification and inspection/maintenance activities which may better reduce the system risk level and consequences of failures, both economic and safety related.

It should be therefore pointed out that respect traditional RBM methods the one proposed here has the advantage of adopting a fully quantitative perspective and of relying as much as possible on parameters which can be objectively assessed. This justifies the assumption of ranking risk on the basis of the sole probability of occurrence, with no explicit evaluation of the magnitude of consequences. In fact consequences of an accident are much more difficult to estimate, may extend to very different realms (financial and property loss, personal damage, environment) being often vaguely defined or contradictorily judged by the parties involved (plant owners, population, government, administrative and regulatory bodies, etc.). However, in case an objective assessment of the consequences can be obtained, this may be easily incorporated in this methodology either as an additional criterion to select the top events to be analysed, or by including a consequence reduction potential term in the ranking index expression.

Furthermore, this method does not focus the maintenance planner attention on the most critical plant components only, but also enables the cost effectiveness of maintenance strategies to be assessed, even in comparison with other viable options for risk reduction.

3.4.5 Application Example

A simplified example is discussed hereafter in order to show a practical application of the method. An industrial plant is considered where a high purity aromatic hydrocarbon (HC) is required for process purposes. The considered HC (1,2,4-Trimethylbenzene, chemical formula $C_6H_3(CH_3)_3$, CAS number 95-63-6) is toxic and flammable, thus posing hazards to process safety and operators health. Owing to space limitations the methodology is here exemplified by only briefly describing each of the application steps.

System Characterization

The purification plant shown in Figure 1 includes a stripping column C-300 where a nitrogen flow is utilized to remove at atmospheric pressure water traces and remaining gaseous pollutants from the liquid HC stream. The HC fed by pump P-300 is filtered in the strainer F-301, heated to 30 °C in the hot oil exchanger E-302, and finally enters into column top where it descends in countercurrent with a nitrogen stream, fed through strainer F-302, to be recovered at column bottom, discharged by pump P-301, and further cooled to ambient temperature in the exchanger E-301 before exiting the purification plant. Saturated nitrogen vapors containing dissolved impurities are conveyed through a vent line with a check valve to an external adsorption plant. The control instrumentation includes measurement of nitrogen flowrate in C-300 (with high and low values alarm), HC level in C-300 (with a high level alarm), and temperature sensors in C-300, E-301, E-302 including high temperature alarms. Main measurement instruments and alarms are integrated by a digital control system. After fully characterizing the process flow, all necessary information about the control system working logic and components reliability and maintainability data have been also collected.

Definition of Accident Scenarios

It is assumed that a preliminary risk assessment based on qualitative techniques (HAZOP and FMECA) has been performed in order to identify critical top events. For the sake of this example only the two top events considered to be the most critical ones are analysed, namely Top Event #1 (TE1): release of liquid HC, and Top Event #2 (TE2): overpressure in process vessels. TE1 implies risk to human operators exposed to contact with liquid HC or inhalation of its vapors, and fire hazards. TE2 may imply propagation of malfunctionments in other plants sections, although catastrophic failure of equipment is highly unlikely as all vessels are equipped with rupture disks opening at 0.49 bar_g. Other possible events like the leakage of liquid HC in the gas venting line and indoor nitrogen leakage or discharge have been judged much less relevant from a risk standpoint.

Quantitative Risk Assessment

As far as TE1 is concerned release may occur in all plant sections in correspondence to piping flanges and welded joints. Excess liquid levels in vessels may occur in case of failure of the level monitoring devices and the emergency shutdown procedure.

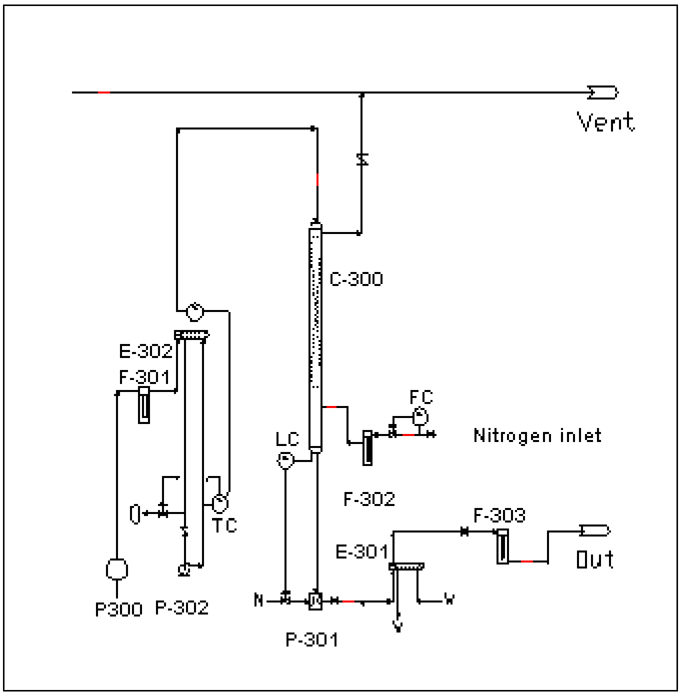

Figure 3.15 Scheme of nitrogen stripping unit

A fault tree analysis was carried out for this top event obtaining the results shown in Table 3.6. The analysis is made over the foreseen 10 years life span of the plant.

Table 3.6 Analysis results for TE1

Probability of occurrence (t= 10 years)	# of expected events ($year^{-1}$)	MTBF (years)
0.081	2.41 10^{-2}	41
Criticality analysis results		
Component	Fussel-Vesely index	
Valves flanges	0.08 ÷ 0.12	

As far as TE2 is concerned, in the stripping section the overpressure may be caused by failure of the mass flows controls or by flow obstructions (failure close of valves, filter clogging, etc.) and, in absence of the control operator intervention, by the failure of emergency shut-down system. In particular, a pressure build up may occur if the check valve on the nitrogen discharge line from the column to the vent header fails closed. Furthermore, no pressure sensing device is installed in the column and possible pressure increase are sensed indirectly from flow or level sensors in this plant or from pressure sensors located in other adjoining plants connected to the one under examination. In particular the pressure of the nitrogen supply line (4 bar) may be reached. Even if this may not cause direct damage to the stripping column and related piping (rated at 8 and 16 bar respectively) the overpressure may be transmitted upstream to other process units according to the specific operating mode and the status of the valves sectioning the different plant units. The results of fault tree analysis are shown in Table 3.7.

Table 3.7 Analysis Results for TE2

Probability of occurrence (t= 10 years)	expected events (year^{-1})	MTBF (years)
0.010	3.15 10^{-3}	317

Criticality analysis results

Component	Fussel-Vesely index
Vent line check valve	1
Nitrogen flow controller	1
C-300 Level controller	0.77
HC filter F-303 (obstruction)	0.29
Human error (no intervention)	0.18

Sensitivity Analysis and Ranking of Base Events

Tables 3.6 and 3.7 also show for TE1 and TE2 respectively the most critical base events or components as identified in the sensitivity analysis according to the value of the Fussel Vesely Index. For TE1 the most critical base events resulted the leaking flanged joints of the control valves.

In case of TE2, instead, the failure of the shut-down control system resulted far more critical than that of piping components. Therefore, modifications to the control system logic seem required. In particular, failure of the nitrogen flow controller resulted having a criticality of 1 meaning that a given percentage variation of the probability of occurrence of this failure immediately reflects in the same percentage variation of the probability of the top event. The same occurs for the blockage of the check valve installed on the connection to the vent line.

Identification of Alternative Risk Reduction Strategies

In order to reduce the TE1 probability, a substitution of critical components or planning a maintenance schedule are hypothesized. Strategies involving a redesign of the control system logic or the process scheme (type S2) are not found to be applicable in this case. The following strategies are thus considered.
Strategy S1: substitution of current flanged couplings with others having improved fittings and gaskets in order to obtaining a 10% increase in reliability.
Strategy S3a: preventive maintenance with inspection of all flanged and welded joints. Joints showing degraded performances are substituted and tested.
Strategy S3b: includes installation of HC leakage sensors on highest risk flanges to have a timely alarm, and breakdown maintenance to substitute leaking joints.
Passing to TE2 the considered strategies in this case are the following.
Strategy S1: substitution of critical components with others having a reliability 10% higher (except filter).
Strategy S2a: installation of a pressure sensor inside C-300 in order to directly trigger an alarm or the emergency shutdown.
Strategy S2b: installation of a bypass with check valve on the nitrogen discharge pipe from C-300. The installation of a second check valve in parallel enables to avoid blockage of nitrogen flow in case of failure of the existing valve.
Strategy S3: preventive maintenance on nitrogen discharge check valve, filter F-303, and flow rate and HC level controllers.

Strategies Planning and Cost Estimation

Referring to TE1 a cost estimation has been performed to improve hardware reliability referring to strategy S1, while for strategy S3a preventive maintenance plan has been developed with inspection at 12 months intervals of all flanged and welded joints resorting to visual inspection, non destructive testing and checking with PC leakage sensors. Degraded joints are substituted and tested with average estimated time for an inspection cycle of 48 hrs. The expected cost of strategy S3a over the foreseen 10 years life span of the plant has been computed as 106500 €.

Strategy S3b has been also planned to include installation of 16 HC leakage sensors on those flanges identified to be at higher risk in order to have a timely alarm in case of HC release. Breakdown maintenance to substitute leaking joints has been assumed as having a MTTR of 24 hrs in order to verify resources capacity and downtime costs. However, life-cycle cost of S3b resulted higher than S3a owing to the added sensors investment and related maintenance.

As far as TE2 is considered the pursuit of strategy S2a (installation of a pressure sensor inside C-300) involves a foreseen installation cost of € 1500, while strategy S2b (installation of a second check valve) has an estimated cost of € 2900. Similarly the cost of executing strategy S1 has been also computed. Passing to strategy S3 a preventive maintenance on nitrogen discharge check valve has been planned at 24 months intervals, while at 12 months intervals that of filter F-303, flow rate and PC level controllers. Cost of strategy S3 has been estimated as being much higher than that of type S2 strategies.

Assessment of Risk Reduction Potential of the Proposed Strategies

Concerning TE1, the effect of the three strategies is shown in Table 3.8 in terms of top event probability reduction. The best strategy from the risk reduction perspective is the inspection + preventive maintenance (S3a) which has a potential for decreasing the original failure probability of nearly 85% respect about 30% of the alternative maintenance policy S3b and only 3% of the hardware substitution approach S1.

Table 3.8 Effects of risk reduction strategies for TE1

STRATEGY	Probability (t=10 years)	% probability reduction
S1:Gaskets substitution	0.079	3
S3a:Periodic inspection + preventive maintenance	0.012	84.6
S3b: Continuous monitoring + breakdown maintenance	0.057	29.4

Referring instead to TE2, as shown by the results of Table 3.9, in this case the best risk reduction strategy involves a modification of the system architecture and working logic. In fact a combination of S2a and S2b yields a 99.9 percent reduction of TE2 probability. Nevertheless roughly similar results are obtained with a maintenance policy, while a S1 type strategy in this case too performs unsatisfactorily by reducing accident probability less than 20% only.

Table 3.9 Effects of risk reduction strategies for TE2

STRATEGY	Probability (t=10 years)	% probability reduction
S1: Components substitution	0.008	18.4
S2a:. Installation of pressure sensor in C-300	$3.9\ 10^{-4}$	96.3
S2b: New line to vent duct bypassing check valve (two check valves in parallel)	$3.6\ 10^{-4}$	96.0
S2a+b: Combination of strategies	$1.3\ 10^{-5}$	99.9
S3: Inspection and preventive maintenance	$3.6\ 10^{-4}$	96.0
S1+S3: Combination of strategies	$2.9\ 10^{-4}$	97.3

Cost-Benefits Ranking of Considered Strategies

Referring to TE1 in this simplified example the S3a strategy is clearly preferred as it has a higher risk reducing potential but is also economically more effective than S3b as the cost of installing and maintaining a large number of leakage sensors is avoided.

Considering TE2, both S2a and S2b abate the top event probability with very low expenditures. If both are pursued the net probability reduction is of 99.9% at a very reasonable cost of 4.400 €. Strategy S1 instead is a poor performer as it reduces much less significantly the probability of top event occurrence and bears relevant spending for the improved components. In this case too preventive maintenance performs very satisfactorily, in a similar manner than S2 strategies but at a much higher costs, therefore in this case it is not cost effective. The same holds for a combination of strategies S1 and S3, with better results than S2a or S2b but worst than S2a+b and at a higher cost. It follows that in this case the preferred strategy is S2a+b.

Identification of Optimal Strategy

As far as the ranking index is concerned, in this example it is unnecessary its utilization at the top event level because it is straightforward to identify the most cost effective strategy. However, in case of a comparison between TE1 and TE2, it can suggest which is the one showing the better trade off among the cost of the required risk reduction strategy and the obtained results. In this case for TE1 it results $RI_1 = 84.6$, while for TE2 the value is $RI_2 = 60.7$.

Therefore, being the risk reduction potential roughly similar for the two top events (84.6 vs 99.9 %), precedence is given to the top event having the higher relative probability even if a comparatively quite higher risk reduction cost follows.

Relying on this kind of information the management can make informed decision and effectively include risk reduction criteria in maintenance planning.
This shows the potential of systematically adopting quantitative risk analyses integrated with managerial decisions based on cost-benefits analysis in order to provide the best guidelines when choosing the maintenance approach in safety enhancement programs for high risk industrial plants.

3.4.6 Conclusion

Risk-Based Maintenance planning is a rapidly spreading practice trying to integrate reliability issues with safety concerns to minimize probability and consequences of system failures. To cope with some limitations of current approaches which do not account for risk on a quantitative basis or do not assess the cost effectiveness of maintenance policies, nor consider alternative risk reduction strategies, a general purpose methodological approach has been proposed. The methodology includes: quantification of top events resorting to fault trees, a sensitivity analysis of the probability of occurrence of top events to identify system's criticalities, the definition of possible improvement strategies including but, for sake of comparison, not limited to maintenance strategies. Finally a multicriteria ranking is provided to assist plant managers in selecting the most effective strategy. As such the proposed methodology provides quantified information for decision-makers to select the best course of actions when planning risk-based maintenance tasks to improve system safety.

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3.5 The Use of Dynamic Object Oriented Bayesian Networks in Reliability Assessment: a Case Study

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Abstract. In the last years dedicated tools, based on probabilistic models, have been applied to production processes, machine and plant to assess their performance. A Bayesian Network (BN) can be defined as a robust graphic formalism that can be easily fit to complex systems characterized by uncertainty. It manages uncertainty through the analysis of the interactions between causes and effects and, thanks to their high level of adaptability, it can be used in different and various types of applications. An useful methodology and application of BNs, in the diagnostics and simulation fields, are the Dynamic Object Oriented Bayesian Networks (DOOBNs). They can be considered as a development of the OOBNs, because they add to a static approach the "dynamic" time parameter. DOOBNs are based on a functional and hierarchical decomposition of complex systems, represented like a tree, and on a variables' classification related to a single task. In the present case study, the DOOBNs are applied to a facility plant, a compressed air production group. The aim of the present study is to evaluate the reliability of the service plan and the impact on it of several decisions regarding the management of maintenance policies. First, we made a model of the system, then we assigned the parameters to be used basing on the analysis of data, collected during some years of operation and maintenance. Then we conducted the analysis, collecting and analyzing the results.

3.5.1 Introduction

The great complexity of many systems returns the necessity to use new methodologies and tools to support decision-making processes, in order to increase the efficiency and the efficacy of the engaged actions.

Moreover, decisions can be taken without a perfect perception of state of the system and without essential information, due to uncertainty. Therefore, probabilistic methodologies are often used.

Bayesian Networks, coming from Artificial Intelligence methods, can be used as decisions aiding systems, assessing values of the main process performance parameters.

3.5.2 Problem Statement

Complex systems management often implies a great uncertainty about the prediction of the operating status.

As well as the items' number, also the possible system configurations grow in quantity. For instance, a n-items system can assume 2^n possible states.

The configuration prediction, made with Markov Chains, might be very complicated because the difficulty level rises with the system complexity.

In order to solve the problem by means of Markov Chains, a simplifying hypothesis might be not considering simultaneous failures. In such a way the number of possible states decreases from 2^n to n.

Moreover, to have a greater simplification it could be supposed the stochastic independence of the events.

Instead of Markov Chains, the Petri Nets or the Monte Carlo method might be used. These techniques, unfortunately, need many simulation histories if the probabilities to be evaluated are very small.

The dynamic object oriented Bayesian Networks (DOOBNs) are a methodology, based on Bayesian networks, which doesn't require neither the Markov Chains' simplifying hypothesis nor the Monte Carlo method.

3.5.3 Theory Used to Solve

The Bayesian networks are directed acyclic graphs (often referred as DAGs), used to represent the uncertainty in artificial intelligence systems.

If we define two events A and B, it could be possible to introduce the following definitions:

P(A): unconditioned probability of A, also called *a-priori;*

P(A|B): conditioned probability of A, given B as true (B is the conditioning event);

P(A, B): joined probability of having simultaneously the A and B events

The Bayes theorem, can be deduced from the three following axioms:

$$0 \le P(A) \le 1 \tag{3.39}$$

$$P(\text{true}) = 1 \quad ; \quad P(\text{false}) = 0 \tag{3.40}$$

$$P(A \vee B) = P(A) + P(B) - P(A \wedge B) \tag{3.41}$$

and from the product rule:

$$P(A \wedge B) = P(A \mid B)P(B) = P(B \mid A)P(A) \tag{3.42}$$

The Bayes theorem comes as follows:

$$P(B \mid A) = \frac{P(A \mid B)P(B)}{P(A)} \tag{3.43}$$

Syntaxes and Semantics in Bayesian Networks

A Bayesian network is defined by a couple (G=((N,A),P), where (N, A) represent respectively the set of nodes and the set of arcs. P is the discrete probabilities distribution associated to each node.

The parents of a node are defined as the set of nodes pointing to that node.

The "root" nodes are all the ones which don't have parents (C and D in Figure 3.16).

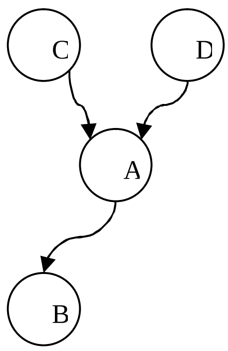

Figure 3.16 a simple BN

The "leaf" nodes are all those which don't have any child; they don't have any causal influence on any other node.

For every node which has parents, the P distribution is a conditional probability function determining the stochastic dependency of a node with its parents. For every child there must be at least one parent.

If $(n_i, n_j) \in A$, that is there's an arc connecting i to j, and $(n_j, n_i) \notin A$, then n_i is considered as a parent of n_j. A conventional indication of the set of parents of n_j is $Pa(n_j)$.

Let us define X a casual variable with M values, associated to the node $n \in N$ (where N is the set of the net's nodes). The possible M states of n, mutually exclusive, might be defined by the vector $S_n : \{S_1^n, \ldots, S_M^n\}$. For every state of n there is a corresponding X value.

It's now possible to define the π(n) vector, representing the probability of everyone of the M states of n

$$\pi(n)=[\ \pi(S_1),\ \ldots,\ \pi(S_M)] \tag{3.44}$$

$$\text{where } \sum_{k=1}^{M} \pi(Sk) = 1 \tag{3.45}$$

The P set, that is the group of joined probabilities characterizing a node, is described by the conditional probabilities table (called CPT). For every node there's a CPT. For instance, in the previous example the CPT of A might be as follows.

		A	A*
C	D	80%	20%
	D*	30%	70%
C*	D	55%	45%
	D*	23%	77%

Figure 3.17 the CPT of A

In the previous picture, the asterisk means the opposite event.

The CPT of the root nodes are simple, since they have only the *a-priori* probabilities of the event.

C	C*
75%	25%

Figure 3.18 the CPT of C

The conditioned probability values, filling the CPTs of every node, come from the information and knowledge of the observed system. As the knowledge increase, consequently the CPTs redaction is more precise.

A Bayesian network is then able to represent and describe a system with a complexity level depending on n, while with Markov chains it depends on 2^n.

The Bayesian network's nodes are the variables, the arcs are the dependence relationships and the CPTs define quantitatively the values of them.

Thanks to the Bayesian network, it is possible to model graphically and analytically, by means of the conditional probability, the dependence within the system variables.

A possible procedure to build a Bayesian network is the following:

Let us choose a set of N elements n_i. These n_i are the nodes of the net. A random variable X_i is associated with each one of them. The whole of all the X_n constitutes the net domain.

Then we choose a hierarchical sorting of the variables, roots, nodes and leaves.

For every item:

- a new node, n_i, is added to the net
- for every node n_i, the corresponding set of parents $pa(n_i)$ must satisfy the conditional independence property.

A conditional probability table is then defined for every node.

The present technique grants the building of an acyclic net, because every node is linked to some of the previously inserted nodes.

In the following figure, there's a simple and well-known example of Bayesian network.

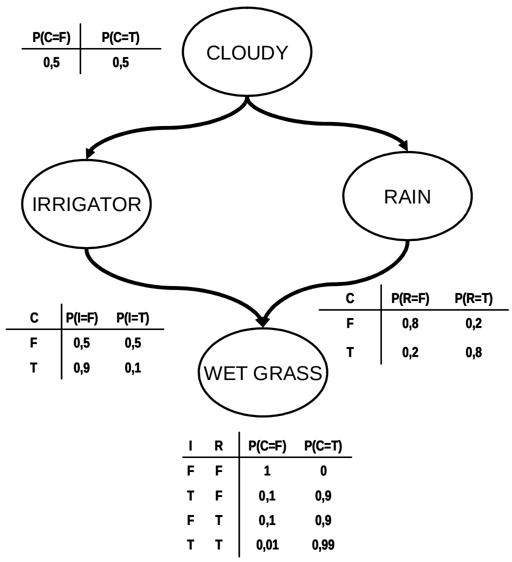

Figure 3.19 a BN for a wet grass

In the complete Bayesian network, are shown both the root nodes probabilities and the conditional probabilities constituting the CPT tables of the son nodes.

Bayesian Nets Inference

The statistical inference is the capability of forecasting an event, basing on observations. In the Bayesian networks, the inference permits to evaluate the probability of the states of some interesting nodes, thanks to the observation of some other nodes. If it wasn't possible to make any observation, the probability estimate of the interesting nodes might be made on the basis of the *a-priori* probabilities' knowledge of the sole root nodes.

Any information coming out from an observation may be formalized as a strong or weak evidence.

A strong evidence of the X random variable indicates that the $n \in N$ node is undoubtedly in one of the possible states $S_n : \{S_1^n, \ldots, S_M^n\}$.

A weak evidence is when the knowledge is not certain. It is a new value for the root nodes probabilities. A weak evidence of a node "n" permits to update the *a-priori* probability values for the possible states of "n".

By means of observations, in the Bayesian networks, it is possible to have four kinds of inference:

- diagnostic inference (from the effects to the causes);
- causal inference (from the cause to the effects);
- intercausal inference (among common causes of an affect); and
- mixed inference (a combination of the previous).

The inference process is gained thanks to an algorithm able to update the probabilities of the net nodes, after having assigned a status to some variables as a result of an observation.

The solution research in an inference process may lead to long calculation with great response times, even in small nets. For such a reason some fast solving algorithms have been developed, though with some approximations.

The most commonly used algorithm are:

Variation method, where the nodes are decoupled and a new parameter is introduced in order to evaluate the inference;

Methods sampling, which uses the Monte Carlo method in order to increase the weights of the observations basing on their probabilities.

Belief propagation cycle, using the Pearl algorithm

Junction tree, the most used algorithm.

Dynamic Nets

Some Bayesian networks are called "dynamic". They are characterized by the CPTs with time dependent functions instead of constant values.

From the operating point of view, there are two possible solutions.

The first one is called "time dependent arc" where a variable is represented by means of two nodes. The first one symbolizes the time step previous to the one under investigation. This latter is represented in the second node. The first node behaves like a buffer where is possible to store the antecedent value to be modified by the time step.

The second solution is called "time dependent node" and for every node state a time dependent "government function" is defined. This solution is less flexible because it can model only a single kind of time based variation.

On the other side, the “time dependent arc” system requires the analytical introduction of the probability government equations.

If we consider system made of many variables, their implementation within Bayesian networks models might be a complex task. Anyway this hard implementation is a different thing as regards the solution difficulty of other methods.

In order to solve this aspect, a new peculiar kind of Bayesian networks has been defined, called Object Oriented Bayesian Networks (OOBNs). An OOBN is a net that, beyond the previously described nodes, contains some link nodes, called *instance nodes* whose function is to connect with each other some portions of a bigger net. In such a way it is possible to represent a complex network as a series of small ones that can be managed, joined by the instance nodes.

The modelling is based on the breaking down of the network structure in hierarchical levels. The overall function is split into sub-functions and basic functions, often referred as elementary functions EF.

Every function represents a productive process of the system. For each EF we can locate three basic elements:

HD, *Having to Do*, the function objectives.

AD, *Being Able to Do*, the input flow required for the correct performance of the function.

RHD, *Report of Having to Do*, the output flow of the function.

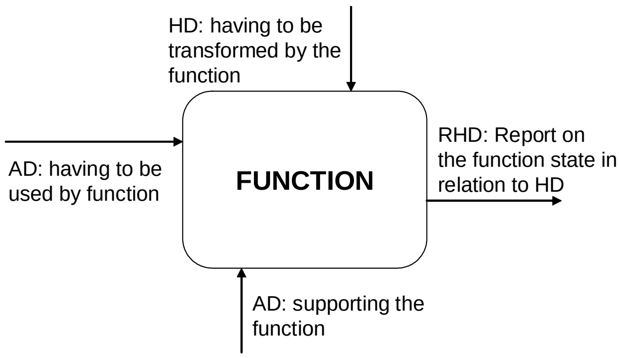

Figure 3.20 functional breaking down

The RHD flow is then transferred to an input of the following function.

This representation permits to decentralize and to structure the knowledge with little dimension Bayesian networks. And thanks to this simplification, the object oriented Bayesian networks are easily used to model industrial systems.

Moreover, the structured model can be used in a simulator, where every LRU is easily broken down in elementary functions and the instance nodes simplify the resulting net diagram.

As already seen with the dynamic Bayesian networks, also the object oriented ones have their corresponding dynamic model, called DOOBN (dynamic object oriented Bayesian network). The difference between the two types is that the first one uses static models while the second one a dynamic approach.

The static models are suitable to make diagnoses. As a matter of fact, known the model structure, from the observation of some variables (the alarms, for instance) we can get the probability of every cause.

The dynamic models are suitable for the real-time simulation because, starting from the government equations, it is possible to reach the time functions of some variables.

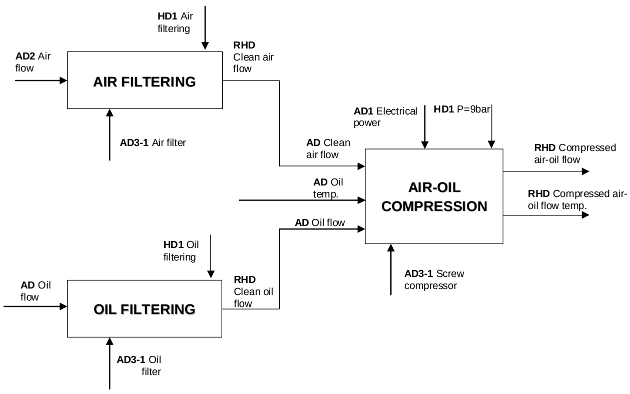

Figure 3.21 an example of breaking down

Building up a Dynamic Bayesian Network for an Elementary Function

Once that the system has been split into simple elements and joined elementary functions, the building of the net is quite simple.

Let us consider the following example:

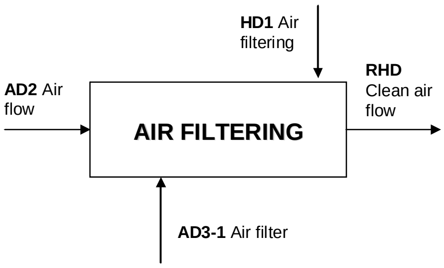

Figure 3.22 air filtering

The elementary function is the air filtering. The supported fluxes are:

AD2 air flow: in order to have a filtering, the air must be present in the plant.

AD3-1 Air filter: the filtering performance will depend directly on the filter status. Besides, its functional status in time dependent, with a failure probability density function *f(t)* distributed as a normal.

RHD air flow, is the treated flow. It derives directly from the presence of inlet air and from the filter status. It might be seen as an “and” gate between the AD2 and AD3-1 elements.

The key factor of the breaking down is the air filter. Its good representation is necessary for a consistent network model.

The use of the time dependent arc or of the time dependent node will be chosen depending on the precision or easiness level required.

In the following picture is shown the net built with the time dependent node.

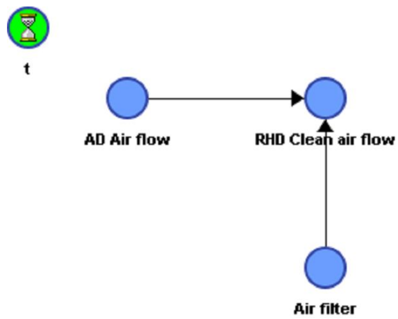

Figure 3.23 DBN for the air filtering EF

Once built the network and defined the nodes CPTs, it is possible to use the inference to evaluate the reliability of the elementary function air filtering.

3.5.4 Modelling Approach

The software used to model the case study is Bayesialab® which showed its flexibility and power in managing Bayesian networks.

In this section the methodologies, used in order to model the maintenance operations for mechanical equipments, will be shown.

For every item of the case study an individual planned maintenance strategy was chosen. This means that besides the times of intervention, also the typology of maintenance must be defined.

There are two limit maintenance cases: the "perfect repair" and the "minimal repair". In the first case the component is considered to be as good as new, that is to say its failure rate is the same of a new item. This goal is usually achieved by means of a substitution. The minimal repair, on the contrary, leaves an item, after its preventive maintenance operations, as bad as old. In other words, the failure rate doesn't decrease. This kind of operations are cheaper but don't improve the system from a reliability point of view.

There is also an intermediate situation called "defective repair" with some reduction of the item failure rate.

Another strategy is the no preventive maintenance option, applied for those cases in which there wouldn't be enough benefits compared with the problems and costs of any intervention made before the failure.

In the following picture the possible scenarios are shown.

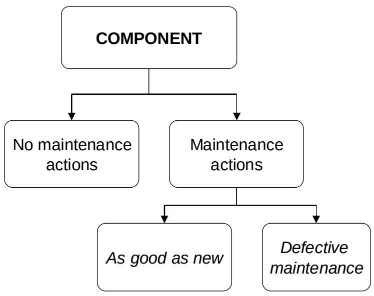

Figure 3.24 possible maintenance choices

Everyone of the three types of maintenance previously described requires its own moulding in a Bayesian network.

Item without Maintenance

The modelling of such items has been made with the use of government equations (hence with the time dependent node), whose reliability function is a decreasing function, as shown in the following picture, where is plotted the reliability of the heat exchanger. For this item no preventive maintenance is made while the failure probability density function is distributed as a Normal.

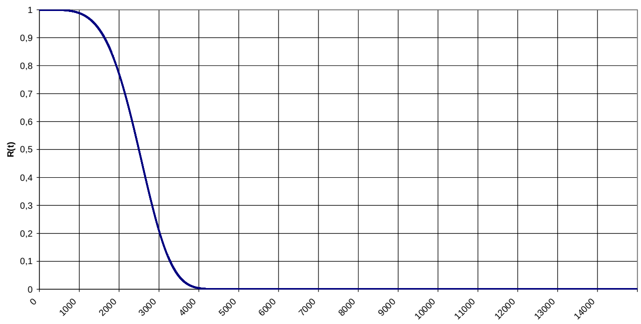

Figure 3.25 no maintenance

The results of reliability calculation in this Bayesian network model are exactly as the theoretical function should be.

Item with Perfect Repair

This kind of maintenance has been modelled following time based interventions, as required from the scheduled maintenance plan. In the object oriented Bayesian network, the node of the item restores its reliability to 100% every time that a maintenance operation is held, with a time step T_1. In that moment it's sure that the item is properly working. The R(t) is the same within every T_1 period.

The analytical expression of the reliability, in the dynamic Bayesian network, is as follows:

$$R(t) = e^{-\lambda \cdot \left[t - \text{int}\left(\frac{t}{T_1} \right) \cdot T_1 \right]} \tag{3.46}$$

where the $t - \text{int}\left(\frac{t}{T_1} \right) \cdot T_1$ factor is introduced to describe the recurrence.

In the following picture the reliability of an item with a perfect maintenance strategy is plotted. The maintenance actions are made every 2500 time units.

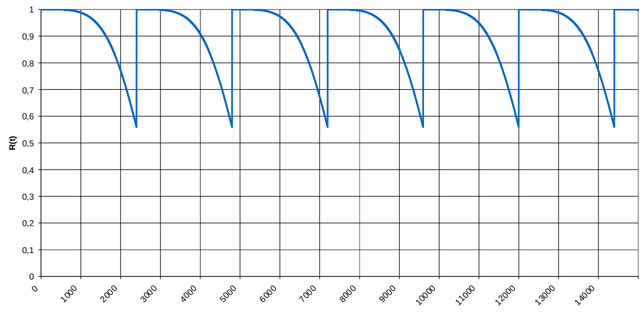

Figure 3.26 perfect repair

Item with Defective Repair

In a plant there are many items that are maintained with servicing or cleaning actions. In such cases the failure rate may decrease, but won't become as low as it was when the unit was new.

In order to represent defective repair inside a DOOBN, another node is required. It must acquire distinct values as the time goes by.

In the following picture the result of a reliability evaluation is shown.

As clearly visible, every time that a maintenance operation occurs, the reliability becomes 100% but, this time, its decrease becomes faster as the item gets old.

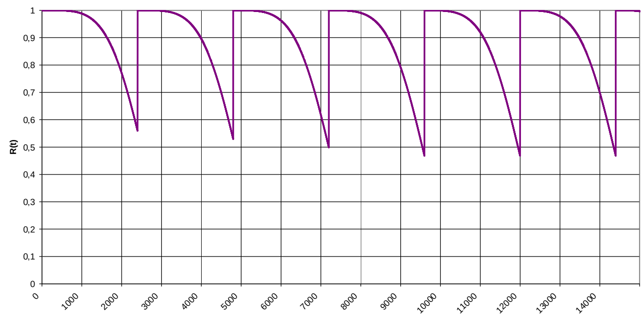

Figure 3.27 defective repair

The air filter has been modelled as an item with defective repair and its visual aspect inside a DBN is shown in the following image.

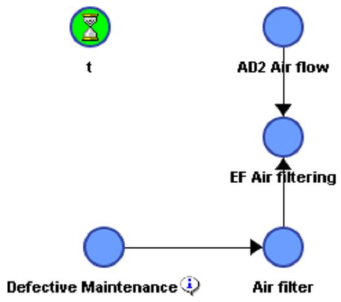

Figure 3.28 DBN for defective repair

The *defective maintenance* node function is to rule the maintenance actions, moving from level 0, level 1 and level 2 (three defective maintenance) towards a fourth perfect maintenance, with a new component.

The defective maintenance is modeled adding operating hours to the item. It acts as if after every preventive maintenance operation, the used unit is replaced with a younger one, but not with a new one.

The *defective maintenance* node has as many values as the maintenance levels.

The next node to be modelled is the *air filter* with as many government equations as the number of maintenance levels.

The air filter output values are the item reliability, varying continuously from 1 to 0.

Now let us consider two nodes, A and B (see Figure 3.29), to show how we can model an item with defective repair.

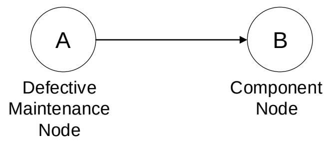

Figure 3.29 Nodes A and B

Node A is the *defective maintenance* node and it can assume, for example, three different states (0, 1, 2) depending on the time variable. They represent the three different maintenance levels that characterize the component B. In Figure 3.30 the logic condition, that rule the defective maintenance node, are shown.

$$P(A \mid t) = \text{if} \begin{pmatrix} 0<t<T0 \\ T0<t<T1 \\ T1<t<T2 \end{pmatrix} \text{then} \begin{pmatrix} A=0 \\ A=1 \\ A=2 \end{pmatrix}$$

Figure 3.30 Logic conditions of the defective maintenance node

Node B is the component node. It can assume two different states (true and false) depending on A’s state; they are ruled each one by three different equations. In Figure 3.31 are shown the logic conditions that govern the air filter node used to evaluate the reliability R(t) in the different time steps.

$$P(B \mid A, t) = \text{if} \begin{pmatrix} A=0 \\ A=0 \\ A=1 \\ A=1 \\ A=2 \\ A=2 \end{pmatrix} \text{then} \begin{pmatrix} B(true)=R_{T0}(t) \\ B(false)=F_{T0}(t) \\ B(true)=R_{T1}(t) \\ B(false)=F_{T1}(t) \\ B(true)=R_{T2}(t) \\ B(false)=F_{T2}(t) \end{pmatrix}$$

Figure 3.31 Logic condition of component node

3.5.5 Application

The plant studied is a compressed air production system.

The first step was the separation of the plant into two functional units: the oil and the air section. The reliability critical items selection had already been made in previous works.

Three main plant functions have been defined:

- Mixture compression
- Mixture treatment
- Air treatment

Each one has subsequently been split into elementary functions, as seen for the object oriented networks.

In Figure 3.32 is shown the higher level of the system decomposition, with the three function above described.

Not every elementary function is described. The choice depends on the failure rates: as lower they are as lower is their influence in the overall reliability. For instance, the oil filtering EF wasn't inserted in the model. The data necessary for this distinction have been deduced by the maintenance database.

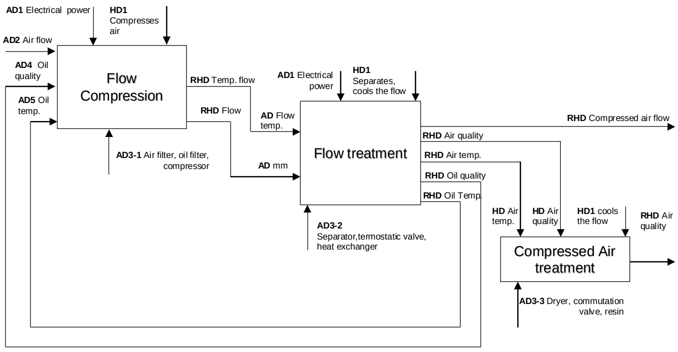

Figure 3.32 the system studied

After this step, all the functions and the EFs have been linked to obtain the whole system.

Some nodes, representing the output variables of the system, have been added. For instance the air flow quality "Qa" is divided in two variables: oil presence, air presence. In such a way, the two main pollutants of the compressed air are highlighted, since they are caused by different events.

The corresponding DOOBN is shown in the following picture.

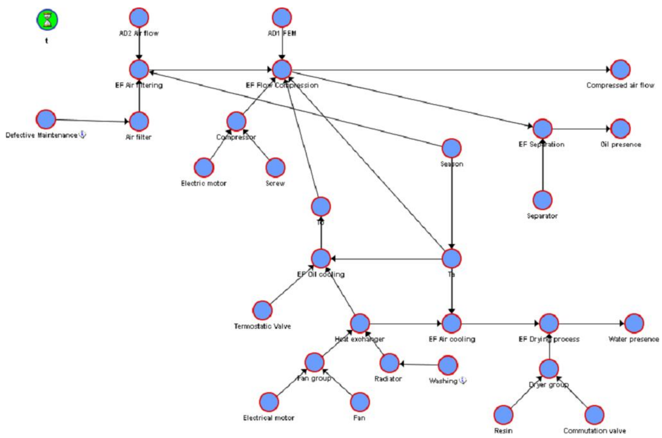

Figure 3.33 the network

This is the full representation of the system.

As clearly visible, the graphical way is very helpful to understand the system functions and the relationships among the nodes

3.5.6 Result and Conclusions

The Bayesian network used for the analysis of the air system has required a single calculation and not many simulation runs. A very important role is played by the time window set for the calculation. In our study a 32.000 hours time (5 years and 6 months) was chosen. This was made in order to compare the results with the real maintenance plan. A general maintenance with the substitution of all the items is held every 29.000 hours, after which the plant may be considered as good as new.

The system performance has been analyzed from two different points of view:

- the compressed air flow; and
- the compressed air quality

The latter has been split into two more nodes:

- compressed air with condensate; and
- compressed air with oil

Each one of these can assume one of three possible values. For the air flow there are:

- regular compressed air flow;
- regular compressed air flow with temperature rising; and
- no flow.

For the compressed air with condensate there are:

- no water;
- small quantity of water; and
- great quantity of water.

For the compressed air with oil there are:

- no oil;
- small quantity of oil; and
- great quantity of oil.

In the following picture the probabilities of these events is shown: regular compressed air flow, no water and no oil.

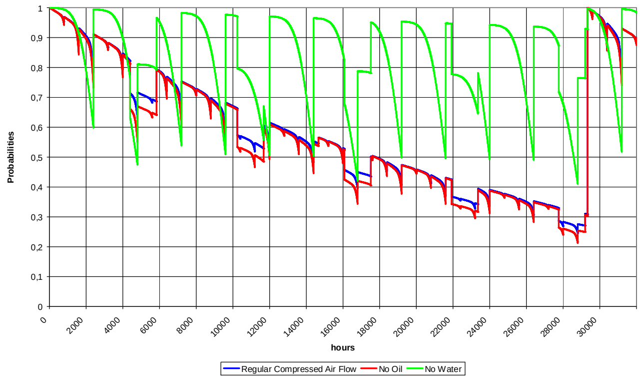

Figure 3.34 probabilities of correct operations

The effects of maintenance actions are clearly visible as discontinuity points.

As better visible in Figure 3.33, there are two different trends: the one of the “regular air flow” and the “no oil” and the one of the “no water” event.

The reason of this difference resides in the failure causes, similar for the first two nodes and different for the third one.

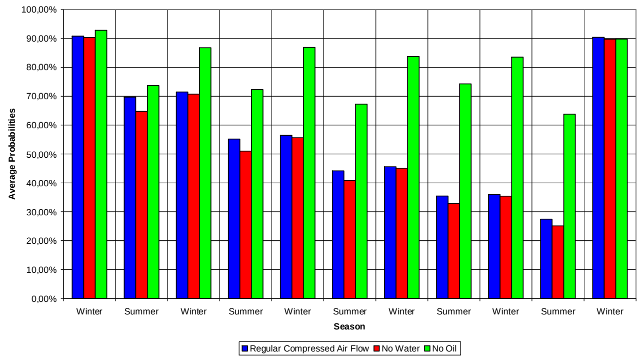

Figure 3.35 average probabilities of correct operations

The histograms show also the difference of probabilities between cold and hot seasons. Actually, the system works with different reliability performance in winter and in summer time.

As a conclusion, in this work a new approach to the perfect maintenance was presented. The time dependent node (with its government equation) was used instead of the time dependent arc. The benefit is the capability of representing many probability functions and not only the exponential one.

Another interesting result is the modelling of the defective maintenance instead of the perfect type. This permits to the net to be more tight to many real maintenance tasks.

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4 Maintenance Management and Organization

Sara A. McComb

4.1 Introduction

Maintenance management is a relatively new field and the corresponding body of knowledge is continuing to grow (Visser, 2002). For example, in Europe, two technical committees of the Comité Européen de Normalisation (CEN) are currently adding to the body of knowledge terminologies, guidance to prepare agreements, control systems for maintenance management, and other development directions (CEN, 2008). In particular, CEN Technical Committee 319 deals specifically with maintenance. They have published one standard (EN 15341) that provides maintenance management with the support of a control system (made up from more than 70 indicators) to achieve maintenance excellence and to competitively use technical assets, regardless of industry. Moreover, this committee has been addressing the issues of defining a maintenance management general framework (including buildings) through a standard currently in progress and identifying three very promising development directions (i.e., responsibilities in maintenance; identification, classification, and costs in maintenance actions; and maintenance in the healthcare industry).

In this section, we add to the body of knowledge about maintenance management by presenting several case studies and methodological approaches that highlight the maintenance management and organizational issues faced by companies attempting to improve their maintenance management systems. We first examine three different systematic approaches to maintenance management. The first represents philosophical approaches to maintenance management (Duraccio *et al.*). The next two provide insight into day-to-day maintenance management activities through their descriptions of monitoring systems (Fornasiero *et al.*) and control systems (De Virgilio). This section ends with a paper describing an approach to evaluate and/or simulate various maintenance policies to ascertain their relative effectiveness (Guizzi *et al.*). Each of these papers is introduced in the following paragraphs.

The first paper (Duraccio, Falcone, and Silvestri) applies the total productive maintenance (TPM) approach to an automotive component supplier. Through their critical examination of an injection molding machine, Duraccio and colleagues describe how the TPM process is measured and implemented. They explain how three levels of maintenance are undertaken by the machine operator, the maintenance staff, and the machine manufacturer, respectively. The most novel aspect of this approach may be the notion that machine operators have a pivotal role in maintenance activities. Operators have historically been removed from the maintenance system, yet they have significant knowledge about the processes they run, and therefore, may be in the best position to ascertain ways to avoid machine failures.

In the second paper (Fornasiero, Panarese, Cassina, and Taisch), the focus shifts to monitoring systems. The authors describe a decision support system that may be used to schedule predictive maintenance activities in such a way that unexpected stops and lifecycle costs can be minimized. The system they recommend is comprised of three modules: the testing module, the aging module, and the cost maintenance management module. The output of each module is used to determine when, and what type of, maintenance should be undertaken. By approaching maintenance management through systematic monitoring, reduced maintenance costs, increased machine life, and decreased variability in production quality are just some of the benefits that can be expected.

The third paper (De Virgilio) focuses on a control system for building maintenance. De Virgilio presents a methodical approach for constructing monitoring indicators and evaluation indices in order to: standardize the process of service planning, evaluate the outcome of services provided, and monitor maintenance costs. The paper then goes on to describe how these inputs can be converted into multiple elements of an overarching control system. In applying the approach described, great care must be given to the measurement of quality, which is by nature subjectively judged. The standardized process presented is designed for application to a variety of real estate maintenance programs. It should not, however, be limited to that domain. The framework presented could also be applicable, with minor modifications, to any maintenance management control system.

The fourth, and final, paper in this section (Guizzi, Santillo, and Zoppoli) suggests a simulation approach for evaluating maintenance management policies before they are implemented. The authors apply a condition based maintenance approach to develop a model of a real production system. The model can assess various wear parameters and associated maintenance interventions based on those wear parameters. For example, when a particular system component reaches a specific wear threshold, the component is taken out of service for a maintenance intervention. Thus this model can be used to ascertain the threshold levels associated with the optimal cost of the maintenance management system or to compare the costs of various policies that an organization may want to consider. The model presented represents a serial system, which is the most costly in terms of maintenance downtime as the whole system must be shut down when one component fails. The approach these authors use, however, has much broader applicability because it could easily be applied to a variety of systems requiring maintenance.

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4.2 TPM Application to a Company of Automotive Components

Vincenzo Duraccio, Domenico Falcone, Alessandro Silvestri

Abstract . In the frame of absolute reliability, in Japan a new criterion of maintenance, namely the Total Productive Maintenance (TPM), has been developed; the TPM is one of the methodologies falling in the Auto-quality field. This paper refers to the application of TPM to a company leader in the production of automotive components. An adequate maintenance system is planned and implemented, adapting the TPM to solve problems linked to breakdowns, micro-stops, efficiency reductions, etc... In particular , the TPM has been applied to an injection moulding machine, a press with a clamping force of 1.300 tons. The maintenance activities have been divided in three different levels. The developed work has allowed to create an effective maintenance tool that can be applied to other machines. The realized maintenance system has allowed to achieve the prefixed object, first of all "zero breakdowns" and "zero defects"; however this work must be considered as a starting point, because the TPM needs of a continuous and constant action of control during all the life of a system.

4.2.1 Introduction

The concept of maintenance in the last years has been considerably modified. According to the initial approach of maintenance, the repairs were carried out only after the component breakdown. After the second world war a new approach was introduced: “preventive maintenance”; preventing the breakdown occurrence through a daily maintenance activity in order to prevent the component degradation. This type of maintenance involves periodic controls, that allow to measure the component degradation and recover the component functionality. Subsequently, the maintenance is no more considered a centre of cost, but a centre of profit. Starting from the 70s, moved by the reduction of productive costs, many companies have invested huge capitals in equipment and plants and have reduced the number of workers. Consequently, the plants have become more vulnerable on machine stops, in consequence of the relevant economic damages involved.

The absolute reliability of the machines becomes one of the most important targets that has to be reached by all the staff of a company, without leaving that only an external maintenance organization is responsible for it. In his new frame, in Japan a new criterion of maintenance, namely the Total Productive Maintenance (TPM), has been developed; the TPM is one of the methodologies falling in the auto-quality field. This paper refers to the application of TPM to a company leader in the production of automotive components. In order to achieve competitiveness and continuous improvement, the company applies many tools, such as the JIT (Just In Time), the Auto Quality, the Kaizen, the TPM.

The TPM method tries to eliminate the main factors of the production losses, the faults, the registrations, the setting changes, the defective pieces. The elimination process of the above causes, starts from the plant reset, then the autonomous maintenance and, finally, programming and planning the preventive maintenance.

In reason of a reduction of the production losses, the company implements the remedies shown in the Table 4.1. In particular, the losses due to defects and repairing involved the Auto Quality, instead the losses concerning equipping and tuning are solved by the SMED method (Single Minute Exchange of Die). The SMED method is based on procedures able to minimize the time of changing the mould and the raw materials.

Table 4.1 Remedies for production losses

Type of loss	Remedy
Failure	TPM
Equipping and tuning	SMED
No load operation	TPM
Speed reduction	TPM
Defects and repairing	Auto Quality
Efficiency reduction due to setup	TPM

The analysed company, through a training case, lets his workers become aware of rapid replacement methods. This case demonstrates that also a simple reorganization of the work allows to save large time without changing the tool.

4.2.2 The TPM

The efficiency and the reliability of a moulding plant can be evaluated through two indexes, called TRS and MTBF.

TRS is defined as:

$$TRS = \frac{\text{Time of efficient operation}}{\text{Time of opening machine}} \tag{4.1}$$

The MTBF (Mean Time Between Failure) is:

$$MTBF = \frac{\text{Working Time}}{\text{Number of Stops}} \tag{4.2}$$

In order to eliminate the failures, the company refers to the rules shown in Table 4.2.

TPM is used by the company to modify the preventive maintenance on the basis of the operation results obtained on the field, rather than from the machine producer. The TPM allows to structure the observation, to adapt the maintenance forms, to train the workers. Figure 4.1 shows the steps to elaborate the preventive maintenance in the considered company.

Table 4.2 Method of failure elimination

OPERATION	EXECUTOR	METHOD
Register the failure	Worker	Register on the form at the position
Repair the machine	Maintenance man	Manage the interventions and the spare parts
Confirm the causes, Define the preventive actions	Workers, Maintenance man and Supervisors	Weekly meeting, Pareto analysis
Create or modify the maintenance forms	Maintenance man	Update and validate the preventive maintenance forms
Use the updated forms	Workers and Maintenance man	Go to the successive level of maintenance, define the training needs and train the workers

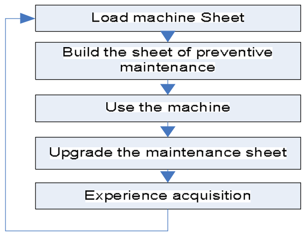
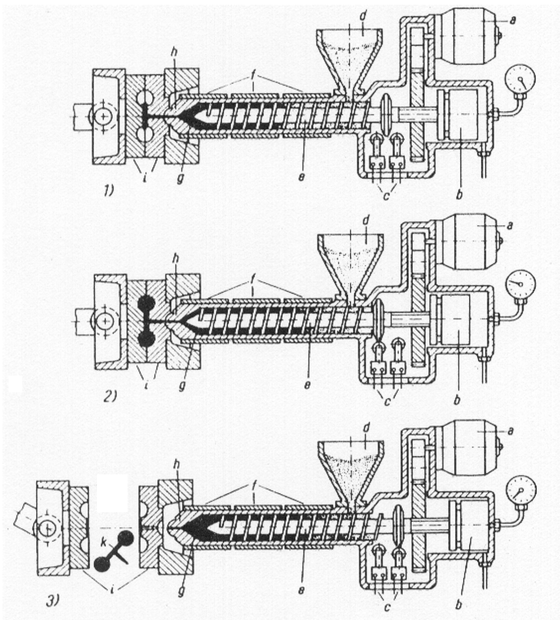


Figure 4.1 Flowchart of the preventive maintenance

4.2.3 Process of Moulding by Injection

As well known, thermoplastic materials present the characteristic to soften with temperature increase with a given plasticity grade, and to recover their normal condition when they cool down. This feature allows the injection moulding that consists in bringing the fluid material in a warm cylinder and then injecting it with high pressure, in very short time, through a tight nozzle into a cooled mould.

Figure 4.2 shows the parts of a press and the three steps of the operation schedule. Through the automatic feeding system, the material in a granular form, reaches the hopper and the melting chamber provided with electrical resistances. In the melting chamber, a screw transports the material towards the nozzle during the injection phase.



a) motor for the spin movement of the screw;
b) hydraulic motor for the axial movement of the screw;
c) interrupter for regulation of pressure and race screw;
d) hopper of plastic material;
e) screw;
f) cylinder of injection with heating resistances;
g) build-up area of the plasticized mass;
h) heated nozzle of injection;
i) mould of injection with the feeding ear-ring.

Figure 4.2 Parts of a press and the three steps of the operation schedule

The steps of the operation schedule are listed in the following:

1) the mould, cooled to the solidification temperature, is filled up by the fused material, coming from the screw;
2) in order to compensate the withdrawal of the cooled piece, the material is pushed further by the screw with proper post-pressure;
3) the nozzle withdraw from the mould by feedback means of the closing unit; the rotating screw transports the plasticized mass into the zone in front of it and, finally, after an adequate cooling time, the mould is opened and the piece is formed.

The fundamental parameters that influence the moulding, are: temperature, pressure and speed of injection, and the temperature of the mould.

Temperature of Injection

The temperature of moulding is a very important element for the mould filling. If the temperature is too low, the material slides with difficulty into the cavity and it is quickly cooled off, generating defective pieces. If the temperature is excessive, the polymer can degrade and excessive slobbers can appear along junction lines.

Pressure of Injection

Generally, the pressure depends on the constant speed of the screw, during all the injection stage. An inadequate pressure creates tensions and defects in the pieces caused by excessive slowing down of the flow; while an high pressure generates slobbers in the plastic material (that make difficult the separation of the piece from the mould). The slobber lines appear both when too warm material reaches with high pressure the edges of the mould, and when the injection pressure exceeds the one of closure.

Speed of Injection

The ideal conditions of moulding require to fill the cavity constant temperature and to cool the plastic material uniformly. Therefore, the filling of the mould must be so rapid that appreciable gradients of temperature are not allowed between the flow, that is cooled by the contact with the cold mould walls, and the point of injection.

Temperature of the Mould

The temperature of the mould influences, considerably, the cooling rate of the material, the product aspect and its mechanical properties. The mould temperature, generally, is regulated by the cooling pipe system with middle-low temperature water (from 30 to 45°C). A mould too cold reduces the moulding withdrawal and accelerates the production cycle, so we need to use very fluid materials and high injection speeds. In the other side, a mould too warm allows the whirlpools and lengthens the production time.

In the considered case, the used material is an high density polypropylene (HDPE) and the produced pieces are: superior and inferior parts of the car evaporator box of the group Daimler Chrysler (Figure 4.3).

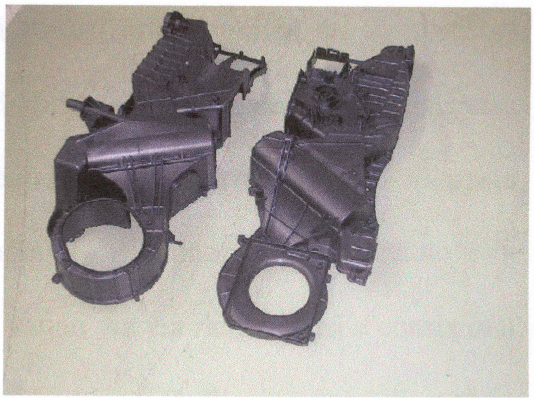


Figure 4.3 Superior ad inferior parts of the car evaporator box

4.2.4 Application of the TPM to the PTA07 Injection Moulding Machine

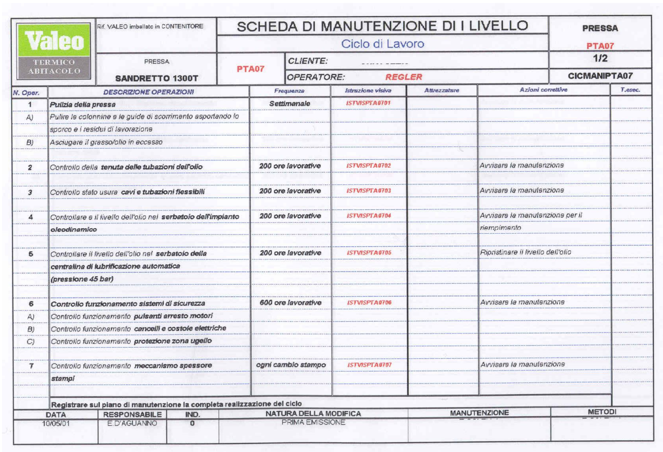
The TPM methodology requires the participation of all the staff, from the management to the production units, in the maintenance activity. In order to realize the TPM, a structure is needed; it has the task of planning the maintenance process and the maintenance engineering. The maintenance engineering has to provide methodological instruments.

The proposed work is focused on the maintenance system organization for the mentioned press-machine. The maintenance activities have been subdivided in three different levels. The maintenance operations of first level, are those of independent maintenance, realized directly by the operator of the press. More complex are the operations of second level, carried out by the maintenance staff and less frequent. The maintenance operations of third level are made sporadically by external staff of the press-machine manufacturer.

The Cycle of First Level Maintenance

The cycle of the first level maintenance is realized by the operator of the press-machine. For this activity, some "forms of preventive maintenance of first level" have been created (see Figure 4.4). Each form can be subdivided in three parts:

- information regarding the form, the emplacement or the machine;
- description of the operations; and
- information about the date and the responsible of the form compilation.



Valeo TERMICO ABITACOLO
Rif. VALEO imballato in CONTENITORE
SCHEDA DI MANUTENZIONE DI I LIVELLO
Ciclo di Lavoro
PRESSA PTA07
PRESSA SANDRETTO 1300T
PTA07
CLIENTE:
OPERATORE: REGLER
1/2
CICMANIPTA07

N. Oper.	DESCRIZIONE OPERAZIONI	Frequenza	Istruzione visiva	Attrezzature	Azioni correttive	T.esec.
1	**Pulizia della pressa**	**Settimanale**	ISTVISPTA0701			
A)	Pulire le colonnine e le guide di scorrimento asportando lo sporco e i residui di lavorazione					
B)	Asciugare il grasso/olio in eccesso					
2	Controllo della **tenuta delle tubazioni dell'olio**	**200 ore lavorative**	ISTVISPTA0702		Avvisare la manutenzione	
3	Controllo stato usura **cavi e tubazioni flessibili**	**200 ore lavorative**	ISTVISPTA0703		Avvisare la manutenzione	
4	Controllare e il livello dell'olio nel **serbatoio dell'impianto oleodinamico**	**200 ore lavorative**	ISTVISPTA0704		Avvisare la manutenzione per il riempimento	
5	Controllare il livello dell'olio nel **serbatoio della centralina di lubrificazione automatica (pressione 45 bar)**	**200 ore lavorative**	ISTVISPTA0705		Ripristinare il livello dell'olio	
6	**Controllo funzionamento sistemi di sicurezza**	**600 ore lavorative**	ISTVISPTA0706		Avvisare la manutenzione	
A)	Controllo funzionamento **pulsanti arresto motori**					
B)	Controllo funzionamento **cancelli e costole elettriche**					
C)	Controllo funzionamento **protezione zona ugello**					
7	Controllo funzionamento **meccanismo spessore stampi**	**ogni cambio stampo**	ISTVISPTA0707		Avvisare la manutenzione	

Registrare sul piano di manutenzione la completa realizzazione del ciclo

DATA	RESPONSABILE	IND.	NATURA DELLA MODIFICA	MANUTENZIONE	METODI
10/05/01	E.D'AGUANNO	0	PRIMA EMISSIONE		

Figure 4.4 First level preventive maintenance form

In the high part of the maintenance form, the collected information allow to identify the machine, the external customer, the responsible of the actions, the form reference and the page.

In order to plan and to organize a maintenance system of first level, it is necessary the tasks are well comprised by the workers; they can be resumed in:

1) to ascertain the anomalies;
2) to resolve the anomalies and to restore the normal operating conditions;
3) to define the normal operating conditions and the evaluation standards;
4) to manage the systems.

To ascertain the anomalies, a continuous cleaning of the system, intended as inspection, is indispensable. Once carried out the cleaning of the press, the operator must verify that no part is damaged and, if needed, he has to inform the maintenance office.

Then, some control operations are scheduled, they permit to verify that the press is working correctly. The operator must control the tightness of the pipes, the usury state, the protection devices, cables and flexible pipes, the absence of oil losses. Further important operation is the lubrication. The operator has to control, every 200 working hours, the level of the oil in the tank. In case of not conformity, he has to refill the oil to restore the standard conditions, in case of simple operation, otherwise he has immediately to inform the maintenance staff for programming the repair.

Safety is a fundamental characteristic of any production activity, for this reason, the press-machine is equipped with proper devices. Such devices must be preserved in good state and periodically controlled. They are:

- motor arrest buttons;
- safety gate;
- nozzle zone protection.

On board of the press-machine, three motor arrest push-buttons are located for any emergency. The push-buttons act on the emergency circuit deactivating all the movements. The operator must control that, pushing the buttons, the motor is disabled and the emergency system acts. Moreover, the operator has to verify the functionality of the gate of the mould opening, and the nozzle zone protection.

The first level of maintenance includes the verification of the correct operation of the press-machine, to avoid defects in the products. Therefore, not only the “zero breakdowns” object can be reached but also the “zero defects” one. The parts of the machine that must be controlled are:

- thickness mechanism of the mould;
- heating system of the plasticization cylinder.

Such controls are repeated at every mould change to avoid to produce defective lots. For all the previously described operations, some visual instructions have been arranged (Figure 4.5 shows an example).

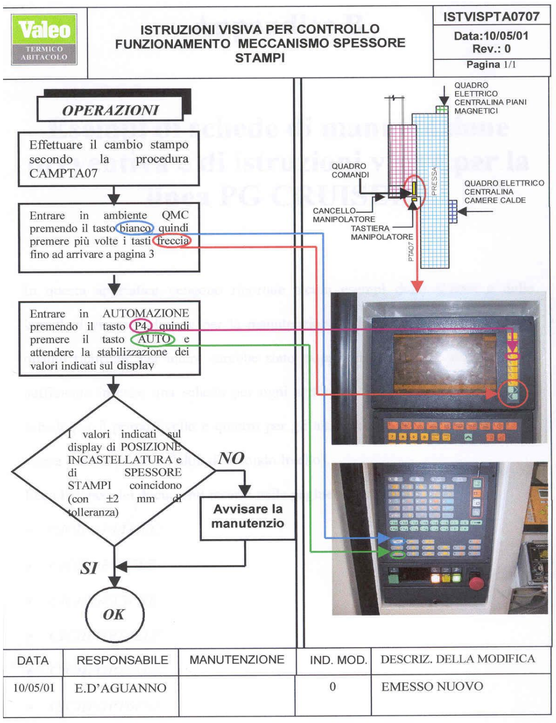


Figure 4.5 Example of visual instructions

The Cycle of Second Level Maintenance

The cycle of second level maintenance is constituted by operations, than cannot be performed by the machine operator but require the maintenance staff intervention. Such operations have been inserted in specific forms of second level maintenance.

In regard to mechanical devices, the inspection has been restricted to the valve of the plasticization cylinder; it must guarantee a satisfactory tightness.

More inspections regard the lubrication system, in particular the pump oil-pressure have to be checked to avoid vibrations or noise. The oil temperature sensor must be accurately controlled to avoid excessive temperatures that could cause severe consequences. Then, the maintenance operator carefully checks the state of the oil filter, possible oil losses and the thrust meter effectiveness.

The heat exchanger and the plasticization cylinder cooling system have to be checked, by verifying that the water capacity and the thermal gap between the input and the output respect the machine requirements. Moreover, the flow meter and the relays that activate the water cooling of the mould have to be controlled.

Finally, the functionality of all the push-buttons and of all the selectors has to be controlled.

For the second level maintenance no visual instructions have been arranged, all the operations are effected by the maintenance operators.

The Cycle of Third Level Maintenance

The organization of third level maintenance follows the same criteria already described, but it is completely executed by the staff of the machine manufacturer, with a fixed frequency. Five forms have been arranged covering different sectors; they are:

- safety devices;
- mechanical devices;
- oleodynamic system;
- lubrication system;
- electrical/electronic system.

Safety devices
Three operations are included: the control of the oleodynamic emergency system, the control of the mechanical emergency system of the mould and the control of the micro spin head. In case of anomalies, the technician must immediately repair the device.

Mechanical devices
The included operations are: the press-machine and the mobile plan sliding unit levelling, the parallelism of the mould plans, the nozzle centring. Moreover, also the control of the climbing couple is included, in comparison with adequate pre-assigned values.

Oleodynamic system
The first operation is the cleaning of the oil filter, that has to be anyway replaced after a given number of working hours. Then, the valves of pressure and flow of the pump have to be checked.

Lubrication system
The external technicians have to fatten the columns of the mould, to regulate the thickness and to control the lubrication alarms.

Electrical/electronic system
The initial verifications concern with the cable control at different points:

- supply terminals and main switches;
- the fuses, the main motor;
- the automatic switches, the heating resistances;
- the automatic switches, the contactors and motors for the mould thickness and the lubrication;
- the electro-valves.

Finally, the operation of several transducers has to be controlled.

4.2.5 Planning and Organization of Maintenance Process

The interventions on the press machine PTA07 have been scheduled according with the working hours rather than pre assigned time intervals, as usual. This has been facilitated by the presence of a display on board of the machine, that, after a determinate number of working hours, automatically gives a proper message.

The interventions have been subdivided according with their severity and the execution time they need. Five dead line of maintenance have been determined in correspondence of the operation rate (200, 600, 1.200, 2.500, and 6.000 working hours).

At the message appearance, the operator has to carry out all the operations of the first level of preventive maintenance, scheduled to reach the assigned number of hours; moreover he must inform the maintenance staff for the remaining operations of second and third level. The frequency of all operations is shown in all the preventive maintenance forms together with the description of the operation that have to be effected.

To record the preventive maintenance operations, adequate forms have been arranged (see Figure 4.6). In the upper part of this form, information regarding the maintenance type, the machine or the emplacement are reported. Proper cells are available to introduce date and operator name.

The central part of the recording form is subdivided in six columns; the first one presents the operation number corresponding to the one of the preventive maintenance.

As example, if the 200 hours message appears, from the first level maintenance form (see Figure 4.3) the operator realizes that operations 2, 3, 4, 5, 8, 9 and 10 have to be carried out. Then, also using the visual instructions, the operator completes the first operation and, when completed the verification, marks with a cross on the row corresponding to the operation. In particular, he can use the column marked N, if no anomaly was detected, otherwise he can use the column marked R. In this case, the operator must write the detected anomaly on the same row under the column "Osservazioni o Difetti riscontrati”. Moreover he marks the cell under the column "Fatto", if the repair has been immediately effected, otherwise he marks the cell under the column “In corso” .

For this press-machine, the spare parts warehouse is not inside the firm, however a proper spare parts list located at two warehouses of the manufacturer company are available. On agreement basis, the manufacturer company guarantees that all the spare parts are available at the factory within 24 hours.

Valeo SISTEMI TERMICI

SCHEDA DI REGISTRAZIONE MANUTENZIONE PREVENTIVA 1° LIVELLO

PRESSA SANDRETTO 1300T	PTA 07	GIORNO	MESE	ANNO	OPERATORE

N°	RISULTATO		OSSERVAZIONI O DIFETTI RISCONTRATI	IN CORSO	FATTO
	N	R			
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					

N =NULLA DA SEGNALARE

R = RIPRISTINO O RIPARARE VEDI COLONNA OSSERVAZIONI

Figure 4.6 Form to record the first level preventive maintenance operations

4.2.6 Conclusion

The considered production process has been equipped with a maintenance system, planned in respect to:

- the original TPM;
- the revised TPM according with the company needs;
- the characteristics of the machine;
- the indications of the machine manufacturer company; and
- the available resources.

The maintenance activity has been subdivided in levels, in order to involve all the production workers, besides the external maintenance staff. In fact, the production workers spend a lot of time near the machine, so they know very well the machine problems and are the most appropriate operators to evidence anomalies and defects.

Great attention has been dedicated to the organization of the first level of maintenance; it is based on the following principles:

- all the documentation has been compiled in a simple and direct way;
- visual instructions have been arranged;
- all the information of the first level of maintenance are available close to the machine;
- the forms to record the maintenance interventions are organised in order to minimize the number of information;
- when needed, the operations have been collected in mini handbook;
- adequate worker training has been effected.

The realized maintenance system has allowed to pursue the prefixed object, first of all: "zero breakdowns" and "zero defects"; however this work must be considered as a starting point, because the TPM needs of a continuous and constant action of control during all the life of a system.

TRS and MTBF indexes can be used to evaluate the maintenance effectiveness, while, if needed, adequate improvement actions can be implemented.

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4.3 Maintenance Management: a Case Study for Machine Tools

Rosanna Fornasiero, Daniele Panarese, Jacopo Cassina, Marco Taisch

Abstract. This paper deals with maintenance management applied to the field of the machine tools. The case study is provided by FIDIA Spa that is a world leader in the design, construction and marketing of integrated systems for the machining of complex forms for the moulds and dies industry. In industrial processes a sudden interruption of the machine, impacts on the competitiveness of the company and it is often the most important contribution in the "total production cost". The integrated Decision Support System here described goes in the direction of predictive maintenance for machine tools to reduce the number of unexpected stops and minimize lifecycle costs of the product avoiding component breakdowns. The overall decision support system can have a double impact on maintenance management. In fact it may support machine user to monitor machine performance and ageing of the components and maintenance service provider to plan and forecast interventions needed and optimize maintenance costs.

4.3.1 Introduction

This paper deals with maintenance management applied to the field of the machine tools. The case study is provided by FIDIA Spa that is a world leader in the design, construction and marketing of integrated systems for the machining of complex forms for the moulds and dies industry. Moulds and dies are used in the manufacturing of mass-produced products and they find application in a very wide and increasing range of production sectors.

The current maintenance approaches in industry are:

1. Breakdown Maintenance or Corrective Maintenance is only performed when a failure occurs; no action is taken to detect or prevent the onset of failures.
2. Preventive Maintenance aims at reducing the number of failures and their financial consequences by performing maintenance actions at a predetermined point of time
3. Predictive Maintenance strategy is based on deterministic and probabilistic models. Data about failure behavior can be obtained via suitable condition monitoring parameters, which give information about the actual state of the system.

During the recent years the maintenance management issue became a key factor for the machine tools manufacturers, to provide their customers relevant cost reductions thanks to the decrease of breakdowns (in number and magnitude) and the decrease of the maintenance contracts costs.

In the present industrial processes a sudden interruption of the machine, impacts on the competitiveness of the company and it is often the most important contribution in the "total production cost". The integrated Decision Support System here described goes in the direction of predictive maintenance for machine tools in order to reduce the number of unexpected stops for maintenance and minimize the overall lifecycle costs of the product avoiding component breakdowns.

The overall decision support system can have a double impact on maintenance management. In fact it may support:

- machine user who can monitor machine performance and ageing of the components; and
- maintenance service provider who can plan and forecast interventions needed and optimize maintenance costs.

4.3.2 Description of the System

As shown in Figure 4.7 three modules compose the overall system:

- the *diagnostic module* that transforms field sensor data in useful indicators of the working condition of the machine
- the *ageing module* that transforms the previous indicators in an estimate of the wear and the "health state" of the machine
- the *cost maintenance module* that enables the service provider to interpret the aging data in order to plan the optimal (technical and economical) maintenance action.

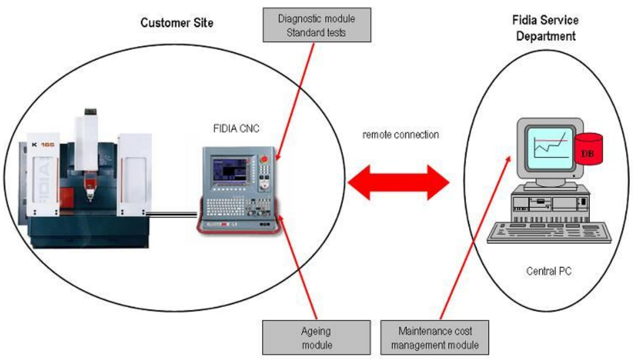

Figure 4.7 System overview

The overall DSS is integrated with a PDKM (product data and knowledge management) at the Fidia service departmernt which permits to gather and use information from different phases of the machine life. In fact for example information about components failures and performance can pass from the maintenance provider to the designers for new product features definition. According to the information collected directly from the previous versions of the product, improvements can be implemented closing the information loop. Other kind of information can be transmitted also for the recycling and dismissal of product components. The DSS evaluates maintenance costs with an iterative process on each machine for components exceeding a given threshold value of "criticality". Once the machine user has verified the status of the components with the testing module, an alarm on aging is sent to the Fidia premises which collects the alarms from all the machine tools under maintenance and calculate the economic value of different maintenance actions according to residual life costs estimation. Risk of failure are evaluated and are used to weight the costs.

Testing Module

The testing module has been developed to continuously monitor milling machines sold by FIDIA to its customers. Having the feedback from the field is very important to improve design of the machine. But feedback from the field is also vital in order to have a modern maintenance management of the product. Years ago customers asked only a good product, nowadays they require a good product and an excellent service on the product. For this reason, during the last years, FIDIA has progressively developed a software tool useful for periodical testing of the machine at customer site. Periodically (e.g. at least every 3-6 months or 10.000-20.000 working hours), the user should execute dynamic tests on the machine in order to evaluate the "health state" of the machine. This testing module for Predictive Maintenance has been developed on the basis of theoretical studies and long time experience of technical servicing. The results of the test can point out and suggest defective behaviors or malfunctions of the machine. This Predictive Maintenance software tool, running on the Computerized Numerical Control that equips every milling centre, instructs the machine to move its mechanical axes on paths, with pre-defined length and direction. During these tests, sensors installed on the machine (i.e. position transducers, current sensors, etc.) record some useful signals that are graphically displayed. Moreover data coming from sensors are elaborated and significant indicators are extracted. The Figure below presents the graphical user interface of this testing module. The final result of a testing session is a report listing all the "health state" indicators. This report is provided as input to the next aging module.

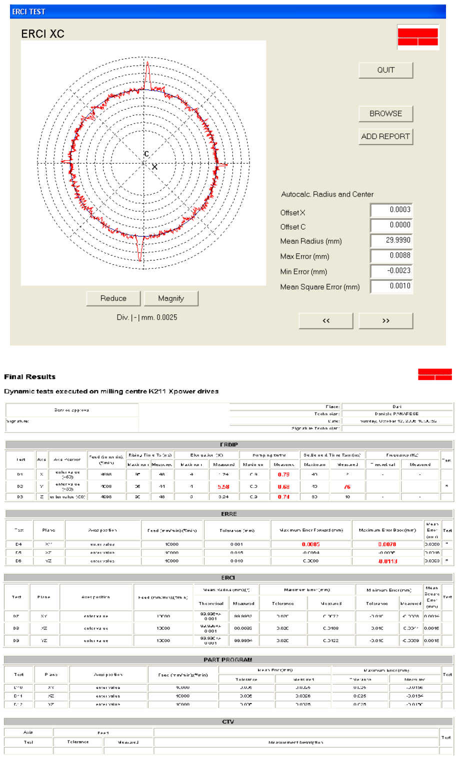

Figure 4.8 The graphical user interface of the testing module

Aging Module

The aging module, takes the global indicators elaborated by the testing module and elaborates them to esteem the wear and the aging of each axis and of the whole the machine.

At the beginning it has been developed following a methodology by the same author (Cassina *et al.*, 2006) on another predictive maintenance application, which exploits self training algorithms, making use of a neural network to train a fuzzy expert system. This approach has been tested, but aging experiments on this kind of products weren't feasible because of their cost and the needed amount of time.

So it has been decided to develop the fuzzy expert system, based on FIDIA engineers experience and simulations. Self improvements will be done in the future when enough field data will be available, gathered through the maintenance crews, or the centralized data management infrastructure (PDKM) that is under development.

The system is composed by five different expert sub-systems, initially developed with Xfuzzy (Figure 4.8). The first four analyzes the results from each test of the testing module, and are composed by an expert system for each axis, and one afterwards that sums up all the information to provide a global aging status indicator for the machine.

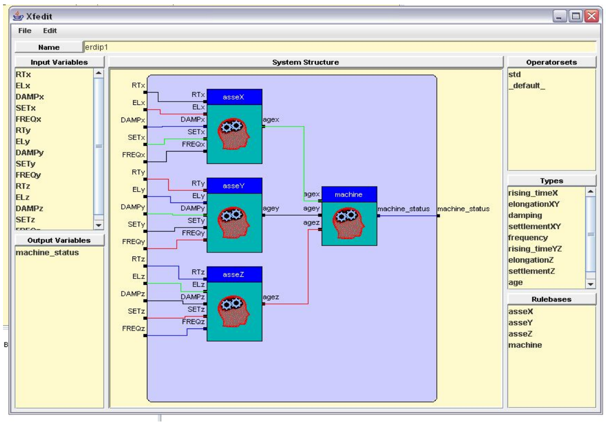

Figure 4.9 Example of an expert system to analyze the results from a test

After these, the last module analyzes the results of all the previous systems, giving an indicator of the reliability of the esteemed aging value.

The aging module starts automatically at the end of the machine tests, and shows to the user a synopsis of the aging indicators, providing him both the global machine status, and an analysis of status of each axis. All these data have also a reliability indicator, which shows if the esteem is sound. The current interface is shown in Figure 4.9.

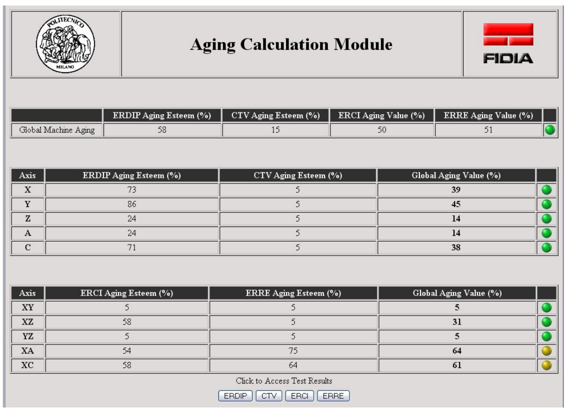

Figure 4.10 Output of the onboard aging module

When the aging exceeds a pre-defined threshold, there is the possibility of an incoming breakdown on the machine. The customer is then invited to send data to FIDIA to be analyzed by the maintenance cost management DSS module, that is explained in the next paragraph.

Cost Maintenance Management Module

Many studies (like for example Pinjalaa *et al.*, 2006; Yam, 2001; Swanson, 2001) highlight the magnitude of maintenance costs on the overall costs for the products some of them putting emphasis on the lifecycle impact of maintenance intervention on the rest of the life of the product (like Kiritsis, *et al*., 2003; Takta *et al*., 2004). Maintenance policies can be grouped into different bunches according to the way the user deals with breakdowns, failures and wear and many different methods can be used like suggested in (Fedele *et al*., 2004). Some studies propose methodologies for estimating the potential benefits deriving from the application of a certain maintenance approach showing how proactive maintenance can improve company performance compared to others (Swanson, 2001), explaining how to set up and model maintenance approach (Carnero, 2004; Grigoriev *et al*., 2006) and how to choose the best diagnostic system (Carnero, 2005). Many studies propose methods for optimising maintenance scheduling through the control of pure maintenance costs (for example Haghani and Shafahi, 2002; Safaai *et al*., 1999; Zhou *et al*., 2007; Anjly *et al*, 1998) but not considering the entire lifecycle costs impact due to performing or delaying a given kind of maintenance on product /component. This module of the DSS aims to the reduction of maintenance costs thanks to the implementation of a pilot approach to maintenance service which defines maintenance strategies minimizing costs related not only to next maintenance intervention but also to the residual life of the component so that a long term view on the costs is guarantee.

The system is meant to provide a list of suggested interventions that can be performed on the machine when the monitored mechanical components fail or are expected to fail according to alarms from the aging module which gives in input the residual lifespan of the machine and components through the PDKM where these information are stored. The system gives the possibility to the maintenance service provider to aggregate machines by location (according to geographical proximity) and calculates the number of intervention necessary on each geographical area. The maintenance provider can choose the area where to do intervention according to the most important criticalities identified by the system.

The methodology is based on the definition and evaluation of three main alternative actions (no intervention, tuning of parameters, replacement) for each monitored component of the machine tools. This module of the DSS compares the costs of the three alternative actions in order to manage the critical components according to estimated differential costs for the residual life maintenance defined for each action. The costs used to compare the three actions are as follows: Action 1: no intervention. In this scenario costs of not performing maintenance are considered. This is a case which is mainly applied at the beginning of life of the components and end of life of the machine. Costs are mainly related to the reduction of production quality which may be compromised by the fact that no maintenance actions are done increasing the failure probability. Production quality is an important category of cost in this context because moulds and dies are highly expensive and to stop the production or ruin a mould may require lot of time to start again production or to repair the piece. Costs computed to this scenario can be grouped into three main clusters: costs deriving from a reduced quality of the final product, costs for unexpected damages on components (due to a delay of the maintenance intervention, mainly linked to higher probability of failure) and, finally, costs for future interventions (taking into account the entire components lifecycle, preventive maintenance is also considered).

Action 2: tuning of the parameters. In this case machine running parameters are modified in order to preserve product quality. When one of the components of the axes deteriorates, the quality of final products may slow down. Modifying machine running parameters would sometimes preserve the quality of the product at the expense of productivity. Given the fact that most of the time considered machines produce expensive moulds, companies prefer to keep quality high. This kind of action is applied frequently in machine sector given the fact that it may be less expensive than replacement of tools and components. In this case costs are mainly linked to loss of productivity, to potential damages (which is lower than in the previous scenario) and to future interventions.

Action 3: replace (i.e. replacing the critical component). For this scenario the DSS calculates the costs for the replacement of the critical component, cost for damages on components/machine and costs for future interventions.

Input to the calculation of the Fidia DSS module can be grouped into two major subsets: data already stored in the DSS because they are similar for most of the machine tools models like for example cost of the machine, costs of each monitored component, the probability that a failure of one component could cause a stop of the machine; and data collected directly from each machine and sent to the maintenance provider like costs of lost production, cost of wastes, type of production, lead time, hourly cost of production…These data are specific for each machine, and for production undergoing and they impact on maintenance intervention costs.

In the figure below it is shown how data are collected from all the machines and LCRC (Lifecycle Residual Cost) for each action, for each component is computed. The system minimizes the LCRC for each component considering that maintenance actions are independent from each other. Residual life of the machine may influence decision on the action to be taken at component level making LCRC for replacement not convenient in case of residual life of the machine lower than residual life of component.

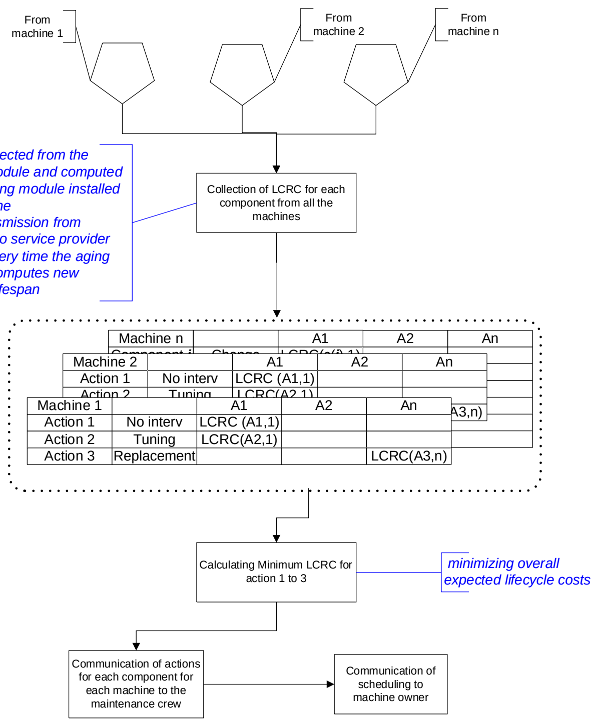

Figure 4.11 scheme of the maintenance management module

Forecasting future intervention and probability of failure are based on historical data and the system will be automatically updated according to historical data collected in the PDKM along the life of the machine. Specific values concerning production, maintenance etc are updated for each machine.

4.3.3 Conclusion and Further Development

In the design of this integrated DSS, different stakeholders requirements have been taken into consideration, referring to actors that will use the tool in different steps of the product lifecycle. The main addressees are in the middle-of-life phase: machine users and maintenance service provider. However, comparing actual performance of monitored components with reliability and features supported at the beginning of their life the system provides value-adding information also to the design department of the machine manufacturer (beginning of life phase) and, finally, to end of life actors devoted to the re-usage, retrieval and dismantling of the components. In fact the DSS calculates the costs of maintenance management not only related to the ageing of the components but relates it to the ageing of the machine. The here-described approach is under implementation and testing. Benefits deriving from the adoption of this tool will be weighed up and compared to already existent solution through proper on-the-field inspections. The consideration of residual lifecycle cost in the DSS permits to have a wider vision on the product and on the services connected to the product itself.

The testing and the aging module will be improved with the feedback coming from the users and the maintenance crews that will use it. At the same time, the aging module will use the gathered data to test the self improvements routines and to be self tuned.

Concerning the cost maintenance management module further developments in the proposed approach will give the possibility to synchronize the availability of each machine tools (according to their production plans) with the availability of the maintenance provider in the definition of maintenance calendar.
FIDIA expects to reach two main business opportunities deriving from the development of such an integrated DSS that supports predictive maintenance for machine tools.

In fact the improvement of machine performances, the innovation in maintenance strategy in machine tools field and the consequent breakthrough among the other competitors are expected to increase the machine sales.

The innovative approach to machine service is awaited to provide a positive perception among the customers. So higher quality and lower costs in service are expected, and this will increase the spreading of this kind of contracts.

Acknowledgments

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4.4 Real Estate Maintenance Services: the Measure of "Success". Development of a Control and Evaluation System for Building Maintenance Services

Alessia De Virgilio

Abstract. In the present real estate scenario, which is characterised by closer and closer links between maintenance and quality, the need to assure the *"success"* of real estate maintenance services through the achievement of results which must meet the expectations of *quality*, *effectiveness* and *efficiency*, become more and more pressing. This paper is, therefore, intended to describe an *operational instrument*, with appropriate *guiding elements*, which can help both the owners (Public Administrations, big private real estate companies) to check the maintenance services supplied by the contractor, and the managers or suppliers of such services to control the quality of their work. This work is aimed to develop a *Control and Evaluation System for Building Maintenance Services* which will first of all allow to *"measure"* or *"quantify the quality"* by converting it, where possible, into one or more measurable parameters, and secondly to *"compare the qualities"* – i.e. the quality required and the quality achieved – through the introduction of models enabling a correlation between the two sides of evaluation and their own tolerance margins. This system is based on the construction of appropriate monitoring *indicators* and evaluation *indexes,* whose values can objectively indicate the level of conformity, effectiveness and efficiency of the service supplied.

4.4.1 Introduction

This paper describes some of the findings of a research made by Architect Alessia De Virgilio, in co-ordination with Prof. Claudio Molinari, at the Department BEST of Politecnico di Milano during the Doctoral Program (Ph.D.) in *"Programming, Maintenance, Rehabilitation of Building and Urban Systems"*.

This research deals with the general issue of the *"control"* and *evaluation* of results in relation to the performance of real estate management activities, with special regard to maintenance.

A general reference framework for this issue is the introduction of a legal "framework" (Law "Merloni", package 626/494), whose rationale is focused on the quality of results as well as on the efficiency, cost-effectiveness and security in the management of products and processes. This Law has also required the systematic and ongoing implementation of adequate monitoring and evaluation tools.

As regards the maintenance of real estate in particular, other factors have made the need for control more pressing: for example the maintenance core business has shifted from the execution of *works* to the provision of *services* and, even more, there has been an increasing recourse to the outsourcing of services by means of contracts based on the results to be achieved. All this implies that the customer's control capacity plays a crucial and strategic role.

This controlling activity is aimed to assess the effectiveness and efficiency of anything that may affect the provision of such services, up to their ultimate result: that is to say the *quality achieved* compared to the *quality requested*.

However it is this very transition from the execution of works to the provision of services that raises difficulties in the exercise of control and in the evaluation of consistency between expectations and results.

As a matter of fact *works* produce "products", and the outcome of such works can, apart from a few exceptions, be easily measured and compared to the project and contract expectations, thanks to the tangible structure of such products.

Services produce "results" which are hardly ever physically tangible, almost always immaterial in their consistency. Such results are to be compared with expectations that, in their turn, are expressed in at least the same immaterial forms, as it is the case, for example, of the relation between requirements and performances of a technical element or a space.

The control over such consistency then becomes much more difficult. The more so when the object of such control that joins together both expectations and results is, on the one hand, the preservation or the improvement of the *quality of use* of the property which undergoes maintenance and, on the other hand, the *quality of the processes* needed to reach this result.

4.4.2 How to Manage Quality Controls in Maintenance Actions Applied to Real Estate

In the present real estate scenario, which is characterised by closer and closer links between maintenance and quality, the need to assure the *"success"* of real estate maintenance services through the achievement of results, which must meet the expectations of *quality*, *effectiveness* and *efficiency*, becomes more and more pressing.

In order to avoid the risk of failure as far as possible, it is necessary to pursue a strategy which enables to *control* and *measure* the results of the maintenance services, since it is this compliance of the results with the upkeep requirements, objectives and policies that is the main evaluation standard of this process.

However if, on the one side, the *measure of the "success"* of maintenance services is a crucial moment, on the other side it raises considerable problems which are still open and can be summarized as follows: *who controls?*, *what is controlled?, how is it controlled?*. The problem therefore is to *"quantify the quality"*, that is to define objective parameters and suitable measuring and monitoring instruments capable of quantifying the expected results.

Moreover if, on the one hand, we experience a market trend that attaches greater and greater importance to the specific sector of the Global Service, i.e. the integrated system of real estate maintenance activities where the contractor is fully responsible for the results in terms of achievement and/or maintenance of the service levels required by the client, on the other hand we are faced with a reference framework still characterized by a non-consolidated *outsourcing* culture and practice in the demand, especially public demand, for integrated technical-management and maintenance services and by a not yet widely recognized and certified *know how* by the supply of these services.

Therefore this scenario shows in all clarity the problem of the inadequacy – when not of the lack – of specific and consolidated *guiding principles* to be used in the complex and critical phase of the control over results. As regards this problem which, in practice, constitutes one of the main obstacles to the correct development of the market in this sector, it is nowadays an immediate priority to have in place *effective and objective tools for the control over the activities* performed by managers/suppliers, for the purpose of performing a constant monitoring on the quality of management results, in order to guarantee compliance with contract terms and verify consistency with the planned strategies.

4.4.3 The Control System Proposed as Tool for Measuring the Results of Maintenance Services

This research stems from the awareness of the importance and topical relevance of these issues.

This paper is, therefore, intended to describe an *operational instrument*, with appropriate *guiding elements*, which can help both the owners (Public Administrations, big private real estate companies) to check the maintenance services supplied by the contractor, and the managers or suppliers of such services to control the quality of their work.

Objectives

The purpose of this research is to work out and organize a **Control and Evaluation System for Building Maintenance Services**.

The System, based on the construction of appropriate monitoring *indicators* and evaluation *indexes*, is made up of different procedural, cognitive and operational instruments which make it possible to:

- standardize the process of service planning, describing the compliance features that the elements of such process must have in an exhaustive, detailed and logical way;
- evaluate the outcome of the service provided, identifying appropriate and differentiated qualitative standards which can secure the safety, effectiveness and continuity of operation;
- monitor maintenance costs, supplying management tables which can show the level of efficiency of services and possibly guide strategic choices.

Methodology

This research tackles the above-described problems by organizing them into two general logical and methodological steps: the first step-objective is to *"measure the quality"* and its immediate corollary is to *"quantify the quality"* by converting it, where possible, into one or more measurable parameters. This corollary then becomes one of the main problems tackled during the research because it affects the very possibility to practically perform that measurement. In fact, quality is not always immediately convertible into measurable variables. Sometimes, this can even be impossible. The second step-objective is to *"compare the qualities"* – i.e. the quality required and the quality achieved – once they have been measured, through the introduction of models enabling a correlation between the two sides of evaluation and their own tolerance margins. The achievement of this objective raises serious problems of *methodology* since, apart from the need to guarantee consistency between the specificity of the single verification and the general approach to the evaluation of "success", it often requires the interaction of different competences, especially where such evaluation refers both to the results and the procedures followed for their achievement.

4.4.4 General Criteria for the Control System

By *control of the results* we mean the definition and planning of the checking activities to be performed at the various stages of the maintenance services (processes or performances), which, according to their *importance*, *critical areas* and *risks* observed, require a *continuous* or *planned monitoring* of the aspects that mostly affect the quality of the services, the results of maintenance activities, the safety of people and the environment in general.

Such performances must undergo continuous, periodic and planned review in order to check their compliance with the decisions taken at the *managerial level* about the aims to attain and with what has been established at the *contractual level* about the service standards to guarantee.

It is envisaged that “critical” activities, i.e. those with a possible impact on the safety and functionality of the building, undergo both a *qualitative* evaluation, that is over their compliance with the policy, objectives, management and regulatory aspects, and a *quantitative* evaluation, i.e. a comparison with reference values in order to establish any non compliance with such aspects. The data gathered from such monitoring are used to carry out an analysis aimed to determine the most appropriate Corrective and Preventive Actions for the situation observed or, if necessary, to impose penalties.

The purpose of this work is to outline a general method for the identification of some parameters, such as *classes of indicators* and *concise indexes*, which systematize and sum up the main peculiarities of the most significant cases under examination and enable to *check/measure/analyse* the levels of the supplied services through a continuous monitoring, both during the works and/or upon completion.

The *techniques* used to measure performances can include the following methodologies:

- inspections, by making use of check-lists;
- examination of documents collecting feedback information;
- analyses of the data recorded on the Information System;
- collection of requests or reports by the Call Centre;
- interviews or questionnaires to the customers concerned;
- any other measurement method deemed necessary.

In order to analyse the data gathered from such investigations simple *statistical techniques* are used, which allow to quantify the adequacy of processes and services and their consistency with the requirements set.

The first step to be performed is the “data collection” and their subsequent processing through mathematical formulas derived from statistical techniques appropriate to the results to be achieved. This enables to obtain values indicating the state of a given phenomenon, by measuring it according to the criteria of greater or lesser importance (“weight”).

Such system can constitute a powerful and innovative instrument to actually *verify a service*, where “verify” means that both the customer and the supplier can check the results achieved by referring to objective parameters, which are the final result of the right mix of general aspects (benchmarks agreed upon at national level) and specific aspects (different targets and quality polices according to the reality considered).

Thus the proposed System enables to transform the data flow resulting from the process of service supply into an actual *decision support system*, which allows to assess the qualitative-quantitative standard of the various services provided, simulate different operational scenarios for the attainment or enhancement of the above standards and provide stimuli and indications for strategies.

Types of control

On account of the above we have worked out a control system which enables to perform and record controlling and measuring activities:

- on the processes adopted;
- on the services provided; and
- on the economic results.

In other words this means that the control must be specified and diversified according to its position within the general *process* of maintenance services management. Therefore there will be:

input controls, i.e. a control over consistency of input elements;

in-process controls, such as the verification of service effectiveness during the execution of the works;

output controls, i.e. a verification of service efficiency upon completion of the works.

According to the timing of the control, i.e. whether this is performed *before*, *during or after* the actual supply of the services, there is a diversification of the objectives, type of information produced, range of the resulting procedures and effectiveness of the control.

An organization of controls based on the *processing structure of activities* makes it possible to keep all the relevant risks under control, given that the service results cannot concern exclusively issues specific to the single subjects (building or plant maintenance, electric supply, cleaning, etc.), but the availability of backup instruments.

To this purpose the proposed System is subdivided into three parts, each part including more than one type of control:

control of service planning:

control over documents;

control over information and data;

control over planning.

Technical-operational control

control over the process parameters;

control over the quality of the performance of the building and its parts;

control over the level of customer satisfaction.

Economic-managing control

Figure 4.12 shows a summary table of the overall structure of the planned Control System, on the basis of the general indexes that should be monitored and analyzed for each service provided in order to represent the quality of the result of the service:

conformity index for the maintenance process;

service effectiveness index;

service efficiency index.

Part A: Control of service planning

The *phase of maintenance service planning* of a real estate is a crucial point in the approach to planning, programming and supply of such services and for the determination of the basic characteristics for the realization of the instruments supporting the performance of activities.

In this planning and development phase all the particulars and details that turn a generic service into a product which is qualitatively adequate and technically reliable should be defined. Badly planned aspects can trigger problems which may also invalidate or compromise the correct execution and management of activities and processes in the subsequent steps.

The control over service planning can be more or less structured and detailed according to the importance and the complexity of the service considered. It consists in an *objective*, *documented*, *systematic* and *critical examination* of the *maintenance process*, by which it is possible to identify and foresee problems and inadequacies, and implement preventive or corrective actions aimed to guarantee that the final service satisfies the client's requirements.

Under the proposed system the control over service planning is developed according to the method of *Inspections* based on check-lists.

Control over documents

The purpose of this procedure is to control compliance of documents, whether compulsory or not, which underlie and regulate the execution of maintenance activities, and guarantee their *availability*, *completeness*, *traceability* and *updating*.

This procedure applies to all the documents to be submitted or obtained before, during or after the execution of all the maintenance services detailed in the tender specifications.

Control over information and data

The purpose of this procedure is to guarantee the *availability* and *traceability of basic information* on the property concerned by the services to be provided, and therefore to ensure a regular and exhaustive *exchange of data*, which is essential for a monitoring activity on the real estate management and for an assessment of the services supplied.

A control system of the results of the services supplied, based on the use of indicators and indexes obtained from calculation algorithms, basically provides a limited number of values. However, to obtain such values it is necessary to resort to the complex *information system* relating to the real estate management, which is made up of information gathered before, during and after the management. Particular attention must then be paid first of all to avoid problems of lack or overlapping of data, and secondly to verify that – as a whole – all the information needed to assess the levels of the services supplied is contemplated in the correct terms and manners, so as to be used in the final calculation formulas.

This procedure can by and large be applied to any kind of information tools (*information system, call centre, etc...*) which support maintenance activities, regardless of the number and type of services supplied.

Control over planning

The purpose of this procedure is to control that the Maintenance Plan – worked out for each functional unit or technical item – is drawn up in compliance with the procedures, terms and frequency of execution of maintenance interventions specified in:

binding sources such as, in particular:

- data and instructions provided by producers of subsystems or integral components of the building (for ex.: maintenance manuals, technical specifications of elements);
- legal provisions aimed to regulate the technical characteristics, use and intervention procedures relating to the building or to its specific functional units (for ex.: Presidential Decree 412/1993 and Presidential Decree 551/1999 relating to heating systems);
- specific technical rules (i.e.: UNI, UNI-CTI, UNI CIG, CEI, etc...);
- data derived from the *technical literature*;
- other information sources (*experimental data* and direct management experience in similar systems).

Although it concerns the whole building, this procedure is applied to the single technical items which undergo maintenance services, according to how the building system was subdivided when the real estate register was set up.

Part B: Technical-Operational Control

The actual *phase of supply of maintenance activities* presents many critical and complex aspects since it represents the moment of a tangible verification of the results of the services supplied.

Owing to the complexity and the interrelation of activities in the services sector, it is not possible to use traditional measurement instruments for output or process effectiveness. In most cases the critical factors which determine the overall performance of a service are of a qualitative nature; however this must not be an obstacle to a *transparent* and *objective* approach to a performance measurement system.

The purpose of the supervisory activity during this phase is to highlight all the services or parts of them that do not comply with the specific requests. The verification is then centered on compliance with contract terms from a *technical-operational* point of view. In this perspective the tender specifications must envisage a system of penalties depending on the seriousness of the consequences of any non compliance by the supplier with the defined standards.

The frequency of such verifications depends on the complexity of the different services.

Under the proposed system the technical-operational control is developed through the processing of data gathered from recording instruments (call centre, information system) or from investigation tools (questionnaires on customer satisfaction).

Control over the process parameters

The purpose of this procedure is to identify and measure the *quality standard of the services supplied.* The quality of the services is the quality of the performance provided by the supplier of the service (contractor) measured on the basis of contract terms and of the specifications for the procurement of services.

In accordance with the regulation UNI 11136:2004, the service quality standards represent the characteristics and frequency of interventions and the terms of supply/execution of maintenance services that the contractor must guarantee in accordance with the reference levels set by the customer.

The service is therefore the sum of the various performances required to the contractor (in terms of proposals, projects, organizational, technical and management activities, etc.) and of their ways and means of execution and supply (in terms of flexibility, professionalism, reliability, timeliness, etc.).

This procedure applies to those activities that may have a significant impact on the environment, health and safety, or that are regulated by legal or contract provisions.

Control over the quality of the performance of the building and its parts

The purpose of this procedure is to identify and measure the *performance quality standards*. The quality of the performance of the property and its parts constitutes the overall or final quality of the performance of a clearly identified property.

In accordance with the Regulation UNI 11136:2004, the performance quality standards of the property and its parts constitute the performance quality levels set by the customer which the supplier must ensure through maintenance interventions.

The measurement of the quality of the performance (standard) is then based on the capability of the property to perform its specific functions, at a higher or lower level, towards both users and the public in general in case of public facilities.

The minimum quality standard that the contractor must always guarantee is generally defined as the preservation of the buildings in the same condition in which they are when the contractor is assigned his/her task (*status quo ante*).

The scope of this procedure is the same as that described above.

Control over the level of customer satisfaction

The purpose of this procedure is to assess the *quality perceived* by the client/user through the verification of the degree of conformity of the services supplied to the need of customers, who are the direct users of buildings.

The tools most widely used for the systematic monitoring of the synthetic or analytic judgment given by the service users and for the measurement of the level of satisfaction are the *questionnaires on Customer Satisfaction*.

This procedure is applied to all the maintenance services detailed in the tender specifications, assessed both on a broken down basis and as an aggregate.

Part C: Economic-Managing Control

The controls over maintenance services must not only allow to verify that the manager has acted in compliance with the activities, terms and performances envisaged under the contract, but they must also allow to assess the general *efficiency* of such services, the adequacy of management strategies and, where necessary, propose any Corrective Actions.

Through the *processing phase of feedback information* oriented toward a precise data analysis it is possible to constantly improve the decision-making and strategic capacity.

This type of control may consist in:

- control over the management on the basis of a cost-benefit analysis of the planned interventions;
- development of simulations for the purpose of analysing long-term effects on the basis of the choice of alternative strategies;
- comparative evaluation of performance with excellence models.

4.4.5 Conclusion

As regards the use and transferability of the findings reached by this research, the planned System is meant to provide a *procedural reference framework* for the phase of control over service performances, aimed to the construction of a *processing model*, but most of all to the definition of *instrumental criteria* and *operating rules* so that, on such basis, each real estate owner and/or manager can develop its own procedural scheme, adequate and suitable to its specific needs and characteristics, by making use of a whole set of parameters (more or less widespread in the actual practice) for the resolution of the single problems.

The issues dealt with do not aim to work out reproducible standards suitable for all cases but, through the use of standard instruments and documents, to stimulate clients or contractors to search the most appropriate solutions to their case. This System has been conceived not only for the purpose of providing operating tools which could easily be used, but also for the purpose of suggesting *methodological guidelines* which may be *flexible* and adequately tailored to the specific circumstances.

From a planning point of view it is of paramount importance to identify, when defining the technical specifications of the contract, the indicators for the terms of the service supply, which are the result of the level of *quality of the service* and of the *functional standard* that the client wants to achieve. This means that it is necessary to envisage an organized structure of the service system based on choices tailored on the client's specific needs.

The definition of the *parameters* and the relevant measurement instruments cannot but be the result of the strategic choices that the client intends to make for the different sectors or areas of his/her real estate.

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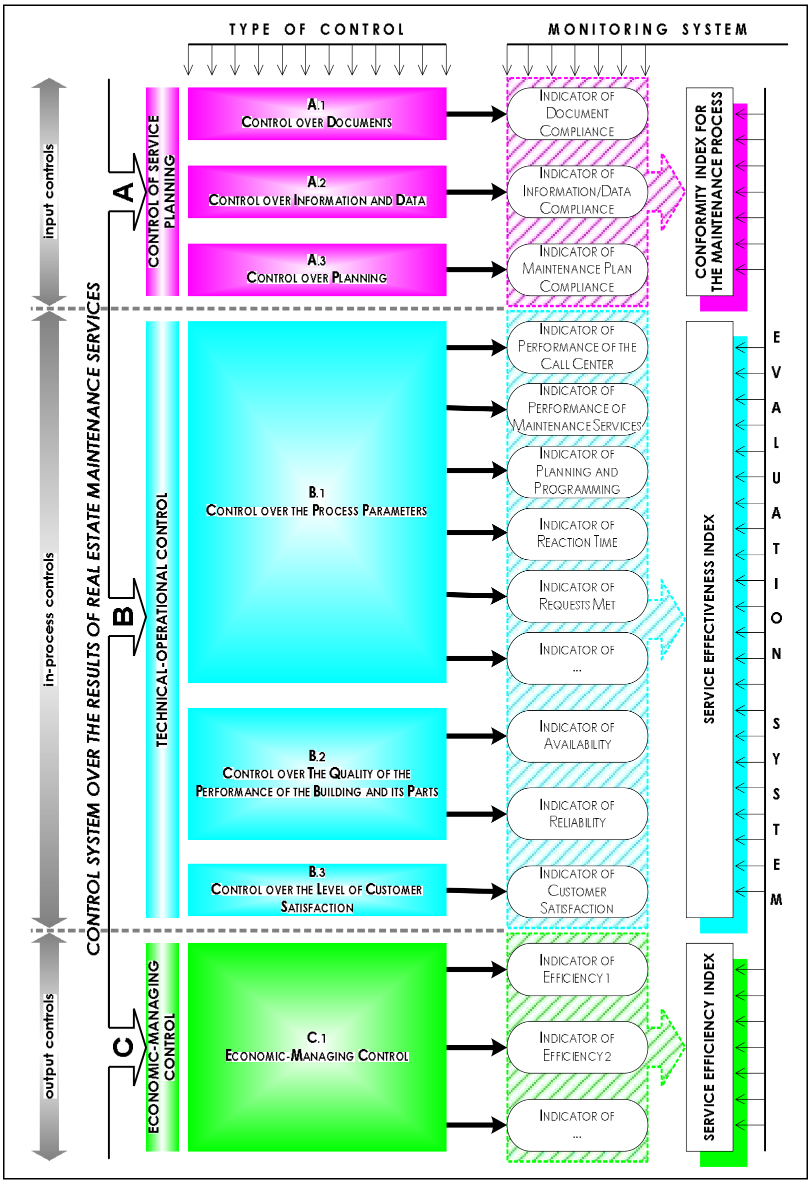

Figure 4.12 Scheme for the general planning of the control system for real estate maintenance services

4.5 Multithreshold CBM: Cost Optimization for an Units Serial System with a Simulation Approach

Guido Guizzi , Liberatina C. Santillo , Pasquale Zoppoli

Abstract. The target of this work is to develop a faithful model of a condition based maintenance process and to optimize its maintenance costs. First of all, we have analyzed different characteristic of several condition based models that have been publicized in the last 20 years. Considering the existing models we have decided to introduce some innovative elements so that the model developed would be more close to reality, the innovative elements are: the possibility of accidental failures, measurement errors during inspections, time consumption for inspections and maintenance and also the fact that the probability of failure doesn't only depend on time but also on the components physical conditions. The model can simulate a system of units that can have very different characteristics, such as productivity or reliability, or also we could simulate a system with inter-operational buffers. We have decided to study the case of a N serial units system because this configuration represents the worst configuration in case of failure. In fact, a failure of a single component necessarily puts the system in a state of wait and therefore of unproductiveness, this allows wide margins for cost optimization. The model that we have developed is based on the concept of thresholds which, when crossed by the parameter of wear, determine different maintenance interventions. The cost optimization consists in determining, by simulation, at what value the thresholds should be fixed to minimize the overall maintenance cost.

4.5.1 Introduction

Condition Based Maintenance (CBM) is a maintenance policy which aims to prevent component failure in a system, by controlling certain wear parameters and activating maintenance intervention when these parameters pass pre-determined thresholds. Deciding what value should the thresholds be arranged at, the same thresholds that determine a maintenance intervention, requests that we know the law that describes the deterioration of the components and also an economic valuation of convenience. Let us remember that our final goal is to minimize the overall maintenance cost, considering that if we arrange the threshold at a low value, we will be more protected against accidental failure but such an arrangement will necessarily involve many maintenance intervention, which obviously have their costs. Instead if we were to place the thresholds at high values we would have limited maintenance intervention, with limited associated costs, but the risk of sudden and unannounced failures with costs that quickly become considerable.

The multithreshold CBM is a more complicated deciding system where the thresholds for each component indicate a different wear state of the unit and as a consequence different decisions. Let us start describing the models inspection method. This model does not consider a continuous control of the state of wear, but inspections at discrete time every predetermined interval; in this way we can model the real act of inspection and associate to each inspection a determined cost and time consumption. In such a case the decision policy of the system can place one or more “alarm” thresholds between which the inspections become more frequent; in this way we would be able to keep under a better control the evolution of the components parameter of wear, trying to avoid unexpected failures.

A particularly interesting case are serial systems, because when a component of a serial system fails the whole system must be stopped, involving serious economic losses, except in the case inter operational buffers are present along the production line. In cases of a stop the cost is very consistent because it considers the unproductively of the production line, but also the costs to reactivate a normal flow of production, so it is typically convenient to use this time of inactivity for maintenance intervention on other components that in a close future would need preventive maintenance; this maintenance anticipating will be indicate such as “opportune” maintenance.

We have examined 21 scientific articles regarding CBM highlighting their characteristics. A great part of these articles (Grall *et al*., 2002; Castanier *et al*., 2005; Kececioglu and Feng-Bin Sun 1995, Barros *et al*., 2003, Christer and Wang 1995, Ohnishi *et al*., 1986, Dieulle *et al*., 2001, Liao et al. 2004, Van der Duyn Schouten and Vanneste 1995, McCall 1965, Park 1988, Newby and Dagg 1999, Chiang and Yuan 2001, Dieulle *et al*., 2003, Van der Duyn Schouten and Vanneste 1993) formulate an analytic model determining a solution to the problem, while the other articles (Castanier *et al*., 2004, Barros *et al*., 2005, Barata *et al*., 2002, Guizzi *et al*., 2006) use a simulation approach to determine the best solution.

In all the works the state of deterioration of a component is determined by a parameter of wear which increases continuously with time. In every article the function of wear of each component is determined by a stochastic law such as a gamma process (Grall *et al*., 2002, Christer and Wang 1995, Dieulle *et al*., 2001, Liao *et al*., 2004, Park 1988, Newby and Dagg 1999) or an exponential process (Castanier *et al*., 2005). Some of the models consider a multithreshold decision process (Castanier *et al*., 2005, Kececioglu and Feng-Bin Sun 1995, Castanier *et al*., 2004, Chiang and Yuan 2001, Guizzi *et al*., 2006), even though only some models take in consideration the use of an opportune maintenance threshold (Castanier *et al*., 2005, Kececioglu and Feng-Bin Sun 1995, Guizzi *et al*., 2006). Almost all the models observed consider that inspections are perfect, except (Barros *et al*., 2003) and (Barros *et al*., 2005); this means that there is no error during the measuring or monitoring process of the components wear.

In this work we have decided to realize a model of a system of N elements in series governed by a multithreshold CBM policy. We decided to use simulation techniques, so a series of simplifying hypothesis would not be necessary, on the contrary of the analytic models, leading to more realistic results. The goal of this model is to determine at what values we should place the different thresholds, which determine the decision that are made, so to minimize the global systems' maintenance cost.

4.5.2 Characteristics of the Model

This CBM model has to be representative of a real production system; each single resource can be modeled as deterministically or stochastically time consuming. The model keeps trace of the actual working time of a component. In fact a component will work only when it receives a work in progress from a precedent unit; in case the precedent unit is stopped (for failure or preventive maintenance) or in case of a temporary unbalance on the working line (caused by the stochastic working process), the following unit has to attend. After a discrete period of time the parameter wear, for each single component, will be increased for a value equivalent to the real operating time.

In all models based on CBM policy it is very important that inspections are correctly modeled. The models closeness to a real situation depends mainly on this aspect. All decisions that will be taken depend directly on inspection values, inspection errors will bring to corrupted maintenance decisions; in fact depending on the value of wear measured the system must decide what to do: preventive maintenance, opportune maintenance or delay in till the next inspection. Every single measurement is effected by uncertainty; this circumstance cannot be ignored because a casual event during a measurement can bring to wrong decisions. Therefore, in the model each measurement of wear will be considered to be not perfect, but affected by an error with a Gaussian distribution with null mean and standard deviation depending on the kind of measuring process.

The model considers three kind of threshold for each unit:

- preventive maintenance;
- opportune maintenance; and
- alarm.

The last kind of threshold can be present in a growing number, where they indicate a reduction of the period of time between inspections.

In most of the models examined, a component is considered to be in a state of failure when its parameter of wear passes a certain value, indicated as the failure threshold. This approach does not take in consideration the possibility that a unit can fail before it achieve a specific value of wear, for extraordinary events. Some of the models considered that the state of failure of a unit is noticed only with an inspection act. This hypothesis is unrealistic, except in cases where we define that a failure threshold is a value of maximum wear after which we necessarily must replace the component because it doesn't guarantee a proper function. Wanting to place the model with the most general non restrictive hypothesis possible, the hypotheses that we used are:

- failure of a component is possible at any value of the parameter wear;
- a wear limit which when is crossed by the wear parameter automatically brings the component in a state of failure does not exist;
- the probability of failure depends on the state of wear of each single component;
- when a component goes in a state of failure, it is instantly acknowledged and automatically implies the stop of the production line.

For this reason, we must build a continuous function defined in R^+ , which must return the probability of failure depending on a certain parameter. In scientific field, time is commonly used as parameter of the probability distribution function. The probability function that has been used in this model is a weibull, which is much more versatile then other, more common functions, such as the Gaussian or exponential. The parameter that describes the weibull function is wear, instead of the more commonly used time, depending on the fact that all units don't necessarily work continuously. This hypothesis is totally coherent with the CBM philosophy, which aims in measuring and controlling the state of wear of a unit to decide on eventual maintenance interventions. The fact that we have picked a weibull distribution does not compromise the model validity because in any case we can modify the probability density function used according to the components technologic characteristics.

In a series production line, stops caused by maintenance interventions on different components create an unbalanced situation along the production system. Wanting to have certain flexibility and contain different unit productivity, it would certainly be useful to insert along the line interpretational buffers. In this model we've considered only one buffer placed at the centre of the N units, in this way the line can be studied as if they were two distinct lines partially independent. Each machinery inside the two branches work as if between then there is a buffer with null capacity. When a unit stops, the other units of the same branch, once concluded the WIP, must stop too.

Instead, the units belonging to the other branch can work normally until the capacity of the buffer allows it. The buffer capacity is not sufficient to cover the whole period of unproductively caused by a maintenance intervention or a failure. In fact the buffer that we've considered is "realistic"; it represents a limited possibility to separate the production line. If we would have considered a production line with an interpretational buffer that has an infinite capacity, it would not have sense to study the two branches together. In the sphere of economic valuation of our system we have considered the buffers costs as the buffers capacity for the unit storing cost per time for each component stored.

Unlike most article publication on this subject, whatsoever intervention is not considered instantly, every maintenance intervention (corrective or preventive), as inspections, are considered time consuming. The period of time considered for each act can be determined by deterministic formulas or stochastic parameters. All this in the intent to move the model closer to reality. The time for an inspection of maintenance act can also stochastically vary depending on different parameter for different causes such as employees, or kind of maintenance act.

At last, we have introduced the possibility to have a limited amount of maintenance resources. Let's consider N element series, of which K of these N components need a maintenance intervention (which means that at least one component is in a state of failure, or the parameter wear has crossed the preventive threshold while the other K-1 components have crossed the opportune maintenance threshold), the model checks that K is not larger then M, where M is the max number of maintenance units (maintenance teams, technicians or component replacements). If K < M is true K maintenance acts will be accomplished, in the other case only M interventions will be made while the remaining K - M will be postponed in till the next production stop.

4.5.3 Model Costs

All inspections are made only if scheduled and with specialized personnel and instruments that have a cost that is variable in function of the time for which they are used, we will indicate these costs with $\mathbf{c_{v,insp}}$. Eventual fixed costs for inspections will be indicate with $\mathbf{c_{f,insp}}$.

The cost of each inspection can be calculated as:

$$\mathbf{c}_{insp} = \mathbf{c}_{f,insp} + \mathbf{c}_{v,insp} \cdot \mathbf{t}_{insp} \qquad (4.3)$$

where $\mathbf{t_{insp}}$ indicates the period of time for inspection to be made.

With every inspection we will not consider costs deriving from production loss because we've supposed that all inspections can be carried out while the machinery is working, the so called on-line monitoring.

Since we considered the hypothesis that every act of inspection is time consuming, we could consider the derivate cost due to labor and instruments during the inspection, in analogy with the preventive maintenance.

Preventive maintenance is carried out while the unit is not functioning, introducing costs for production loss. The indirect costs deriving from maintenance will be divided in fixed indirect costs, such as setup costs, that will be indicated with $\mathbf{c_{f,ind}}$. The other share of indirect costs will be indicated with Cv,ind and they will depend on the period of time that the unit is not working plus eventual penalties for late delivery. For preventive maintenance, we obviously must use resources such as man labor and specific equipment which will represent our direct costs. We will break down these costs in fixed and variable: the fixed costs $\mathbf{c_{f,main}}$

depend on the replaced components and consumable resources that have been used; the variable share of costs, will include man labor and reusable equipment, these costs will be indicated with $\mathbf{c_{v,main}}$. All variable costs will be considered per unit of time that they are used.

If we consider $\mathbf{t_{main}}$ as the period of time for a maintenance intervention, we can calculate the cost of any maintenance process as:

$$\mathbf{c_{main}} = \mathbf{c_{ind,main}} + \mathbf{c_{dir,main}} \tag{4.4}$$

where:

$$\mathbf{c_{ind,main}} = \mathbf{c_{f,ind}} + \mathbf{c_{v,ind}} \cdot \mathbf{t_{main}} \tag{4.5}$$

$$\mathbf{c_{dir,main}} = \mathbf{c_{f,main}} + \mathbf{c_{v,main}} \cdot \mathbf{t_{main}} \tag{4.6}$$

At the end of a maintenance process the unit repaired will be considered "as good as new" and also we will have to schedule when the next inspection comes, choosing the latest date possible, being that the component is considered as if new.

The opportune maintenance takes place only in case there's a maintenance shut down due to a corrective or preventive component replacement. And therefore an opportune maintenance intervention has the same costs as a preventive maintenance, except for the indirect costs that can not be associated to opportune maintenance that takes the "opportunity" of a plant shutdown to anticipate component replacement.

Corrective maintenance comes when a component fails. The indirect costs have the exact same expression as a preventive maintenance, where the only difference is that $\mathbf{t_{main}}$ will indicate the time of a corrective intervention.

Regarding the direct costs for a corrective maintenance intervention we will have that the costs of such an operation can be quite different from a preventive maintenance, caused by the fact that a component failure can complicate its replacement. Let us indicate, in an analogue way of the other costs $\mathbf{c_{v,fail}}$ variable costs of failure and with $\mathbf{c_{f,fail}}$ fixed costs of failure. The expression for the cost of corrective maintenance or failure is as the following:

$$\mathbf{c_{fail}} = \mathbf{c_{ind,fail}} + \mathbf{c_{dir,fail}} \tag{4.7}$$

where:

$$\mathbf{c_{ind,fail}} = \mathbf{c_{f,ind}} + \mathbf{c_{v,ind}} \cdot \mathbf{t_{main}} \tag{4.8}$$

$$c_{dir,main} = c_{f,fail} + c_{v,fail} \cdot t_{main} \quad (4.9)$$

As in the case of a preventive maintenance, even in a corrective replacement we will consider the component "as good as new" and the next date for an inspection will be scheduled the latest date possible.

4.5.4 The Simulation

The model has been developed in an "event driven" simulator: Arena® 8.0. We also implemented a VBA code that places in the systems parameter: the number N of units in series; their characteristics of wear and also the production parameters. The VBA code automatically generates the model in Arena with the same characteristic specified in the code. In addition we also used Access to build a database where all the data coming from simulations would be store and opportunely organized such as: costs, parameters, threshold values, number of failures, and so on.

Initial Data for Simulation

The model that we considered for our simulation is formed by eight units perfectly equivalent to each other for their productivity and deteriorating rate without interpretational buffers. This configuration, without compromising the generality of the study, lets us achieve very interesting results regarding the CBM optimization.

The parameters of cost for type of intervention on the system are reported in Table 4.3.

Table 4.3 System cost parameters

Description		Euro
Fixed cost of failure	$c_{f,gua}$	4.000
Fixed maintenance cost	$c_{f,man}$	400
Fixed setup cost	$c_{f,ind}$	300
Cost per hour of unit stop	$c_{v,ind}$	180
Cost per hour of maintenance and inspection labor	$c_{v,gua}$ $c_{v,man}$ $c_{v,isp}$	20
Fixed cost for inspection	$c_{f,isp}$	100

Regarding the period of time necessary for each maintenance intervention we have hypothesized as following:

1. The arrival of piece to the production line is described by a triangular distribution;
2. The time necessary to process each piece is considered constant;
3. The parameter wear increases in time by the means of a Gamma distribution;
4. The probability of failure is described by a weibull;
5. Time used for a single inspection is stochastically determined by a triangular distribution;
6. Time occupied by a preventive or opportune maintenance intervention is described by a uniform distribution;
7. A corrective maintenance is determined by a triangular distribution.

Naturally, in a generic application of this model we can modify both the distribution used and the parameters of cost or wear. In this way we can adapt the model to whatsoever system as long as were able to identify the right distribution, typically using historical data.

Finally, we set the initial values of each threshold that determines the decisions that we make; we hypothesized that the failure thresholds be placed at 700, while the other thresholds will be obtained by simulation and be placed so to minimize overall maintenance cost. Let's remember that the parameter wear is determined by a Weibull distribution and that the other thresholds are casually placed as long as they maintain their relative placements.

Table 4.4 Initial thresholds before simulation

Initial thresholds	Wear
Failure	700
Preventive	450
Opportune	400
Alarm 4	360
Alarm 3	270
Alarm 2	180
Alarm 1	90

We decided to place the initial thresholds following simple logic considerations, that are based on the process of failure but also on maintenance acts. The considerations made are based on a single unit and a series of process hypotheses (for example maintenance and inspection acts have been considered instantly); in this way we can obviously observe how a global minimum of cost on a series of units is not obtained by simply putting together single optimized units.

Number of Repetitions

The simulation duration is for 220 days with an initial warm up (transitory) of 20 days; in this way when the simulator starts accumulating data the initial configuration of a components wear is completely aleatority. Having the possibility of assuming one of the infinite states of wear.

The number of repetitions has been calculated with a statistic test on the semi amplitude with a interval of confidence of 1% of the measured value of the mean, and with a significance of 95%. We applied the two phases procedure, that brings to estimate the number of repetitions at the beginning and during the reduced phase.

We calculated that a repetitions needs about 1 minute and 10 seconds, considering even the warm up. At first we decide to carry out the simulation with a batch of 20 repetition, which require about 25 minutes, to determine an approximated value of the standard deviation and of the expected value. Once we got an estimation of these values, with the two phase procedure we determined the number of repetitions necessary to guarantee the precision requested on the confidence level.

Before starting an evaluation of the interval of confidence, we verified that the data in possession, obtained by a very long simulation run, were distributed as a Gaussian distribution. From this data we obtained the following evaluations:

Statistic Mean: $\overline{\mathbf{x}}$ = 833612.20 €
Standard Deviation: s =35972.65 €

At this point we determined the interval of confidence by using the Students Test. Appling the two phase procedure we calculated that the number of repetitions necessary as 75; in fact the semi amplitude fixed at 5% of the confidence interval is minor 8336.12, which is 1% of the value of the estimated mean.

Results of the Simulation

The total cost of the system, obtained by simulation are reported in the following Table 4.5:

Table 4.5 Results of the simulation

tot. main. corrective costs	1.562,37	
total machinery shut down costs	178.601,45	
depending on maintenance		89.327,03
inactive machine		89.274,42

Total inspection costs	11.098,60
Tot. opportune main. costs	0,00
Tot, preventive main costs	38.980,43
Overall Global Costs	230.242,85

During machinery shut down costs will include "machine inactive" costs, which represent the costs associated to a unit, not because it is in a fail state or being repaired, but because the production flow has been interrupted by the failure of other units along the production line. From Figure 4.13 it is obvious that the largest share of cost derives from indirect costs, while opportune maintenance costs are null. These means that the value at which the opportune thresholds were placed did not interact with the systems decisions.

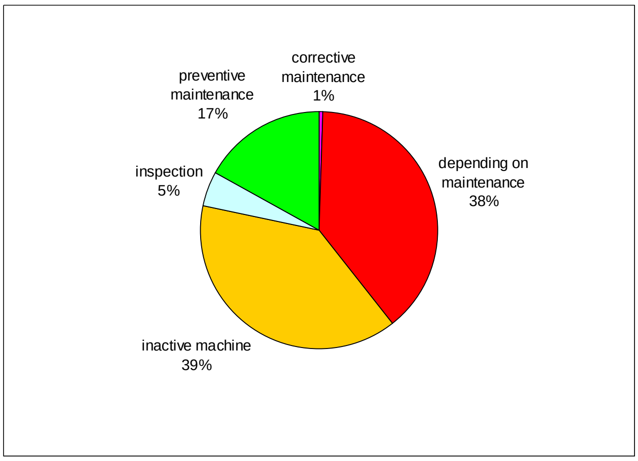

Figure 4.13 Maintenance cost divided by shares of the costs

4.5.5 Optimization

To optimize our model we decided to use an metaheuristic method, a metaheuristic procedure does need a longer time in calculation, but allows to arrive to a more efficient solution. For the optimization we have used an internal tool of Arena called Optquest. We decided to carry out a 100 interactions each one having a variable number of repetitions that go from 5 to 20. The number of repetitions can be less then 20 when the confidence interval is under 5%. Each run starts with a phase of warm up bringing the system out of a transitory state, then simulation continues for other 80 days, where data is stored and elaborated.

Optimized Results

Before obtaining the approximated global minimum, Optquest passes by a series of local temporary minimums. At the end of the metaheuristic process the optimized thresholds were the following:

- Preventive: 680;
- Opportune: 450;
- Alarm: 170.

And so, as we expected, the optimized thresholds are almost identical for all units. Even the global cost per unit and the different shares of costs were similar and equally divided between units, with the necessarily aleatority differences. The costs associated with the optimized thresholds are brought in Table 4.6.

Table 4.6 Costs with the optimized system

tot. main. corrective costs	4.528,27	
total machinery shut down costs	160.537,62	
depending on maintenance		56.739,23
inactive machine		103.798,39
Total inspection costs	14.288,50	
Tot. opportune main. costs	862,00	
Tot, preventive main costs	22.905,53	
Overall Global Costs	203.121,92	

The value of costs are also reported in Figure 4.14.

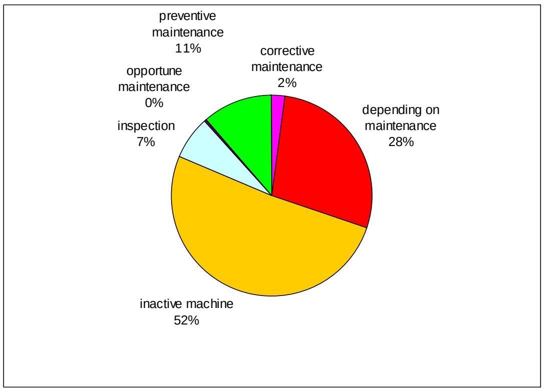

Figure 4.14 Composition of the optimized overall maintenance costs. In the following bar diagram we have compared all types of costs before and after the optimizing process.

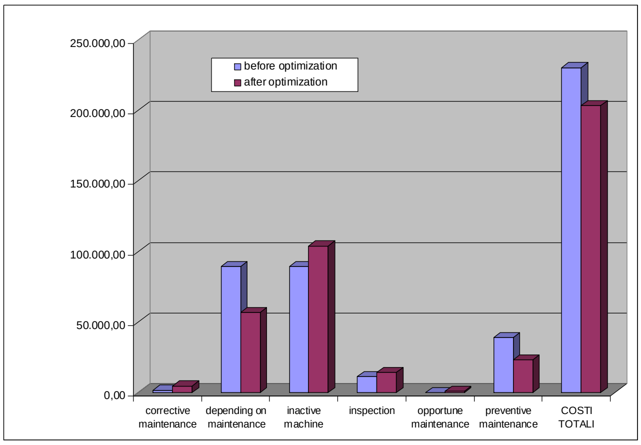

Figure 4.15 Comparison of the systems costs before and after optimization

Let us note that the total reduction of maintenance cost, which is about 12%, is obtained principally by placing the preventive thresholds at a greater value, this allows to reduce direct costs associated with preventive maintenance, but more importantly reduces indirect costs regarding the units waiting along the production line. We can believe that the settings of the preventive thresholds, for the characteristics of deterioration of all the identical units, was too cautious; in fact, before optimization, we had a derisive amount of break downs, that caused high costs in direct and indirect preventive costs.

This aspect can be also confirmed by the fact that before optimization the share of costs that derived from opportune maintenance were null; that means that in most cases, preventive maintenance would be accomplished without exploiting the production stop for other units maintenance.

Instead, once accomplished the optimization, even if limited, a certain quantity of opportune interventions have appeared.

As we intuitively expected, placing the preventive thresholds at a greater value increased the risk of failure bring along its relative costs, but the overall positive results on the economic convenience is quite comforting.

At last, the costs depending on inactive machine (machinery if functioning correctly but not working because of maintenance interventions on other units) has increased. This phenomenon can by explained by observing the fact that before optimization the preventive threshold was sufficiently low to allow more component replacement at the same time. While after the optimization the number of units that simultaneously get replaced are less, and therefore the time a unit waits in a functioning but inactive state increases, increasing all associated costs.

In Table 4.7 are report the percentages of time spent by the units in different states: failure, inactive (caused by the stop of the production line), in maintenance (all maintenance interventions are considered) or occupied in production. Let us notice that the eight units considered react in an identical way. And also the fact that the time available on each machine is practical the same, this because the deterioration law before and after the optimization are identical; the average availability before was 92,9% while after the average became 92,5%.

Table 4.7 Average % of time spent by the units in different states

MACH.	% FAILURE	% INACTIVE	% MAINT.	% OCC.
1	0,0000386	5,051	1,977	92,973
2	0,0000638	5,021	2,004	92,974
3	0,0000300	5,014	2,011	92,976
4	0,0001116	4,994	2,028	92,978
5	0,0000773	5,016	2,006	92,979
6	0,0001296	4,981	2,040	92,979
7	0,0000608	4,990	2,030	92,980
8	0,0000230	4,979	2,043	92,978

4.5.6 Conclusion

The decision regarding the use of an event-driven simulator has opened to the possibility of considering certain aspects of a maintenance policy that analytically would be too complex to be treated. The characteristics that have been added compared to the major works in literature are: accidental failures, measuring errors, maintenance and inspection operations time occupied and the probability of failure depending on the state of wear. This allows to adapt the model in a very realistic way to many different real processes.

The results that have been obtained with optimization are: a reduction of the expected annual costs in maintenance; but also the advantage of a greater, even if limited, unit availability. The optimization has evidenced the convenience in reducing the preventive maintenance in favor of opportune maintenance.

Some peculiarities of this model can be widely implemented in many applicative cases. Having built a CBM modeled policy that decides each maintenance operation on considerations that derive from the productive system in which it is integrated, we could also create dependencies that link indirect maintenance costs to production losses. This model can also be used for dimensioning the interoperational buffers or the expected maintenance resources necessary for a certain period of time.

Regarding eventual future developments, it could be interesting to remove the hypothesis “as good as new” repair or replacement. We could also try modeling different configurations such as for example units synchronized in parallel and with unit redundancies.

At last we consider the possibility of integrating different maintenance policies on the same model, for example we could have a system where some units work in till failure applying only corrective maintenance while other units can be preventive, scheduled or on condition based maintenance depending on the technical-economical convenience of each unit.

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5 Facility Management, Outsourcing and Contracting Overview

Roberto Cigolini

Abstract. The discipline of facility management has basically originated from the experience of the field and most of the business models are driven from the American market. The majority of surveys agree that organizational objectives vary according to different business environments. The link between a given company and its facility management department has been studied in details with a widespread agreement on the importance of tailoring to the specific context the facility management organizational model and the approach to the relationships with suppliers. In Europe two Technical Committees of the Comité Européen de Normalisation (CEN) are currently adding to the body of knowledge terminologies, guidance to prepare agreements, control systems for maintenance management and directions of development. On the basis of findings coming from both the literature and the standardization state of the art, the framework reported here has been focused on the multi-service result-oriented approach. The standpoint if the framework is in the early recognition that the main problem in the field implementations of result-oriented approaches lies in determining whether the expected results have been achieved or not; then, given that two key tools are available, i.e. the service level agreement and the reporting system, the framework suggests a new organizational and managerial structure, even simpler than the traditional (i.e. not integrated) one and whose kernel is based on the Define, Measure, Analyze, Improve and Control (DMAIC) approach early introduced by six-sigma.

The International Facility Management Association (IFMA) defines facility managements as a profession that encompasses multiple disciplines to ensure functionality of the built environment by integrating people, place, process and technology (IFMA, 2008). The discipline of facility management was introduced in 1975 (Maas and Pleunis, 2001) and grew in the United States throughout the 1980s and around the world in the 1990s. In Europe, facility managements was first established in the United Kingdom and the Netherlands (Hassanien and Losekoot, 2002) building upon the lessons learned in the United States. Other European countries (including Italy) did not show a proactive awareness of the opportunity offered by the facility management movement nor did they develop an organizational model tightly linked to their specific market needs. More recently, European standards for facility management have been developed by the Comité Européen de Normalisation (CEN), which are adopted by each national standard body. From a research perspective, the field of facility management is relatively new. Some theoretical taxonomies on facility management services have been developed (Barret, 1995; Nutt, 2002; Chotipanich, 2004). Other researchers have focused on the relationship between an organization and its facility management provider, which may be an internal department or an external supplier (Friday, 2003, James and Mona, 2004; Lee, 2002; Rondeau *et al*., 1995; Magee, 1998; Kenneth *et al*., 1999; Piper, 2002; Atkin and Brooks, 2000).

In the followings, after an overview of the facility management, outsourcing and contracting framework, we build upon this growing body of academic knowledge by presenting several papers focusing on facility management, outsourcing, and contracting.

5.1 Facility Management, Outsourcing and Contracting Framework

Innovation of technologies recently increased the complexity of organizations in the real estate branch of industry (Barret 1995, 2000), mainly due to that (on average) more than 50% of the buildings' value is tied to systems in their broader meaning, i.e. lighting, heating, hoisting, plumbing, electric installations, etc. whose effectiveness on the one hand improves the users' life quality, while – on the other one – it significantly increases management and maintenance requirements (Teicholz 2001). This raised a relevant attention towards the discipline of facility management, according to the International Facility Management Association (IFMA), which defines facility management as the practice of coordinating the physical workplace with the people and work of the organization, integrating the principles of business administration, architecture and the behavioral and engineering sciences. Findings coming from both the literature and the standardization state of the art show that facility management is a rather new discipline for which there is a twofold need: on the one hand for a comprehensive framework, especially in conjunction with the outsourcing practice; on the other hand, for structured approaches and organizational models, especially in conjunction with multi-service result-oriented contracts (Cigolini *et al.,* 2008).

In the recent years, service outsourcing has interested an increasingly greater number of business divisions, ranging from subcontracting some phases of the production process, to outsource logistics and transports. The reasons behind this trend are costs, know-how and service-level (Maurice and Greaver 1999, Auguste *et al.,* 2002, Ritter and Sternfels 2004, Arrunada and Vasquez 2006). The outsourcing practice theoretically allows great savings, since subcontracted services are part of the supplier's core business: the supplier should have developed a specific know-how, by comparison to the customer company for which the outsourced service represents a no-core activity. Furthermore, scale economies and investments in technologies – to optimize resources and processes – are preferably available for the supplier due to its services volume higher than the requirements of a single company. Finally, relying on external resources allows both to have on hand skilled and qualified personnel, and to simplify the organization, by improving flexibility and overcoming the hurdle of being diffident to changes. However, to actually benefit from these opportunities, the outsourcing phase has to be carefully assessed and properly managed e.g. through appropriate standards on agreement and on key performance indicators. These standards are very important to prevent from losing the control of activities and processes and from replicating the same complexity of the management structure (and even the high overhead costs) of an internal organization (Quinn and Hilmer 1995, Maurice and Greaver 1999) through multiple relationships with a huge number of suppliers.

For these reasons, many companies focused on the efforts to achieve results instead of on the activities, and a result-oriented approach is introduced. In this way customers and suppliers should have a common purpose, in that through the result-oriented approach the focus of the agreement is moved from merely providing a service to ensuring the result (Greaver 1998): e.g. for the air-conditioning service the result-oriented approach suggests to agree on the desired temperature and humidity instead of on the frequency of regulations and maintenance interventions, that are usually employed under a traditional approach. When deciding whether to use a result-oriented approach or not, a given company can either choose a different supplier for each service, with a different result-oriented contract (i.e. the traditional result-oriented approach), or choose a single supplier to provide all the services (i.e. the integrated multi-service result-oriented approach).

Unfortunately, field implementations of result-oriented approaches to mange outsourced services in the facility management area suffer from the hurdle of determining, without bias, whether the expected results have been achieved or not, i.e. in measuring the results itself (Harmon *et al,*. 2006). To solve this problem two key tools have been introduced (Hiles 2000, 2003), i.e. the Service Level Agreement (SLA) and the reporting system (Curl 1999, Kenneth *et al.*, 1999). The SLA is a dynamic document (usually enclosed to the contract) that reports the customer's requirements in terms of expected service quality, and it manages all the operational elements of the customer–supplier relationship, by defining the ways the services are supplied and the structure of bonuses and penalties. The reporting system links results (as defined by SLAs) and indicators (known as Key Performance Indicators – KPI; see e.g. Magee 1998 and Cotts 1999) to measure results without bias during the services supplying in terms of both the service quality (i.e. service level) and the performances (i.e. costs and quantities). Finally, despite a widespread use of SLAs and KPIs, a poor ability to manage and to control a range of complex services of various types yields high costs and operational inefficiencies, without an appropriate organizational and managerial structure, which is actually even simpler than under the traditional (i.e. not integrated) approach.

The traditional not integrated approach is characterized by splintered communications and information flows concerning the services: all the actors have several interfaces and different suppliers can overlap their areas, which creates hurdles to manage operations, to recognize responsibilities and to measure performances. By contrast, the integrated multi-service result-oriented approach allows the customer to have only one interface for each service, which leads the responsibilities to be straightforwardly attributed to the right supplier of person: the customer has no relationship with the subcontractors for the services not directly provided by the integrated multi-service result-oriented contract supplier, which is actually the sole player in charge of and responsible for managing and controlling subcontractors.

Another building-block of the integrated multi-service result-oriented approach is the customer satisfaction measurement (Hayes 2000): to do so, the perceived service quality has to be combined with the importance given to each service by the customer and to compare the perceived and the actually supplied quality: sometimes outsourcers oversupply a not requested quality level on a service perceived as not critical by the customer, while the quality supplied in a perceived critical service does not properly fit customer's expectation so that appropriate actions have to be taken. In this area, KPIs highlight specific characteristics of a supplied service and they are usually embedded into a dashboard, i.e. a control scorecard showing quantitative indications on the current status (Piper 2001) of the set of services included in the contract itself. To develop an effective dashboard, all the data should be collected correctly and promptly, e.g. by providing all the suppliers with the proper technology and with a guideline for the process, and a procedure should be developed to calculate all the KPIs.

Finally, regardless the organizational structure, the analysis of various real-life cases (Harmon *et al.,* 2006) suggests the performance control to be the key for a successful integrated multi-service result-oriented relationships: a fair communication pattern between customer and supplier actually represents the backbone of the whole framework. If something is missing or inadequate at this level, information systems, dashboards, KPIs etc. will yield an increasing costs effect without any specific benefit. Thus, implementing an integrated multi-service result-oriented relationship is never effortless from the organizational point of view and the overall simplification in the long term requires a significant effort in the short one. For this reason, the majority of companies (George 2003, Friday and Cotts 1995, Pande *et al.,* 2000, Sievert 1989) have to resort to the Define, Measure, Analyze, Improve and Control (DMAIC) methodology, firstly introduced within the six-sigma framework (Gupta and Wiggenhorn 2003, Pyzdek 2003) due its strong basis on measurements as prerequisite for control.

5.2 Overview of Papers in the Field of Facility Management, Outsourcing and Contracting

The first selected contribution deals with the challenges, possibilities and limits of existing and future European standards in the area of facility management (Van Der Zwan 2007). To this purpose, the European Council has declared that an open and transparent market in the area of services is desired, to compare figures, quotations and even organizations; standardization represents one of the major tools to realize this and standardization in the area of facility management directly involves several business services: CEN TC 348 is the platform on which European Standards in the area of Facility Management are developed. In particular, four new standards are to be developed and, i.e. quality, service levels and key performance indicators; taxonomy; processes; space measurement. These new standards are planned to be published in 2010 so to allow reliable benchmarking.

By going ahead in the field outlined by Van Der Zwan (2007), the paper conceived by Straub (2007) presents the Dutch standard for condition assessment of building and installation components introduced in 2006. This standard helps building inspectors to provide property managers with objective, reliable information about defects and condition of building components so that property managers can exercise control over maintenance performance levels and maintenance costs. Aggregated condition data could be used for setting condition targets for assets and for benchmarking buildings, housing estates and assets. Furthermore, technical data collected during a condition survey on-site is needed for maintenance planning of each building; supplementary technical information is needed for the detailed planning and executing of maintenance work: condition assessment improves the communication between inspectors, the responsible maintenance planning department and management. In the end, the assessment and setting of priorities for planned maintenance work is a way to tackle problems of lacking maintenance funds: using the condition scale in the planning process gives the opportunity to vary the performances of building components and maintenance performance levels can be based on the (minimum) condition of building components after executing maintenance work.

The contribution of Martinez (2007) is aimed at managing maintenance contracts, particularly when they are placed within a Private Financial Initiatives (PFI) project: PFIs have rapidly become an excuse to improve facility management skills as well as to raise maintenance to a much more strategic level. The main purpose of these schemes (other than the substantial economical relief to the cash flow of public administrations) is to transfer the risk of maintaining a given level of services during the 25 years of the contract. The special purpose vehicle (or joint venture) in charge of maintaining these levels, is often not nominated to choose the equipments or the installations they will have to be responsible of neither it is appointed responsible for other services like cleaning or security. The paper presents how on a large, non-UK-style PFI, the maintenance contract can act as the controller of the rest of the services, by using a very flexible model where static service level agreements have been substituted by some sort of card where not only service level is included but elements such as reporting, procedures, indicators or implied personnel are part of the so-called 'puzzle piece'. By looking ahead to the future, the author guesses that facility management practitioners must get familiar with PFI schemes because a large part of facility management and maintenance contracts will run under some level of similarity to this projects: this type of model can be extended to contracts where several providers are involved and the amount of risk transferred within these contracts, will always be full for services like maintenance and far from being this a handicap, it has to be used to develop stronger models, built around this operational issue but with an important input of strategic weight; the actual maintenance contracts based on a mere activities fulfillment will turn into systems performance evaluation.

Finally, the contribution of Aiello *et al.* (2007) deals with the design of effective maintenance outsourcing contracts. Recent developments in maintenance planning and management demonstrate that optimized maintenance policies may drastically improve the performance and reduce the operating cost of facilities. However maintenance activities are typically outside of the core business of production facilities, hence enterprises often fail to catch the opportunities that may originate by properly optimized management strategies. A strategic maintenance management encompasses the possibility of outsourcing maintenance activities, while allowing enterprises to concentrate their resources on their core activities. In order to be effectively undertaken an outsourcing strategy must be supported by a proper performance oriented contract. The paper aims at providing an adequate methodology to address such issues and at defining a framework for the definition of the relevant contract variables such as availability levels, penalty policies, rewards and service cost. The methodology here proposed is based upon the evaluation of the expected profit function of both the outsourcer and the provider, by performing a trade-off analysis on the basis of the transaction costs.

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5.3 The Challenges, Possibilities and Limits of Existing and Future European Standards in the Area of Facility Management

Jappe van der Zwan

Abstract. The European Council (EC) has declared that an open competition in the area of services between market sectors and different parties was desired. This means an open and transparent market is desired, in order to be able to figures, quotations and even organizations can be compared. Standardization is in the opinion of the EC one of the major tools to realize this. Standardization in the area of Facility Management fits perfectly into its policy as it directly involves several business services. One of the most important advantages is that the market itself is able to determine the content of these European standards. Under the responsibility of the European Standardization organization CEN (www.cen.eu), the technical committee CEN/TC 348 “Facility Management” is the platform on which European Standards in the area of Facility Management are developed. This initiative has been recognized by EC as a very good example of a market defining its own standards. The first two European standards have been published. In EN 15221-1 the basic terms of Facility Management are defined and their relation is explained. EN 15221-2 provides guidance for the preparation of an effective Facility Management agreement. The next phase in the development of 4 new standards focused on reliable benchmarking in Facility Management:

1. facility management – taxonomy (structures and definitions);
2. facility management – processes;
3. facility management – quality, service levels and key performance indicators (benchmarking); and
4. facility management – space measurement

These standards will be ready in June 2010.

5.3.1 Introduction

Facility Management is developing in various European countries. Driven by certain historical and cultural circumstances, organizations and business areas have built different understandings and approaches. In general, all organizations, whether public or private, use buildings, assets and services (facility services) to support their primary activities. By coordinating these assets and services, using management skills and handling many changes in the organisation’s environment, Facility Management influences its ability to act proactively and meet all its requirements. This is also done to optimize the costs and performance of assets and services.

In this paper challenges, possibilities and limits of existing and future European FM-standards are identified.

5.3.2 Standards and Standardization

Standards

Standards are agreements on all different kind of subjects. They are created for and by the market. The content of the standards is to be determined by the market itself. Standards are private international law, so it is not mandatory to use them. So these standards will only be used when the added value is clear. Sometimes standards are made mandatory by the European Commission or national governments. They become law and regulations, bit still the content is to be decided by the market parties itself.

Standards are made on national level, European level (via CEN) and international level (via ISO). The focus in this paper is on CEN.

CEN is a system of formal processes to produce standards, shared principally between:

- 30 National Members and the representative expertise they assemble from each country. These members vote for and implement European Standards;
- 8 Associate Members, 5 affiliates and 2 Counsellors;
- the CEN Management Centre, Brussels.

Standards development is mainly done in Technical Committees (TCs). In total there are over 350 existing TCs active. These TCs deliver European standards.

The main principles of standardization are the following:

- standards come from the voluntary work of participants representing all interests concerned: industry, authorities and civil society, contributing mainly through their national standards bodies;
- draft standards are made public for consultation at large;
- the final, formal vote is binding on all members;
- the European Standards must be transposed into national standards and conflicting standards withdrawn.

Standardization

Standardization diminishes trade barriers, promotes safety, allows interoperability of products, systems and services, and promotes common technical understanding. All standards help build the “soft infrastructure” of modern, innovative economies. They provide certainty, references, and benchmarks for designers, engineers and service providers.

In addition**,** regional or European standards are necessary for the single market and support the Union's policies for technical integration, protection of the consumer, and promotion of sustainable development.

Therefore, standards may provide for compatibility between products or systems, may serve to enhance quality, may efficiently reduce variety and promote understanding of technology by providing information.

These generalities are underlined by research on the economical aspects of standardization.

- the Fraunhofer Institute concluded that the economical return of standardization is 1% of gross national product. This means 1 Euro investment in standardization returns 100 Euro;
- in the study "The empirical economics of standards" by DTI Economics from June 2005, one of the conclusions was that elasticity of labour productivity with respect to the number of standards is about 0.005 (1% increase standards catalogue is associated with 0,05% increase in labour productivity: standards contributing 13% of the growth in labour productivity in the UK over the period 1948-2002. Also standardization could enhance innovation, of course depending on the timing.

Relation with the European Committee

In the view of the European Committee services are the input for the rest of the economy. They have declared that an open competition on the area of services between market parties is desired. This means that we should be able to compare figures or quotations (or even organizations). An open and transparent market is important for them.

The question is how to improve the competitiveness of services. One of the conclusions was that standards could be useful! In a meeting at the start of the project, they emphasized that for support and connection with the European committee for the initiative of developing European standards in facility management, the definition of facilities should be described at such a way that it can be integrated in the so called "NACE-code".

So the European commission is focusing very much on services. And one of the main objectives for the European committee is to create an open and transport market. Standardization is in their opinion one of the major tools for that.

The platform in which standardization in the area of Facility Management takes places is CEN/TC 348 "facility management". This CEN/TC is seen as one of the good examples of a market defining its own standards.

5.3.3 Facility Management in General

The main benefits of facility management approaches in organizations are:

- a clear and transparent communication between the demand side and the supply side by using dedicated persons as single points of contact for all services, which are defined in a facility management agreement;
- a simple and manageable concept of internal and external responsibilities for services, based on strategic decisions, which does lead to systematic insourcing or outsourcing procedures;
- an integration and coordination of all required support services;
- a reduction of conflicts between internal and external Service providers;
- a transparent knowledge and information to service levels and costs, which can be clearly communicated to the end users;
- a most effective use of synergies amongst different services, which will help to improve the costs and performance of an organization.

The development of standards on facility management would help smaller and larger organisations offering facility services in this market to cooperate and exchange knowledge and business on international bases. By creating a European platform this will break down barriers between markets for facility management service providers as well as their customers.

5.3.4 General Tendencies in Facility Management

Facility management has changed considerably in the past years. From a discipline that was primarily building oriented, it is becoming more and more a business service oriented discipline. European-wide the development has different accents, approaches and timescales but a few general tendencies can be addressed. The following tendencies are seen:

- the scope of facility management is different in the various European countries, but in general expanding and is moving towards a general view on business services. The added value of facility management is the integration of these business services. Trends in various countries towards broadening the range of services are forecasted to continue;
- it seems building operations and maintenance are still the biggest sector, but business services and ICT quickly growing in an emerging e-economy;
- in the process design-build-(operate)-maintain organizations extend their activities to the chain. Organizations build and maintain building for a period of time. Also the management and provision of several services may be included. Public policy is a driving force in this development process;

- outsourcing non-core and lately as core business is a very common business approach. In most situations it started from the cost effectiveness approach, but now it also emphasizes on the added value to the primary activities. It has become a vital part in organizations;
- as the FM-market professionalizes, it is foreseen that the length of contracts will increase;
- service providers become more and more multi-service providers, including more services and the management of these services. Hard and soft services are being integrated;
- generally, the FM-market remains diverse, highly fragmented and very competitive, with consolidation into very large, global operating companies but in also the introduction of smaller organisations;
- as facilities become an increasing part in costs, more attention is given from a financial point of view. Focus on benchmarking increases. Also the measured approach to service delivery is needed to ensure a consistent quality of service is maintained. Benchmarking is one of the major issues now and in the coming years;
- the level of professionalism varies throughout Europe, but the development of a more professional facility management within the different European countries goes fast.

Standardization in the area of facility management supports the maturity of profession. Both within the facility management-sector, but also outside the facility management-profession.

5.3.5 Quantitative Indicators

Introduction

As the profession is still relatively young and the scope of facility management differs in various European countries. It is difficult to gather market statistics. Within the existing classification system throughout Europe (Eurostat), facility management is not (yet) a separate class. On a level per country relevant information sometimes can be found, which give at least an indication of the size of the market.

The figures below indicate that, although a rough estimation, the market is big, but more research needs to be done on this to get more reliable figures.

EN 15221-1

In EN 15221-1 *facility management – terms and definitions*, the following sentence is part of the introduction: "The market of facility management (internal and external) in Europe with an estimated volume of several hundred billion Euros"

Table 5.1 IPD/NFC Index

EUR/workplace	2005	2004	2003
Accommodation	EUR 4.884	EUR 4.621	EUR 4.368
EU total EUR 1.250 billion *			
Facility Services	EUR 1,947	EUR 2.024	EUR 2.578
EU total 531 billion *			
ICT	EUR 4.284	EUR 4.242	EUR 4.200
EU total EUR 1.156 *			
External facilities	EUR 112	EUR 415	EUR 578
EUR total 31 billion			
FM/organization	EUR 429	EUR 438	EUR 625
EUR total 125 billion *			
Total per workplace per year (20m2)	EUR 11.657	EUR 11.740	EUR 12.349
EU total EUR 3.093 billion *			

* Estimations based on IPD and NFC Index figures, 2005
Source: NFC Index, www.nfcindex.nl
Source: IPD Total Occupancy Cost Code, www.opd.co.uk
Source Villa FM, www.villafm.eu

BIFM

In the UK estimates vary, but market research suggests that the sector is worth GBP 96 billion per year. Source: British Institute for facilities management (BIFM), www.bifm.org.uk.

5.3.6 CEN/TC 348 "Facility Management"

Roadmap

The history of European standardization in facility management starts in September 2001. In the Netherlands the Dutch standard NEN 2748 “facility management-terms and definitions” is published. NEN 2748 organizes the field of FM by defining and classifying activities. Facility management costs can be determined and can be a mean for internal and external benchmarking.

During the process, the Dutch national standardization committee concluded that not only the Dutch market needed a standard, but also the European market could benefit from standardization in this area. So the proposal to bring NEN 2748 to a European level was done. As other European countries were already working or even had standards this proposal was rejected and on the subject a CEN/BT/WG was established. This working group had the assignment to discuss the exact scope of the future body, its work program and the way of developing future standards, and had to make a concrete proposal for endorsement. This was in December 2001.

A first meeting of this working group was organized in November 2002. A total of 41 participants from 14 different countries particpated during the first meeting in Amsterdam. After the meeting in Amsterdam, meetings were held in Berlin and Delft. In May 2003, the working group felt their task was completed. A business plan was written and approved, so the project was ready for take-off. Most important conclusions were the fact that a CEN/TC was needed for the subject and the focus would be on 2 standards: a standard on facility management terms and definitions and a standard giving guidance on how to prepare facility management agreements.

In September 2003 the official CEN/TC 348 “facility management” was established. In 2006, the first two standards were published: EN 15221-1 and EN 15221-2.

As these are voluntary standards, the intention is that the market accepts these standards as beneficial to enterprise and implements them. Only if standards are accepted as useful to business and implemented, will the goals will be reached. If not, the standards will be useless. In the process on developing standards, this is becoming more and more important. It implies that relevant stakeholders should be brought to the able in order to be able to realize this.

Objective

The objective of CEN/TC 348 "facility management" is to reach the benefits of standardization as described below.

The target group for the standards to be made is public and private stakeholders.

The benefits of standardization should be:

- improve competitiveness in global market;
- improve effectiveness of primary and facility management processes;
- improve transparency in procurement and contracting;
- quality improvement of output;
- supports certification;
- means of communication between stakeholders;
- development of new tools and systems.

Organisation

CEN/TC 348 “facility management”
Chairman: Mr. Remko Oosterwijk (The Netherlands)
Secretary: Mr. Jappe van der Zwan (NEN).

- *WG 1 “terms and definitions”*
  Convenor: Mr. Paul Stadlöder (Germany)
  Secretary: Mr. Jappe van der Zwan (NEN);
- *WG 2 “facility management agreements”*
  Convenor: Mr. Stan Mitchell (UK)
  Secretary: Mr. Jappe van der Zwan (NEN)
  CEN Member responsible: NEN;
- *WG 3 "quality in facility management"*
  Convenor: W. Moderegger (GER)
  Secretariat: E. Finck (DIN, Germany);
- *WG 4 "taxonomy of facility management"*
  Convenor: M. Christen (CH)
  Secretariat: E. Huegentobler (SNV);
- *WG 5 "processes in facility management*
  Convenor: Prof. K. Alexander (UK)
  Secretariat: C. Molloy (UK);
- *WG 6 "space measurement in facility management"*
  Convenor: Prof. U. Elwert (GER)
  Secretariat: E. Finck (DIN).

Participants and Liaisons

The following countries do participate actively within CEN/TC 348 and its working groups: Austria, Belgium, Denmark, France, Germany, Hungary, Ireland, Italy, The Netherlands, Norway, Sweden, Switzerland and United Kingdom.

In these countries mirror committees have been established that to follow the work of CEN/TC 348, judge its documents and bring forward their input, point of view on the subject. Mirror committees should represent the interested parties in the FM-market and are coordinated by national standardization bodies. Other countries follow CEN/TC 348 more form the sidelines, but still have to obligation to implement the standards when they are finalised.

Also liaisons are established or are to be established between CEN/TC 348 and major other CEN/TCs, like CEN/TC 247 "building automation, control and building management" and CEN/TC 319 "maintenance", but also other major parties on the European market like EuroFM and ETSA.

EuroFM is the leading facilities management network in Europe with more than 75 member institution from 19 countries. In supporting its mission, the advancement of FM knowledge across Europe, EuroFM has played an important role of liason partner in the development of standards so far and is actively supporting the next phase of this project.

EuroFM and CEN/TC 348 wish to support each other in the process of developing market standards in the FM industry in Europe and thus wish to coordinate their activities.

Challenges

The main challenge within standardization is to reach consensus regarding the content of the standards. A difficult job considering the following aspects:

- different languages: within CEN/TC 348 all different languages are spoken. Of course, meetings are in English, but communicating and understanding each other proves to be difficult. Lots of discussions take a lot of time because of the language difficulties. This is the main challenge within the process and, of course, this underlines the importance of a European standard on terms;
- different views of facility management: the views on the subject differ. This is logical, because a group of professionals have all their different views. There is nothing strange on that but as reaching consensus in complex matters is always a challenge;
- different development stages of facility management: it is very interesting to see that the maturity of facility management differs in the various countries. What was common practice in a country yesterday might be common practice in another country today. Concepts that are state of the art and really work well in one country are outdated in other countries.

Maybe the best example is outsourcing, which is hot in some countries, but very cold in others;

- different cultures and markets: of course also different cultures and markets within the various countries influence the way business is done.

EN 15221-1 Facility Management–Terms and Definitions

In order to have a common language, this standard aims to describe the basic functions of facility management and defines the relevant terms, which are needed to understand the context. In other words the basis of facility management is laid down.

The purpose of EN 15221-1 is to define the terms in the area of facility management in order to:

- improve communication between stakeholders;
- improve effectiveness of primary activities and facility management processes, as well as the quality of their output; and
- develop tools and systems.

EN 15221-1 is a lead document in terms of standards in facility management that other initiatives should follow. Initiatives for other standards, guidelines and technical specifications cannot be made without reference to this lead document.

The definition of facility management is: *integration of processes within an organisation to maintain and develop the agreed services which support and improve the effectiveness of its primary activities.*

Facility management covers and integrates a very broad scope of processes, services, activities and facilities. The field of facility management is structured and a list of examples of services/activities and facilities is given. The basic concept of facility management is to provide integrated management on a strategic and tactical level to coordinate the provision of the agreed support services (facility services). This requires specific competencies and distinguishes facility management from the isolated provision of one or more services.

Annex A presents the facility management model which provides a framework describing how facility management supports the primary activities of an organisation. It deals with the demand and supply relationship and presents the different levels of possible facility management interaction. In order to succeed and deliver required results, facility management shall be in close synchronization with the mission and vision of the organisation and its objectives. Therefore, facility management acts on the main levels: strategic, tactical and operational. The activities on these levels are described.

EN 15221-2 Facility Management–Guidance on how to Prepare Facility Management Agreements

The objective of EN 15221-2 is to provide guidance for preparing an effective facility management agreement. Such an agreement by nature, defines the relationship between an organisation that procures facility services (client) and an organisation that provides these services (facility management service provider).

The purpose of EN 15221-2 is to:

- promote cross-border client/facility management service provider relationships within the European Union and to produce a clear interface between the client and the facility management service provider;
- improve the quality of facility management agreements so that disputes and adjustments are minimised;
- assist in the selection and scope of facility services and to identify options for their provision;
- give assistance in, and advice on, the drafting and negotiation of facility management agreements and specify arrangements in case of dispute;
- identify types of facility management agreements and make recommendations for the attribution of rights and obligations between the parties of the agreement;
- simplify comparisons between facility management agreements.

The document is a working and standardised tool intended for parties who wish to draw up the facility management agreement within the European common market. It offers headings, which are not exhaustive. Parties may or may not include, exclude, modify and adapt these headings to their own agreements.

EN 15221-2 is applicable to:

- facility management agreements for both public and private European Union cross-border, as well as domestic, client/facility management service provider relationships;
- full range of facility services;
- both types of facility management service providers (internal and external);
- all types of working environments (e.g. industrial, commercial, administration, military, health etc...).

This European standard is primarily written for facility management agreements between a client and an external facility management service provider. However, a large part of this standard can be applied to cases where the facility management service provider is an internal entity within the client's organisation and be very helpful to set up an approach based on Services Level Agreements (SLA). It does not replace any specialized standards related to services within the scope of the facility management agreement.

5.3.7 New Work Items

During the development process CEN/TC 348 drafted a shortlist of possible new standards. After a consultation of all members, it was decided to give the main focus on standards that could enhance reliable benchmarking. From the shortlist, 4 new standards to be developed were identified, all supporting the need to be able to compare and improve performance in the area of Facility Management. These new standards to be developed are:

- facility management – quality, service levels and key performance indicators;
- facility management – taxonomy;
- facility management – processes;
- facility management – space measurement.

With these additional European standards the following benefits will be achieved:

- a common language for all professionals in Europe;
- faster, transparent and comparable specifications;
- different structures linked together and compatible with each other;
- basis for the development of tools and systems and to create interfaces between systems;
- clearly defined performance indicators and effective benchmarking.

The set of standards is planned to be published in 2010, it will be a great step towards reliable benchmarking.

5.3.8 Lessons

CEN/TC 348 proves to be a good platform for developing the standards. Within a relatively short period of time, good results have been booked. The main importance is the quality, professionalism and commitment of the people involved within CEN/TC 348. This could also be seen as one of the weaknesses as the system strongly depends on (voluntary) work of participants. From a project point of view, the strategy of CEN/TC 348 is to limit the number of standards to be developed simultaneously. Coordination between standards is very important. Capacity of the participants is limited and quality is of the biggest importance.

Standardization will only be successful if participants see these benefits and participate actively (“broadly based”). This means that all interested parties should participate in the development of the standards. Partially this is handled by the CEN system with mirror committees in various countries. But the communication around CEN/TC 348 and standardization needs to be improved and facilitated, in order to create more awareness for the interested organizations.

A liaison with EuroFM is established. It is important because EuroFM is the leading FM-network in Europe with a wide exposure and a lot of knowledge.

At the end standardization is not successful as standards are being developed, but only if these standards are also used. Standardization of Facility Management is accepted by national branches and EuroFM. This could enhance the implementation. A successful implementation depends on the availability of products and tools that eases the implementation of a standard. An important restriction is that the effort for implementing standards is reasonable. Another critical issue for successful implementation of standards is that they are broadly based as the results will be a balance of the different interests between the demand side and the supply side.

The work within the CE/TC 348 is done in an open, respectful and professional manner. More and more countries become aware that standards have a lot of added value to the profession. This doesn't mean that there are (fundamental) different ideas, opinions, approaches etc.., but as standardization is a process of consensus, at the end coming to a conclusion and publishing standards is of highest importance.

5.3.9 Contributors

Big standardization projects cost money. NEN is a non-profit organisation, but the costs need to be covered. For this packages have been developed and the following contributors have been found. Those organisations see the added value of the standards both for their own organisation but also for the FM-community as a whole. Without their support it will not have been possible to realize the 4 new standards. It also implies the broad interest of organisations.

The main contributors are: Facility Management Nederland (FMN), KLM Facility services/Sodexho, Imtech, Nordined Prequest and Capgemini. Other contributors are: NFC Index, FMweb, Dutch Government Building Agency, Ministry of Transport, Public Works and Water Management, Shell, ABN Amro, DTZ Zadelhoff, DNB, UPC, Delta Lloyd, Ballast Nedam Services, Facilicom , Wielinga Consultancy and Jones Lang LaSalle.

5.3.10 Conclusion

CEN/TC 348 proves to be a good platform for developing the standards. The first two European standards have been published. In the EN 15221-1 *facility management – terms and definitions* the basic terms of facility management are defined and their relation is explained. The EN 15221-2 *facility management – guidance* *on how to prepare facility management agreements* provides guidance for the preparation of an effective facility management agreement. It is a working tool for interested parties and it respects the EC directives that requires public contracts above a certain amount to be made available to all facility management contractors throughout the EC.

The implementation of the standards is important and needs to evaluate in the coming years.

Four new standards are to be developed:

- facility management – quality, service levels and key performance indicators;
- facility management – taxonomy;
- facility management – processes;
- facility management – space measurement.

With these additional European standards the following benefits will be achieved:

- a common language for all professionals in Europe;
- faster, transparent and comparable specifications;
- different structures linked together and compatible with each other;
- basis for the development of tools and systems and to create interfaces between systems;
- clearly defined performance indicators and effective benchmarking.

The set of standards is planned to be published in 2010, it will be a great step towards reliable benchmarking.

5.4 Dutch Standard For Condition Assessment of Buildings

Ad Straub

Abstract. Asset management and maintenance management should be based on objective, reliable information about the performance of buildings and building components. Technical data collected during a condition survey on-site is needed for maintenance planning of each building. Supplementary technical information is needed for the detailed planning and executing of maintenance work. In 2006 the Dutch standard for Condition Assessment of Building and Installation Components was introduced. This standard helps well-trained building inspectors to provide property managers with objective, reliable information about defects and condition of building components. Property managers can exercise control over maintenance performance levels and maintenance costs. Several large property owners want to use the condition data for strategy formulation and asset management purposes too. Aggregated condition data could be used for setting condition targets for assets and for benchmarking buildings, housing estates and assets.

5.4.1 Introduction

Building maintenance can be divided into three strategies: corrective, preventive and condition-based (Horner *et al.* 1997). Some authors refer to preventive maintenance as time-based maintenance, planned maintenance or cyclic maintenance. Condition-based maintenance is defined as preventive maintenance based on performance and/or parameter monitoring and the subsequent actions (CEN 2001). Condition assessment, maintenance planning and performance control are key processes in condition-based maintenance.

Technical data collected during a condition survey on-site is needed for building maintenance. All building components have to contend with performance loss through ageing, use, and external causes. Performance loss is measured in terms of defects ascertained. The defects are registered during a condition survey or condition assessment. In for instance the United Kingdom client experiences of stock condition surveys has been far from satisfactory (Chapman 1999). The practice of condition assessment by building inspectors yields variable results due to subjective perceptions of inspectors. Surveyor variability is defined as the situation where two or more surveyors, surveying the same building, arrive at very different survey decisions (e.g. Kempton *et al.* 2001; 2002). This variability is caused by a variety of factors such as previous experience, attitude to risk and, heuristics – the use of ‘rules at thumb’, and biases – a learning towards a particular opinion regardless of the available evidence.

The use of condition marks of building components makes the technical status transferable between building inspectors and property managers. Property managers can exercise control over maintenance performance levels and maintenance costs. Is also makes the technical status transferable between the maintenance department and those involved in setting up the asset management.

Research Question

This paper mainly discusses the process of condition assessment with the help of a standardized tool, namely the Dutch standard for Condition Assessment of Building and Installation Components.

The main research question is: How can the practice of condition assessment be standardized? The second research question is: How can large property owners and especially housing associations use condition data for maintenance planning and asset management purposes?

The paper is based on an analysis of the Dutch Standard of Condition Assessment of Building and Installation Components, a literature review, the outcomes of various conducted and ongoing research projects by the author about condition assessment and maintenance planning by Dutch housing associations.

This paper is comprised of six parts: standardization, the condition assessment process, maintenance planning, condition aggregation, limitations and conclusions.

5.4.2 Standardization

A lot of national and international research has been done to create objectivity in the inspection process, especially for large-scale surveys, that should result in unambiguous information for maintenance and retrofit strategies (e.g. Abbott *et al*., 2007; Caccavelli and Genre 2000; Damen *et al*., 1996; 1998; Jags and Palmer 2000).

As a result of several research projects and the use of the method by the Dutch Government Buildings Agency and in the Dutch Qualitative Housing Registration, the process of condition assessment using standard lists of defects and a six-point scale has become popular by property managers of housing and real estate, consultants and contractors in the Netherlands. A representative survey among Dutch housing associations shows that in 2003 90% of the building inspectors register the type of defects and the extent of these defects. A third one of the housing associations use condition marks to record the technical status of the building components (Vijverberg 2004). But, the condition assessment methods vary for the hierarchical classification of building components, classified defects and the use of condition parameters. Several condition assessment methods lead to variable resulting condition marks, whilst examining the same defects (Straub 2003).

Standard Condition Assessment

The different results of various condition assessment methods are not a drawback in practice. Important is that within an organisation all building inspectors handle they're own method the same way. However, it is a handicap in the transfer of people and knowledge between property managers, consultants and maintenance contractors and e.g. for benchmarking purposes within and between organisations. Standardization is seen as a tool to uniform this.

In 2002 the Dutch Government Buildings Agency took the initiative to standardize the condition assessment of building components, including building services. The aim of this standard is an objective assessment of the technical quality, to provide property managers with unambiguous, reliable information about the technical status based on assessed defects.

The standard Condition Assessment of Building and Installation Components is aimed at (NEN 2006):

- property owners, managers and administrators;
- tenants;
- consultants;
- contractors;
- inspectors of control bodies.
- Application may include:
- visualisation of the physical condition;
- maintenance planning;
- prioritising of maintenance budgets;
- control of physical conditions;
- communication about the actual assessed physical condition and desirable condition.

The standard will at the end comprise three parts:

- part 1: Methodology (NEN 2006);
- part 2: List of faults (NEN 2007);
- part 3: Aggregation methodology (forthcoming 2008).

The focus of the standardized method is large scale property. Condition assessments should be performed visually by trained inspectors using some small equipment and measuring tools. The standard is limited to condition assessment. Maintenance planning and prioritising maintenance work are not included, although some examples for doing that are given. Maintenance actions are not related to the condition ratings.

The translation of the Dutch standard is the responsibility of the author of this paper and not of the Netherlands Standardization Institute.

Six-point scale

The well-known six-point scale is the basis of the standardized method. The condition categories are of a chronological order that describe possibly occurring defects without references to remedial work. Table 5.2 gives the general descriptions of the condition marks.

Table 5.2 Six-point scale Dutch standard for condition assessment (NEN 2006)

Condition mark	General condition description
1	Excellent
2	Good
3	Fair
4	Poor
5	Bad
6	Very bad

Pitt (1997) argues that whatever condition categories are adopted, essential is that they are clearly defined. Data collectors are well trained to ensure data consistency and reliability. The use of a six-point scale is maybe special for the Netherlands. In large scale property condition assessment methods often four or five-point scales are frequently used. The scale used in the English House Condition Survey adopts the categories: seriously defective or unfit, defective, just acceptable and satisfactory (Department of the Environment, 1991). The number of codes, characterising the state of degradation of building components in the European EPIQR-project (Energy Performance and Indoor Environment Quality, Retrofit) has been set at four: A Good Condition, B Slight degradation, C, Medium degradation and D End of life span (Caccavelli and Gnere 2000). In South Africa a five-point scale has been proposed for the strategic management and maintenance of hospitals (Abbott *et al.* 2007). The condition rating is from 5 to 1: very good to very bad. Condition assessment ratings are related to maintenance actions, e.g. a very bad condition (5) means involves replacement, a fair condition (3) means repairs. Condition rating for the National Health Services in the UK is also done on a five-point scale (asset grading condition).

The use of a six-point scale might be remarkable from a psychological point of view. Psychologists advise to take for judgments odd classes. Because of the limited human capacity for process information the number of classes should be seven, plus or minor two. The six-point scale is a relic from the past and has to do with the scale division. The six-point scale is not linear but ordinal. A linear scale division presupposes a linear relationship between the conditions and the remaining service life of the building components. In reality the condition and service life of discrete building components and sets will run differently. An ordinal scale division means that the values the variable can have can be classified, but their meaning is not univocal. A building component in condition 3 does not mean 3 times being worse than a component in condition 1. Condition 1 of the six-point scale indicates the upper value of the scale. This absolute value cannot be exceeded. Condition 5 indicates the lower value of the scale. This bad condition is not an absolute value. Condition 6 has been added to distinguish a very bad situation, meaning that the component should already have been replaced.

5.4.3 Condition Assessment Process

The condition assessment process follows the pattern in Figure 5.1. The assessing of defects occurs first. Without this information one could not formulate maintenance activities and estimate costs. Subsequently the inspector passes through the following condition parameters: importance of defects, intensity of defects and extent of defects. The extent and the intensity of a defect combined with the importance of the defect lead to a condition mark, probably with a defect score as an intermediary product.

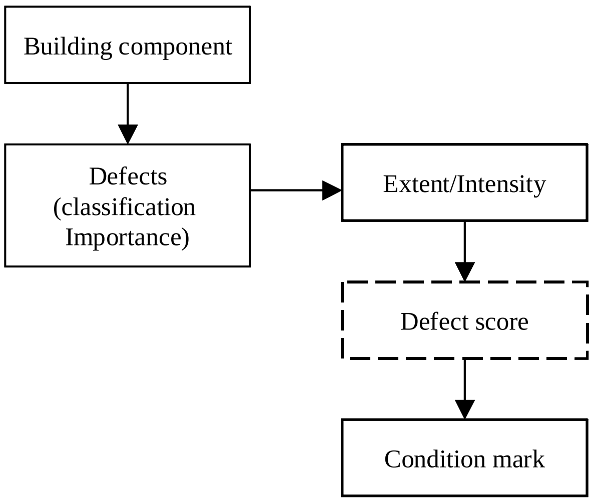

Figure 5.1 Condition assessment process

Building Components

For an objective visual assessment building inspectors need a clearly defined and hierarchical classification of building components. The list of faults (defects) uses the first four codes of the Dutch SfB-classification (NL SfB). This hierarchical classification directly influences the classification of the importance of defects.

The building component list covers 80 to 90% of the common building components in housing and real estate. In all other cases the given framework for importance rating should be used.

Importance of Defects

The importance of the defect indicates to what extent it influences the functioning of building components. The Dutch Standard for Condition Assessment classifies the importance of defects of distinct building components into minor, serious and critical. See Table 5.3. Critical defects significantly threaten the function of the building component. Generally material intrinsic defects like corrosion and wood rot, defects that threaten the building structure, e.g. stability and distortion, and "functional defects", are weighted as critical defects. Functional defects are those that are already associated with a failure. Serious defects are gradually damaging the performance of building components, for example defects in the material surface. Defects to the finishing, for example coatings, are classified as minor defects.

Table 5.3 Framework for defects (NEN 2006)

Importance	Type	Explanation
Critical	Basic functioning Basic constructional Material intrinsic Basic quality	Critical defects harm directly the functioning of the building component
Serious	Minor functioning Minor constructional Material surface Basic quality and ageing of secondary components	Serious defects mean degradation of a building component, without directly harming its functioning
Minor	Maintenance (1) Finishing Basic quality and ageing of tertiary components Deterioration (2)	Minor defects do not harm the function of building components

(1) Maintenance: maintenance actions meant to keep the building component in running were not executed, e.g. legal tests.

(2) Deterioration: condition assessment based on the theoretical service life of the building component; this may be applied if the condition can not be assessed visually.

Intensity of Defects

The intensity of defects strongly influences the condition of building components. The intensity of defects deals with the degradation process. Ageing defects like material intrinsic defects and defects involving the material surface e.g. wear and soiling, develop over a certain period and will occur in several intensities. But defects caused by calamities, for instance glass breakage, just occur in one stage. The intensity rating has given a lot of discussion in the standardization committee. Finally, it was decided to use three intensity classes. See Table 5.4. The list of faults determines if intensities are applicable for a building component.

Table 5.4 Classification of intensity of defects (NEN 2006)

Intensity class	Name	Description
Intensity 1	Low	The defect is hardly visible
Intensity 2	Middle	The defect is progressing
Intensity 3	High	The defect cannot progress any further

Extent of Defects

Besides knowledge about the intensity of defects knowledge about the extent of defects is needed to assess the condition. Methodological questions rise how many classes be manageable for building inspectors and how many classes be useful to link maintenance activities to the extent of defects in the policy making process. Clearly, to estimate the extent and chose for the appropriate class is difficult, even for more experienced building inspectors. Obviously difficulties doing so also depend on the defect involved. One may differentiate general ageing defects normally covering the whole building component from localized defects. In the case of general ageing defects the intensity of a defect corresponds with the condition.

The Dutch Standard for Condition Assessment standard distinguishes five extent classes. See Table 5.5.

Table 5.5 Classification of extent of defects (NEN 2006)

Extent class	Percentage	Description
Extent 1	< 2%	The defect occurs incidentally
Extent 2	2% -10%	The defects occurs locally
Extent 3	10%- 30%	The defects occurs regularly
Extent 4	30% - 70%	The defects occurs frequently
Extent 5	≥ 70%	The defect occurs generally

Condition Marks

The extent and the intensity of a defect combined with the importance of the defect lead to a condition mark. The Tables 5.6, 5.7 and 5.8 give the matrices for successively critical, serious and minor defects.

Table 5.6 Matrix of resulting condition marks for critical defects (NEN 2006)

Intensity	Extent				
	< 2%	2% - 10%	10% - 30%	30% - 70%	≥ 70%
1 Low	1	1	2	3	4
2 Middle	1	2	3	4	5
3 High	2	3	4	5	6

Table 5.7 Matrix of resulting condition marks for serious defects (NEN 2006)

Intensity	Extent				
	< 2%	2% - 10%	10% - 30%	30% - 70%	≥ 70%
1 Low	1	1	1	2	3
2 Middle	1	1	2	3	4
3 High	1	2	3	4	5

Table 5.8 Matrix of resulting condition marks for minor defects (NEN 2006)

Intensity	Extent				
	< 2%	2% - 10%	10% - 30%	30% - 70%	≥ 70%
1 Low	1	1	1	1	2
2 Middle	1	1	1	2	3
3 High	1	1	2	3	4

5.4.4 Maintenance Planning

Just as the collection of survey data the decision-making process for planned maintenance holds subjective elements and often is not transparent. Condition-based maintenance can be seen as a tool to implement a desired differentiation of the technical quality of buildings by formulating performance levels. Varying performance levels is advisable in the case of a diverse portfolio and if the maintenance management system easily provides possibilities to do so. This might be the case for Dutch housing associations that do not focus solely on the production and management of cheap and decent dwellings, with only a limited differentiation in rents, tenure, target groups and quality. However, housing associations acknowledge that the technical quality is just one aspect of quality (e.g. Straub, 2002; Straub and Vijverberg, 2004). The technical quality is an important aspect if the housing estate strategy is consolidation. This is the case for larger parts of the housing stock of housing associations.

A condition-based maintenance planning by housing associations comprises besides preventive maintenance (CEN 2001) also corrective maintenance actions, replacements of building components and even material and limited functional modifications of building components. An important sub process of maintenance planning is prioritizing maintenance work.

Maintenance Performance Levels

Formulating maintenance performance levels in planned maintenance means deliberate about maximum performance loss, appropriate maintenance activities and the available financial means. Maintenance activities can be distinguished according to type (cleaning, repair and replacement), part of the building component to which an activity applies, the specification of materials, the quantity of the work, the frequency of short cyclical preventive maintenance actions and the nature of an activity (preventive or corrective).

Maintenance performance levels can be based on the (minimum) condition of building components after executing maintenance work. Maintenance managers have to examine which defects have been solved and which defects are still present? See Figure 5.2.

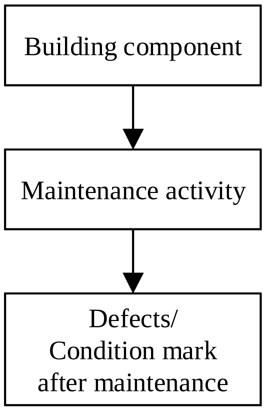

Figure 5.2 Condition assessment process after maintenance

Maintenance managers are able to set condition targets – a minimum condition – of building components by forecasting the condition status of components after executing maintenance activities, dealing with more and less acceptable remaining defects. See Figure 5.3.

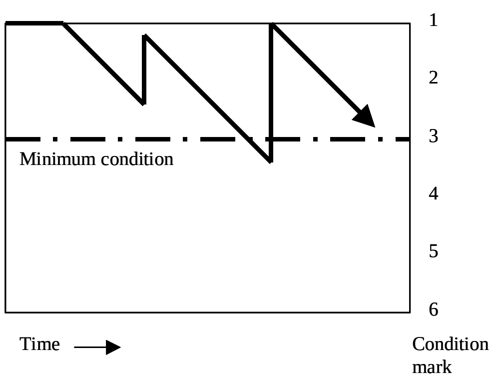

Figure 5.3 Maintenance planning using condition targets

Some Dutch housing associations apply this method. However, knowledge about maintenance activities and performance and setting maintenance performance levels is scarce. To perform efficiently and effectively the performance of a building component after executing maintenance work should be clear. We found that the performance of building components after partial replacements, repairs and cleaning is not clear for most technical managers of Dutch housing associations (Straub 2001). After an integral replacement of the component the condition status will be as new (condition mark 1). In case of partial replacements and repairs the condition gap before and after the activity is insecure. The new condition depends on the solved defects at that particular moment of time. Hermans (1995) found that cleaning and repainting of surfaces does not influence the technical performance of substrates. The degradation will just process more gradually. Nevertheless, the aesthetic performance of a surface improves. In fact, through functional material modifications performance alterations take place. The product characteristics of the building change and the original performance capacity increases.

Priority Setting

Maintenance management systems should enable users to calculate maintenance performance levels and priority setting of maintenance work dealing with the risks of failure of components. Until 2000 most maintenance management systems were lacking possibilities to calculate maintenance performance levels in planned maintenance. The systems just supported the tuning of the 'maintenance stock' for the available budget by setting priorities. Normally, maintenance work needed to secure the safety performances has precedence to work just for aesthetic or sustainable reasons. The initial year of the latter work will be delayed. Shen and Spedding describe a multi-attribute model for priority setting in planned maintenance of real estate (Shen and Spedding 1998). Others describe models for priority-setting of maintenance work by risks (e.g. Horner *et al*., 1997; Loy and Coleman 2006; Pitt 1997). Loy and Coleman (2006) argue that risks, as related to the functional; operation of buildings, generally fall into three interrelated categories: business, environment and health and safety. They link consequence grading criteria to condition rating. Horner *et al.*, (1997) outline a decision diagram using similar risk categories, using significant items. Significant items are those which failures effect health, safety, environment or utility (including cost).

The Dutch Government Buildings Agency uses a risk-priority matrix in tuning the annual maintenance stock for the available budget. The matrix has been included as appendix of the standard Condition Assessment. The risks of defects of building components that are not solved are rated on a three-point scale. The risk categories are rated beforehand. See Table 5.9.

Table 5.9 Risk-priority matrix (NEN 2006)

Risk	Priority								
	9	8	7	6	5	4	3	2	1
Safety and health									
Cultural-historic value									
Utility and business									
Consequence damage									
Increase response maintenance									
Aesthetics									

5.4.5 Condition Aggregation

Several Dutch housing associations and other property owners of large building stocks, e.g. the Government Buildings Agency and the Ministry of Defense want to use aggregated condition data for their asset management.

Aggregated data is important management information for property and facility managers for benchmarking and budget allocation purposes. Besides, aggregated condition data can be used for setting condition targets of buildings and housing estates.

Aggregating condition marks means weighing the technical status of a building component against the other building components of a building. In a proposed method first the weighted average of building components being part of a main component is determined. Main components are for example facades, roofs, windows and doors, balconies and walkways and heating. The weights are diverted from the hierarchical levels of building components used in the Dutch Qualitative Housing Registration 2000 'KWR 2000'. This means that construction parts count for 4, finishing and equipment parts count for 2 and painting counts for 1. For example in case of facades the condition of the brickwork counts for 4, the condition of exterior staircases (equipment) and plasterwork (finishing) count for 2 and the condition of the painting counts for 1. Secondly the weighted average of main components of the housing estate (housing block) is determined. The weights are diverted from the financial share in the replacement costs of the building, based on data of the KWR 2000.

In 2006 a case study indicated that the relationship between the aggregated condition marks and the maintenance costs recorded in a long-term maintenance planning is not univocal. Also the relationship between the maintenance costs and condition improvement - aggregated condition marks before and after maintenance - is not clear. The main reason for this is the fact that the aggregation of condition marks of building components comprises all building components, including components that do not need maintenance work within the exploitation period. For example generally occurring defects of the material surface with a low intensity will lead to a condition mark 3 (see Table 5.8).

Because of this weak relationship two indicators for aggregated condition marks will be developed: the calculated technical condition index, including all building components, and a maintenance index, without building components that are not normally not replaced and/or not included in the long-term maintenance planning.

5.4.6 Limitations

Condition assessment according to the standard should be used as a strategic management tool. A condition survey is a tool in assessing the technical status of the properties to underpin the long-term maintenance expectations. Condition assessment is not meant for preparing the year maintenance budget and planning of the work. Supplementary information is needed in the phase of preparing execution of remedial work. Supplementary information might be the precise location of the defects and causes of defects to take adequate maintenance actions.

The condition assessment methodology and condition parameters of the standard is meant for the assessment of large scale property. Condition assessment for individual homes is something else. However, e.g. home-buyer surveys are dealing with similar problems, as a poor standard of recognition of defects or potential defects (e.g. Hollis and Bright 1999). Hollis and Bright suggest a high rare of substandard reporting for residential surveys too. In the Netherlands a standardization process for individual home surveys started in 2007.

The introduction of standard lists of defects, condition parameters and condition marks could mean a clear break of the common working processes of building inspectors. Maintenance managers should be ware that the Dutch standard for condition assessment does not say anything about the sample size and distribution of building components.

Building and facility managers may doubt the benefits of a new method and especially the willingness and skills of their inspectors to work in that way. Experience shows that well-trained inspectors are able to manage condition surveys. The most difficult part is to forget about the old way of thinking and working. Well-educated and/or certified building inspectors should have enough knowledge and experience about elements, defects and remedial work. Nevertheless, it takes a lot of effort and time to use it in a different way: register the found situation and separately choose for maintenance activities. Maintenance managers have to evaluate training needs for their surveyors.

5.4.7 Conclusion

Condition-based building maintenance using the standard for gives a useful tool for inspection maintenance work. Building inspectors can provide property managers with objective data about the defects and the condition status of building components. Condition assessment improves the communication between inspectors, the responsible maintenance planning department and management.

The eyes of well-educated and experienced building inspectors remain important in getting condition data. The use of advanced performance measurements, sensor technology and intelligent decision support systems to monitor and report on changes in the performance of building components is still in its infancy. Performance profiles of building components depend on the local circumstances.

If inspectors are made responsible for the choice of maintenance activities at-site based on condition data, they need good instructions how to do that including a standard list of activities. More objective seems to choose maintenance activities by a planning department at the office.

The assessment and setting of priorities for planned maintenance work is a way to tackle problems of lacking maintenance funds. In addition to this using the condition scale in the planning process gives the opportunity to vary the performances of building components. Maintenance performance levels can be based on the (minimum) condition of building components after executing maintenance work. In this approach assessed defects and condition marks before at one side and acceptable defects and conditions marks after executing maintenance work at the other side, are steering instruments in the maintenance planning process.

It is to be expected that as a result of the Dutch Standard for Condition Assessment the process of condition assessment using standard lists of defects and the six-point scale will become more popular among housing associations and other large scale property owners. Building inspectors can be trained in using one method for all principals. It makes the data also suitable for asset management and benchmarking purposes.

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5.5 Managing Maintenance Contracts to Control Facility Management Services within a PFI Project

David Martinez

Abstract. Private Financial Initiatives (PFI) have rapidly become an excuse to spread the word and improve Facility Management skills and also to raise maintenance to a much more strategic level. The main purpose of these schemes, other than the substantial economical relief to the cash flow of public administrations, is to transfer the risk of maintaining certain level of services all through the duration of the contract: an average of 25 years. The SPV (Special Purpose Vehicle) or Joint Venture in charge of maintaining these levels, is in many occasions not nominated to choose the equipments or the installations that they will have to be responsible of. On addition to this, many times they are not appointed responsible for other services like cleaning or security. The management model able to support these peculiarities with the risk transfer intended on the contracts must be extremely adaptable to the particularities of the contracts. The paper presents how on a large, non-UK-style PFI, the maintenance contract can act as the controller of the rest of the services, by using a very flexible model where static SLA have been substituted by a "card" where not only service level is included but elements such as reporting, procedures, indicators or implied personnel are part of what we called "puzzle piece".

5.5.1 Background

PFI concept has increased its popularity across Europe like no other contracting model in the past fourteen years. It is contemplated, after privatisation, the best solution to reduce the deficit in public balance sheets. Many central and local governments in every country inside and outside the European Union consider PFI schemes as the only solution to provide the taxpayers with the demanded infrastructures or to renew their own portfolio without affecting budgets in the short term.

There is no doubt, about the important contribution that PFI schemes has brought to the expansion of Facility Management, and in particular in non very mature markets on the field, where it has been decisive to its quicker development

PFI contracts have increased their popularity across Europe like no other contracting model in the past decades. They are consider, after privatisation, the best solution to reduce the deficit in public balance sheets, that is why PFI schemes are the selected solution for many central and local governments to provide the taxpayers with the demanded infrastructures without affecting budgets in the short term.

Europe's PFI market is growing so rapidly through the continent that is difficult to find a newspaper without a new PFI or more generally a PPP (Private Public Partnership) project almost every week. The best attitude is to be cautious and consider the chances of success and also the risks threatening any project. Anytime a new technology or strategy is imported, especially after a testing period abroad, it is necessary to analyze how the new "concept" will fit in the newborn market. It is necessary to compare the conditions under which the tested models succeed, with the actual ones, where the project will be attempted to be implemented.

5.5.2 Public and Private Partnership Types (PPP)

It is necessary to analyse the different possible structures of partnership between the public and the private sector (PPP). By doing it several combinations can be found. The names are sometimes confusing and differently understood. We present here some of the combinations based in the roles with their descriptions.

BOOT (Build-Own-Operate-Transfer)

A method of financing projects and developing infrastructure, where private investors construct the project and own and operate it for a set period of time (earning the revenues from the project in this period), at the end of which ownership is transferred back to the public sector. The government may provide some form of revenue guarantee via long-term contracts.

DBFO (Design, Build, Finance and Operate) same meaning as Build-Operate-Transfer (BOT)

Similar to a BOOT project, but the private investors never own the assets used to provide the project services; however they construct the project and have the right to earn revenues from its operation for a period of time. This structure is used where the public nature of the project - for example, a road, bridge or tunnel - makes it inappropriate for it to be owned by a private-sector company and therefore ownership remains with the public sector.

BLT (Build-Lease-Transfer)

Similar to a BOT or BRT project except that a lease of the project site, buildings and equipment is granted to the private sector during the term of the project. This has a variant called BRT (Build-Rent-Transfer) but the project site, buildings and equipment are rented to the private sector during the term of the project.

BOO (Build-Own-Operate)

A method of financing projects and developing infrastructure, where a private company is required to finance and administer a project in its entirety and at its own risk. The government may provide some form of payment guarantee via long-term contracts, but any residual value of the project accrues to the private sector.

JVC (Joint Venture Company)

Another type of PPP developed in local government to deliver investment in local services over a long term contract is JVCs, which involves the public and private sectors and seeks to increase capital investment to assist service delivery, or to encourage economic development and urban regeneration.

The question now is, where did PFI schemes fit?

A general typology found in the literature identifies three types of PFI schemes:

first, Design, Build, Finance and Operate (DBFO) projects which are financially free standing; second, DBFO's including the leasing of publicly provided services to the private sector contractor; and third, joint ventures.

Another more actual classification is based in the form in which capital investment is recovered determine these classification:

Public service provider. This type is the ideal form of PFI in which the private contractor builds and operates a facility, and recovers its investment by selling services to the public sector. However, simple finance leases of facilities are not included. It has a track record in delivering public services such as hospitals, prisons, roads, and information systems.

Recovery of investment from fees. Here the private contractor builds and operates a facility under license from the government. Like toll roads and toll bridges, the investment is recovered through fee revenues, and public expenditures are not involved in principle. BOT (build, operate, transfer) projects commonly seen in Southeast Asia are of this type.

Public-private joint project. While both public and private sectors provide funding to build facilities, operations are managed by the private sector. Since the investment cannot easily be recovered from operating profit, the project often depends on value enhancement from redevelopment or railroad construction projects. In this type of PFI, effective support from the public sector is allowed, however in most occasions the support comes not as operating subsidies, but is rather limited to contributions for acquiring and using assets for the development.

5.5.3 The Original PFI: the UK Model

The original PFI model, born in the UK over a decade ago now, had one of the key answers to guaranty the service levels defined and pre-agreed over a long period of time, the creation of, what it was called, the SPV (Special Purpose Vehicle). This SPV was created to run with a single vision and sole objective the project, and was meant to be a composed of all the players: funding bodies, construction companies, project and facilities management expert, sometimes even legal or other specialized advisers. The SPV had to guaranty over the whole length of the contract, usually over 25 years, that the level of the quality provided all through the range of services needed to operate the premises, were maintained and levelled with the agreed standards. On the original model, the SPV was responsible of the whole range of services, from construction to maintenance, from security to reception, from cleaning to waste management. The SPV was the body accepting the risk and responsibilities of maintaining the facility in a operational level all the time, according with the agreed standards. The UK market has the experience and the capability of performing under such conditions as they have been doing it for a long period of time now.

5.5.4 The Imported Version

What happened when this PFI schemes are imported into newer, less FM developed, markets? Well, one of the main consequences is that the mention tool, the SPV, turns into a mere JV (Joint Venture) just formed by construction companies and sometimes the financial institutions that support the operation. This is due, among other reasons, to the fact that the contract do not contemplate the provision of all services needed, just the maintenance of the installations and constructive elements. This weakens the role of the vehicle, when needs appear, cleaning, for instance, that are not covered in the main contract, and external players have a role in the project but with different objectives than the others, they have a goal on their own, not the team’s goal. These “other” suppliers are not related to the well going of the whole of the project, just their actual contract and its renewal. After this introduction, me must explore the particular situation of the Judicial City of Barcelona.

5.5.5 The Project

The project will reunite all justice related portfolio and other judicial installations in a complex of 8 buildings (Figure 5.4).

Figure 5.4 Justice city of Barcelona

It has approximately 240.000 m^2, and is located in Hospitalet del Llobregat, a village in the periphery of Barcelona city. The project, with a construction budget over 320M€, has been conceived as a PFI, with a DBOT structure and for a 30 years contract. At this time, this is the largest project awarded in Spain of this type, and the largest in one sole location over Europe.

Although it has been conceived as a PFI, the project has been following the traditional steps for a conventional contracting model: The initial tendering process was just covering the architectural design. Afterwards the mayor tendering process was to award with the construction and maintenance of the installations, where a SPV presence was expected. This was given to URBICA, a SPV (Joint Venture is more appropriate), that it is compounded mainly by construction companies: FCC, Ferrovial, OHL, COPISA and EMTE. The GENCAT (Generalitat de Catalunia, the public party) awarded the concessionary with the maintenance of the installations and the building fabrics and also with the privilege of exploiting some common areas of the complex. The contract was based on a classic preventive, corrective and substitutive maintenance for all the equipment, installations and constructive elements, internal and external. All other elements such as furniture, computers, or services such as cleaning, catering, reprographics, etc are not been awarded, awaiting for an independent tendering process.

A graphical representation of the project, regarding the service responsibilities is shown in Figure 5.5.

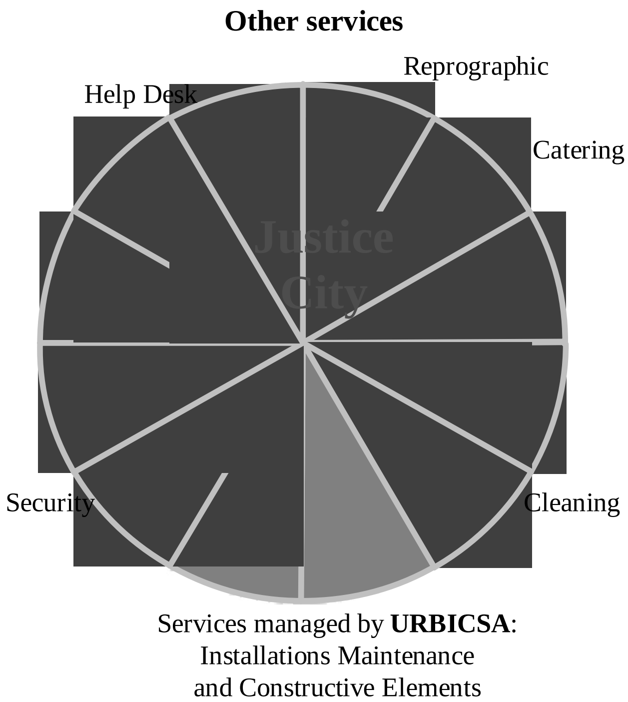

Figure 5.5 Structure of the services

The main concern when sketching the model, was to figure out how to integrate the services and competencies that had been awarded, with all those which still remain un-conferred . There are some important synergies between services that had to be addressed, since different contractors could be doing related or complementary tasks. It was also important to delimit the boundaries of when risk was accepted or transferred and who was accepting it.

For instance, if a phone fails, the responsibility is distributed as follows: The machine is responsibility of the main contractor of the GENCAT for this type of equipment (not tendering process, not SLA associated), The connector in the floor is responsibility of the concessionary as well as the wiring until the connections rack (responsible for the maintenance under the contract with an appropriate SLA). For the communications rack and switches, the responsible is the IT unit of the GENCAT, which due to security reasons, these duties have not been outsource (it has some internal SLA but with limited transfer of risk) . The line from the exterior of the complex is responsible the phone service provider (with a very basic agreement of service level) and there was a missing link: What happened with the section from the main connection to the rack, well, nobody was responsible. This type of ambiguity had to be clarified. This was one of main goal of the model, to avoid dark areas where responsibility was not assigned.

The other area of interest was to explore the scenarios where URBICSA could be also awarded with some other services, like cleaning, but bearing in mind that there was the possibility that other companies, different to URBICSA could be doing the delivery.

5.5.6 The Model

For the initial approach of the model it was necessary to identify who the main players of the project were, and to label their roles and responsibilities to create a plan of hierarchy. Three main actors were found:

Justice Department: The "owner" of the PFI and the future client of the premises. Is part of the GENCAT, the main body where all administrations are included, health, culture, etc.

GISA: Is the official project manager and technical adviser of the GENCAT,. Their role in this project is very important since they are legally, as quoted in the contract, technical responsible for it. They must act as auditors of the maintenance programmes and evaluate the concessionary.

URBICSA, the company awarded with the construction and maintenance of the installations and constructive elements. They are responsible of executing the maintenance plans agreed and developed for GISA.

Just reading the above lines an immediate question rises: Who is responsible for the remaining services, such us cleaning, security, etc. This, as mentioned above, is the reason that the whole model will turn around the concept created to manage the tasks already under URBICSA control.

The model was initially based on the maintenance contract. Specific service level agreements (SLA) were developed in the original project assigned to the winner, along with the construction. These levels were settled with Justice Department and then accepted. On addition to these basic SLA contents, several other elements were included to improve the managing capabilities with the intention of making them extensive to the other services, creating a perfect matrix between them and their relationships. Among these elements there are: internal and external reporting levels, documentation, implied personnel, procedures, etc. along with the basic ones founded on any standard SLA such as coding, response time, solution time, scope of the services, performing indicators, etc.

The idea is to understand services and needs as processes, but instead of developing a map, with strategic, operational, auxiliary, ones, inputs, outputs, etc we condense all this in a single "card". In Figure 3, each triangle is identified as a service or a group of services. Each triangle has some influence over the others in form of procedures.

If security (SEC) is taken as an example, once the card for this service has been developed, and agreed with the implied personnel, the Justice Department, Police Department, etc. among reporting, indicators, plans, there are some procedures that will be applicable in some of the other services of the model. Same happens with Environment (ENV) or cleaning, or catering. This assures that all the relationships between services are properly studied and applied with the right procedure. This assures that no gap or misunderstanding on a service should appear.

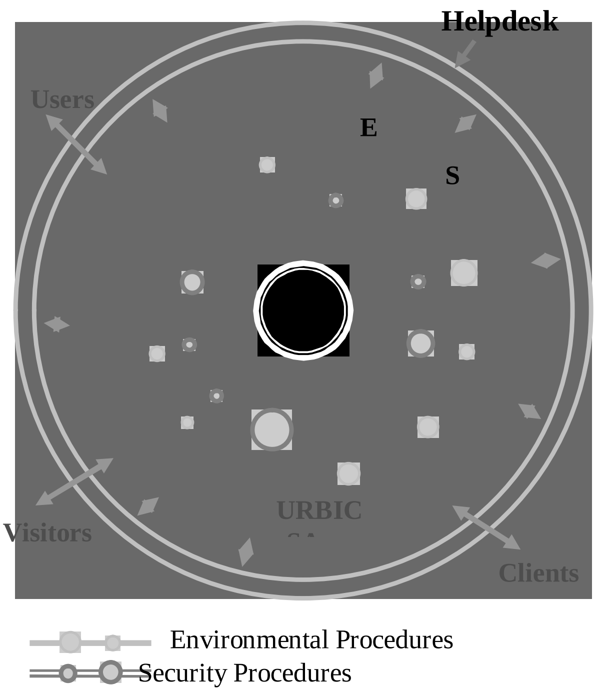

Figure 5.6 Concept of the management model

The KPI (Key Performance Indicators) are common for all the services and reflect the strategy of the model. This indicator change on the scope depending on the players. For instance, the Justice Department is interested in the availability of the services, the value of the assets, its depreciation, and very important customer satisfaction. GISA must dig deeper, and check the maintenance plans, non-scheduled stops, etc and URBICSA will go even more into detail with their sub-contractors.

As a core element of this model, a tool must implemented that allows the whole system to run with the same clock. It will centralised and monitor all events, periodical or eventual that affect the running of the city. The system has not been defined yet, but some clear conclusions are that it must share the same database, have direct communication with all parties and allow key player to take decisions over the system in real time. Also, the system must be reachable for the general users, and all judges, or judicial secretariats that interact with the judicial city. It will also be available to all external parts, could be visitors or external clients.

Talking about users, clients or customers, the important conclusion is to agree on the concept of what is wanted to say. It is worth to mention the new Facility Management European Norm, EU15221-1 and EU15221-2 where a common definition for term and concepts have been achieved. It was also used to determine the scope of the contracts that will run some of the other services not related to URBICSA.

All these information contained in the card needed to be resumed and available to identify inter-relationships in the more concise possible manner. The solution was called the "Puzzle piece", which is part of every service.

5.5.7 The Puzzle Piece

The puzzle piece looks as shown in Figure 5.7. Several elements appear on it.
A. *index*: the number Indicates the importance of the service. It comes from multiplying Impact and Probability. If one of the two terms is 5, you will add five to the final result. In the example, the index 6 indicates a low priority service.
B. *impact and probability*: these two numbers, as their names indicate, represent the Impact over the organisation if the service fails to perform. This number is given by experience, the organization, the policy and the inner strategy for the services. Probability is given depending on the age of the systems, reliance, and also experience. In the example, 3 and 2 indicate medium impact and low probability;
C. *working hours*: this is the time frame where the service must be available. This is used not only for considering out of hours maintenance but also to calculate response time and solution time;
D. *response time and solution time*: these two time based measurements are very important. They establish the time that the contractor has to confirm that has received the failure on the system and the time that they have until the service is recovered to normal;
E. *service code*: this is the code for the service. It must be unique and it will used along with the other elements related with this service, such us indicators, procedures, reporting documents, etc. the code includes all the path of the service, as it will be explain in the name;
F. *procedures* (decision): Here are shown all the procedures related to the decisions in case that there is a change on the scope or level of the service. Some of these could include security limitations, environmental issues to consider, customer needs to accomplish, etc.

G. *service map*: this indicates where the service is located, and its relationships with other services. This is very useful to identify key personnel and decision makers. In the example can be seen how;
H. *name of the service*: includes the whole path of the service, from the main service down to the sub levels. In this case the main service is STI (Internal Transport Systems). Next level has four elements AS, MO, EM and GO (elevators, service lift, mechanical stairs and rooftop crane), and within the AS (lifts) level, three more J, P and G (for judges, police and security forces and for the general public).
I *implied personnel* (decision): These are the codes of members of the management team that have the capability to accept any changes on the scope or level of the service. This is very useful not only to identity internal responsibilities, but to build a team based on number and type of services assigned.
J *implied personnel* (failure): these are the codes for the key personnel that must be involved in case of failure or actions taken over the service. Here we have the official justice coordinator (CJ), the responsible for security (RS), and the coordinator of the judges (CSP).
K p*rocedures* (failure): these are all the procedures related to maintain the service operative. There are not only procedures of the service itself, it could be relationships with other services, actions in case of failure, restrictions or limitations in case of an incidence or even rules applied from an continuity plan.

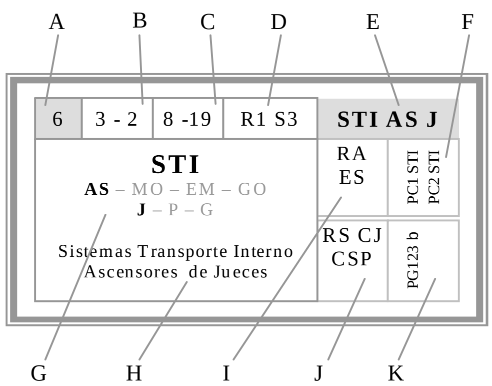

Figure 5.7 Puzzle pieces

5.5.8 Flexibility

The flexibility of the model is latent when it allows to determine for one or more services the same or different suppliers without loosing control and maintaining the model stability. Across the matrix, where all services are listed procedures that implies different services are identified and related to each other. Among these services we identified, obviously maintenance, cleaning, security or the helpdesk, but also other that help cover the whole needs of the model such as energy and environmental management, supplies customer satisfaction, quality or flags provision. All dimensioned and operating at the same level.

As a closing remark is worth mentioning that this type of such a flexible model, could be a solution also for private companies, which are not interested on a single external provider and want to establish a common management strategy all trough their services providers, without compromising their freedom to change part of his subcontractor, without changes on the general model and still maintaining a total control.

5.5.9 Conclusion

We must get familiar with all types of PPP and PFI schemes because a large part of the future facility management and maintenance contracts will run under some level of similarity to this projects. The amount of risk transferred within these contracts, will always be full for services like maintenance and far from being this a handicap, it has to be used to develop stronger models, built around this operational issue but with an important input of strategic weight.

The actual maintenance contracts based on a mere activities fulfilment will turn into systems performance evaluation. Any management model for this type of projects must count on a tool, as a helpdesk, where to centralised and register all activities, and as to be used as so, never just as a “complaints or incidences desk”.

The future definition of service level agreements will include elements such as procedures, reporting, indicators, personnel, etc. In practise is as if every service is considered as a process, and developed as so, adding flexibility and dynamism to the model.

This type of model could be extend into contracts where several providers are implied, and the goal is to transfer an amount of risk, but maintaining under control the responsibilities and duties of each player, where they know each other’s compromises and duties.

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5.6 The Design of Effective Maintenance Outsourcing Contracts

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Abstract. Recent developments in maintenance planning and management demonstrate that the establishment of optimized maintenance policies may drastically improve the performance and reduce the operating cost of facilities. However maintenance activities are typically outside of the core business of production facilities, hence enterprises often fail to catch the opportunities that may originate by properly optimized management strategies. A strategic maintenance management should hence encompass the possibility of outsourcing maintenance activities to ensure the necessary performance of production systems, while allowing enterprises to concentrate their resources on their core activities. In order to be effectively undertaken an outsourcing strategy must be supported by a proper performance oriented contract. The present paper aims to provide an adequate methodology to address such issues and to define a framework for the definition of the relevant contract variables such as availability levels, penalty policies, rewards and service cost. The methodology here proposed is based upon the evaluation of the expected profit function of both the outsourcer and the provider, by performing a trade-off analysis on the basis of the transaction costs.

5.6.1 Introduction

Maintenance activities have recently gained a substantial interest due to the strategic management opportunities arisen in the market. Recent developments in maintenance planning and management demonstrate that the establishment of optimized maintenance policies may drastically improve the performance and reduce the operating cost of facilities. However maintenance activities are typically outside of the core business of production facilities, hence enterprises often fail to catch the opportunities that may originate by properly optimized management strategies. In such context market opportunities have arisen for enterprises that make of advanced maintenance management their core business, thus offering their services to companies willing to outsource. A strategic maintenance management may hence encompass the possibility of outsourcing maintenance activities to ensure the necessary availability of production systems, while allowing enterprises to concentrate their resources on their core activities, thus originating economic, financial and operative advantages. As a matter of fact, however, many enterprises are adverse to outsourcing strategies: this is frequently due to inadequate or unbalanced contracts.

In order to be effectively undertaken an outsourcing strategy must be supported by a proper performance oriented contract. Although much interest has been focused upon the determination of optimal maintenance policies, not much attention has been focused to the importance of a proper establishment of contract variables such as performance level costs, penalties and incentives. While the problem of determining the optimal maintenance policy may be a major concern for service provider, the determination of optimal contracting conditions regards both the contractors and may be essential for a successful agreement.

The present paper aims to provide an adequate methodology to address such issues. An overview of the different outsourcing contracts is hence preliminary provided, focusing upon the most significant contractual aspects. The analysis finally focuses upon Global Service (GS) contracts which are particular contracts which involve two contractors, an “outsourcer” and a “provider” in a performance oriented agreement. The maintenance service provider freely organizes and manages specific maintenance operations upon the outsourcer’s equipment in order to ensure the pre-established performance level. The establishment of such performance levels involves the definition of specific, Service Level Agreements (SLAs) which in turn involves the definition of suitable measurable indicators (Key Performance Indicators, KPI). SLAs typically have penalties associated with not meeting the specified performance levels, and sometimes have rewards when performance levels are outperformed. SLAs hence must be very carefully defined, and must be agreed between the outsourcer and the service provider at the contracting phase. Frequently, a Maintenance Information System must also be implemented to allow both the outsourcer and the provider to monitor and control the performance level achieved at each period, thus allowing the evaluation of penalties and rewards.

According to the considerations reported above, it is clear that the contracting activity for a global service is a critical task that must be accurately performed. The contract variables in fact coordinate the relationship between the outsourcer and the provider whose individual profit functions are typically conflicting. The relationship between contractors must hence be properly coordinated in order to achieve a cooperation strategy to ensure a global optimal result. Such coordination strategy clearly depends upon the selection of appropriate contract variables.

In order to properly coordinate an outsourcing contract the individual profit functions of the contractors must be calculated and penalties, rewards and performance levels must be properly established in order to ensure the optimal overall performance of the system. To accomplish such objective the possibilities of establishing a win-win strategy between the contractors must be analyzed.

In the present paper a coordination model is presented which involves the evaluation of the individual profit functions of both the contractors, taking into account fixed and variable maintenance costs (for the service provider), as well as system downtime costs (for the outsourcer). Such costs clearly depend upon the maintenance policy and the service level (system availability) established. Due to the stochastic nature of the relevant maintenance parameters the related risk must be properly distributed between the contractors, by means of suitable penalty and reward policies. Aim of the paper is to provide a framework for the definition of the relevant contract variables such as availability levels, penalty policies, rewards and service cost.

5.6.2 Maintenance Policies and Costs

Maintenance is typically perceived as any activity carried out in order to repair any equipment that has failed, or to restore to its favourable operating condition when performance decreases due to the wear. Over the years, many maintenance strategies have been formulated to overcome the problem equipment breakdown. Some of the common maintenance strategies are given below.

Corrective Maintenance

Corrective maintenance consists of all the activities of repairing, restoration or replacement of components, required to re-establish the operating condition of equipment after a failure. This is one of the earliest maintenance program being implemented in the industry and still it is the only possible strategy when no information is given about the failure rate. This approach to maintenance is totally reactive since the maintenance intervention is triggered by the system fault. This strategy hence has no scheduled tasks and the corrective maintenance activity is required to correct a failure that has occurred.

Preventive Maintenance

This is a time-based maintenance strategy where on a predetermined periodic basis, equipment is taken off-line, some pre-established maintenance tasks are performed and the equipment is then put back on-line. Under this maintenance strategy, replacing, overhauling or remanufacturing an item is done at a fixed intervals regardless of its condition at the time. Each maintenance action may re-establish the state of the equipment "as well as new" thus resulting in a perfect maintenance action, or it may establish an imperfect state which means the machine is fixed to a condition that is worse than the new component. Complex maintenance models may establish a relation between the time required to perform the maintenance action and the availability level reached (Jaturronnatee *et al*., 2006). Although this is a well-intended strategy, the process can be very expensive if the maintenance interval is too short or too long compared to the intrinsic failure characteristics of the machinery. The frequency and the duration of preventive maintenance tasks also influences the total availability of the system, hence the determination of a correct maintenance plan which optimizes system costs or system availability is crucial.

Predictive Maintenance

Predictive maintenance is a condition-based approach to maintenance. The approach is based on measuring of the equipment condition in order to forecast the occurrence of the next failure. Maintenance actions to avoid the occurrence of failures are then established and undertaken. Predictive technologies (i.e. vibration analysis, infrared thermographs, ultrasonic detection, etc.) are utilized to determine the condition of equipments, and to decide on any necessary repairs. Statistical forecasting techniques based upon equipment performance monitoring are also adopted to determine the maintenance tasks to be performed. This approach is more economically feasible strategy as labours, materials and production schedules are used much more efficiently. The main drawback however is that it is frequently difficult to find a reliable correlation between a measured parameter and the failure characteristic of the equipment.

Proactive Maintenance

Unlike the three type of maintenance strategies which have been discussed earlier, proactive maintenance can be considered as another new approach to maintenance strategy. Dissimilar to preventive maintenance that is based on time intervals or predictive maintenance that is based on condition monitoring, proactive maintenance concentrate on the monitoring and correction of root causes to equipment failures. The proactive maintenance strategy is also designed to extend the useful age of the equipment to reach the wear-out stage by adaptation a high mastery level of operating precision.

Maintenance Costs

The main concern when establishing a maintenance policy for a specified equipment is to achieve cost efficiency providing the adequate availability of the system. In recent years, there is a growing concern on the subject of higher maintenance cost and maintenance productivity. Typically, maintenance cost can be divided into two main groups. The first group referred as direct costs are easy to justify and to report. These direct costs consist of items such as labour, materials, services, etc. The other group of maintenance costs is hidden costs or indirect costs which are harder to measure. These hidden costs of maintenance involve for example breakdowns and unplanned plant shutdown, excessive set-up, change-overs and adjustments, idling and minor stoppages, running at reduced productivity, start-up losses, quality defects, etc. For each maintenance action performed on a generic equipment the Total Cost for Individual repair (TCI) can be calculated as:

$$TCI = C_{sp} + C_m + C_l + C_p \tag{5.1}$$

Where C_{sp} = cost of the spare parts; C_m = cost of materials; C_l = cost of labour; C_p = cost of downtime (i.e. cost of lost production).

In order to evaluate the individual cost of a generic maintenance action, the above listed cost elements should be evaluated. A complex system may undergo different failure conditions (Failure Modes), each one requiring a specific corrective maintenance action. In order to evaluate the cost elements given before, hence, a preliminary Failure Mode and Effect Analysis (FMEA) should be performed. In addition some of the cost elements, such as the cost of spare parts, are fixed and strictly fault-dependent, while some others are time-dependent. In particular the cost of labour for a generic maintenance task can be expressed as a function of the Mean Time To Repair (MTTR):

$$C_l = C_h \cdot MTTR \tag{5.2}$$

Being MTTR the average time required to perform the maintenance activity and C_h =maintenance labour cost per hour. The cost of downtime, as lost production, can be simply (detailed evaluation of downtime cost is outside of the scope of the paper) evaluate as:

$$C_p = \frac{MTTR}{T_c} \cdot p \tag{5.3}$$

With p= marginal revenue and T_c= cycle time.

The Expected annual cost of a generic maintenance policy can hence be calculated as:

$$TEMC = MDT\left[C_h + \frac{p}{Tc}\right] + \sum_{i=1}^{N}\left(C_{spi} + C_{mi}\right) \tag{5.4}$$

Where MDT is Mean Expected Downtime incurred in 1 year, and N is the total number of maintenance actions performed each year.

5.6.3 Coordination and Global Service Contracts

A contract is defined as an agreement by which one or several economic agents commit themselves to one or several others to giving, doing or not doing something. The contract as an inter-individual coordination mechanism can be analyzed along two different approaches (Debande *et al.*, 1996). The agency theory approach (Jensen and Meckling 1976) aims at solving the coordination problems between two contractors, a principal and an agent, within the framework of a bilateral relation when, on the one hand, the agent can choose the level of his commitment, and, on the other hand, his actions affecting the welfare of both parties cannot be observed by the principal actor. This literature (Guesnerie and Laffont, 1984a; 1984b, for instance) aims at defining optimal incentive contracts between economic agents holding unequal information. The transaction costs approach (Williamson, 1975; 1985) rests on the notion of the limited rationality of the agents. The transaction costs are the costs of coordinating the organization in its interactions with the outside environment and in its interactions between actors inside the organization. This analysis aims at explaining the organization structure, the control and management procedures which allow coordination of agent activities at the lowest cost.

Outsourcing consists of two parties, the user company and the subcontractor, who have conflicting interests. Taking into account the interests of both parties, coordination is necessary. The reason is that by coordination the outsourcing supply chain can achieve the maximal profit possible. With a proper contract the total profit can be split between the user company and the subcontractor such that both parties are better off than when the outsourcing supply chain is not coordinated. In other words, with a coordinating contract both parties can ‘make a bigger pie’, and share it in such a way that each gets a bigger piece.

A contract determines the legal parameters of the service and the responsibilities of each part and must pay attention to the combined value. The issue that is addressed in this paper is how to coordinate the contractors to achieve global system optimality. In order to achieve such condition the utility functions of each contractor must be taken into account. If the space of all possible contracts can be explored exhaustively, and the overall utility function for different possible contracts is linear, with a single optimum in the utility function for each agent, the system can be easily optimized. In such a context, the reasonable strategy is for each agent to start at its own ideal contract, and concede, through iterative proposal exchange, just enough to get the other part to accept the contract. When the utility functions are simple, it is feasible for one agent to infer enough about the opponent’s utility function through observation to make concessions likely to increase the opponent's utility. Real-world contracts, however, are generally much more complex, consisting of a large number of inter-dependent issues.

A global service maintenance contract involves two contractors, an "outsourcer" and a "provider" in a performance oriented agreement. The outsourcer contracts with the service provider a defined scope of work, and the service provider charges the outsourcer a fee. In exchange for the fee, a service is provided at a guaranteed quality level. Global Service contracting for maintenance management involves the outsourcer to freely establish the most suitable maintenance strategy according to the failure characteristics of the equipment maintained. Such strategy may be heterogeneous, encompassing corrective, preventive, and condition based maintenance, as well as spare parts management.

Global service contracts hence rely upon the establishment of a certain performance level and a service fee. Typically the outsourcer establishes the desired performance level and the vendor establishes the corresponding fee. The definition of performance levels involves the specific, Service Level Agreements (SLAs) which in turn involve the establishment of suitable measurable indicators (Key Performance Indicators, KPI). SLAs typically have penalties associated with not meeting the specified performance levels, and sometimes have rewards when performance levels are outperformed. SLAs hence must be very carefully defined, and must be agreed between the outsourcer and the service provider at the contracting phase. Frequently, a maintenance information system must also be implemented to allow both the outsourcer and the provider to monitor and control the performance level achieved at each period, thus allowing the evaluation of penalties and rewards. In such case the investment should be properly shared. For such reasons, GS contracting for maintenance outsourcing is generally troublesome, but it has a drastic influence upon the success of the contract. As a result of the contracting phase the following fundamental contract parameters must be established.

Duration of the Contract

The duration of the contract defines the amount of time contract is enforced. Depending upon the intrinsic failure characteristics of the equipment maintained the duration of the contract may be a critical issue for the vendor to establish the suitable maintenance policy since equipments degrade with age and/or usage. The contract must also define the terms and conditions at which both parties may prematurely solve the contract.

Services, Place of Performance, Initial Inspection

Depending on the type of contract, the maintenance services are derived from the performance description. The details of the nature and scope of these services are based on the vendor's work plans which can be modified and adapted from time to time at his own discretion to ensure that requirements are met. In general any substances used to clean and maintain the instruments, along with spare parts, exchanged parts and wearing parts only form part of the scope of the maintenance contract if they are explicitly included. In as far as possible and reasonable, reconditioned exchanged parts instead of new spare parts usually can be used at the vendor's discretion. The ownership of exchanged parts is transferred to the vendor. Unless otherwise agreed in the maintenance contract the services will be performed at the location where the equipment is being used at the time the contract is concluded. If the location is changed by the outsourcer he shall inform the vendor of the transfer. If the vendor approves the transfer the maintenance services will be performed at the new location. For instruments that have not been maintained regularly by the vendor since they were first commissioned, or for which maintenance has been interrupted for more than one maintenance interval, the vendor may reserve the right to carry out an initial inspection at the outsourcer's expense.

Performance Requirements

The performance requirements can involve several measures such as the upper limit on the number of failures over the lease period, the time interval between successive failures, the time to repair each failure and so on. When these are not met the vendor incurs penalties which must be explicitly stated in the contract.

Not Included Services

The GS contract must also define the services that are outside of the agreement. Such services will only be performed by the vendor on the basis of a separate contract and at a separate charge. A typical issue in such case is the management of spare parts which may be charged to the outsourcer or to the vendor. Are in any case charged to the outsourcer the exchange parts which are necessary, not as a result of natural wear and tear, but as a result of external influences, such as improper use, operation or other interventions by third parties, as well as other circumstances that cannot be attributed to the vendor. Are also charged to the outsourcer all the exchange expenses of instrument-specific consumables, unless this takes place within the context of maintenance without significant additional cost.

Maintenance Personnel

In GS contracts typically the outsourcer requires the maintenance tasks to be performed by trained and expert personnel. For such reason the vendor may be entitled to subcontract the maintenance work to third parties, however, such subcontracting shall not release the vendor from his contractual obligations towards the outsourcer.

Maintenance Times

Being GS a performance oriented contract it does not necessarily include time obligations for the vendor. The maintenance intervals are in fact derived from the performance, unless they are laid down in the contract. The time when the maintenance work will be performed shall be agreed upon by the parties. The vendor shall agree with the contractor the preferably maintenance periods. If the outsourcer suffers damage and he can prove that it is the result of a delayed performance, the outsourcer shall be entitled to demand compensation up to the price of the maintenance work that was not performed on time.

Payment

As payment for the services, the vendor may be entitled to charge, depending on the type of agreement, a flat maintenance fee for each date or specific period of maintenance work. If the maintenance personnel are held up in the performance, the waiting times may also be charged to the outsourcer. The outsourcer shall also bear any additional costs incurred if, the maintenance work cannot be performed or cannot be performed in full within the agreed time for reasons attributable to him. The GS contract typically contains positive and negative incentives. A positive incentive is one involving rewards. If the contractor exceeds the minimum levels of performance, a monetary reward is paid. A negative incentive is a penalty imposed for failing to meet a contractual requirement. The type of negative incentive intended here is related to a specific performance requirement, such as availability. The presence of a negative incentive and a positive incentive will ensure that the performance requirements are met. However, the negative incentive provides no motivation for exceeding the requirement.

Information/Cooperation Duties

In order to allow the vendor to perform the required maintenance operations the outsourcers shall make the equipments available to the vendor's maintenance personnel and representatives at the agreed time. The outsourcer shall make available for the duration of the maintenance work all the tools and the appropriate support staff to operate the instruments and support the maintenance personnel. The information required about the instrument to be maintained shall be passed on and the associated documents made available to the maintenance personnel and representatives. The outsourcer shall inform the maintenance personnel of any peculiarities and problems that have appeared in relation to the instrument to be maintained without being asked for such information.

5.6.4 Performance Measures

A key issue to achieve the optimum benefit from maintenance outsourcing is to track the performance level related to the maintenance policy established.

For such reason effective performance measurements must be established and clearly agreed upon. Tracking the level of service is a critical task to achieve effective maintenance outsourcing advantages.

In the maintenance partnership scenario in fact, performance guarantees and continuous improvement goals provide greater control over maintenance results and assure production goals are being achieved.

When maintenance is outsourced, the first question is how to measure performance. To determine the "best" measure, one must first determine the requirements of the system in question. Furthermore for plants running, on a 24 hour per day, 365 day per year basis, high availability is absolutely essential.

Given that essential requirement, one of the measures for contractor maintenance should be derived from availability. The other should be based on economic considerations. According to the production objectives and the plant uptime required a suitable set of indicators (KPI, Key Performance Indicators) must be established in order to obtain an effective performance measure (Forni *et al.*, 2003).

Some of the most common performance indicators employed in maintenance outsourcing contracts are given below.

Availability-Related Requirement

Even with adequate redundancy, system failures will eventually occur. The number of system failures will be determined by several factors such as reliability of all components and equipment, use of redundancy, effectiveness of maintenance, and so forth. When a failure does occur or when a preventive maintenance action is performed, the job of maintenance is to restore the system to full operation as quickly as possible. The downtime related to the maintenance task will reduce the overall availability of the system which turns into costs for the outsourcer.

Availability related measures will hence be enforced. Such measures may be the maximum downtime, maximum time to restore system, and turn around time.

Maximum Downtime

Specifying the maximum downtime (MaxDT) is specifically intended to limit the periods of non-operation. A stated period of operation must be stipulated for a MaxDT requirement. For facilities, the requirement would normally be stated for each year of operation.

Maximum Time to Restore System

Related to MaxDT is Mean Time to Restore (MTTRS). MTTRS relates to the maximum time it will take to restore the system from any one failure event. In other words, although the parameter MDT limits the downtime over a one year period, it is statistically possible for one failure event to take a long downtime to correct. Such a long downtime for the single action is usually unacceptable. MTTRS limits the downtime that results from any single system failure.

Turn Around Time

Only a limited number of spares can be bought, especially at the equipment or "box" level. Consequently, when a failed piece of equipment must be removed and replaced at the facility level and repaired at a field or depot level, the length of time it takes to return the equipment to the spares supply is important. The shorter the turn around time (TAT), the fewer the number of spares that need be purchased, all other factors remaining constant.

Economic Requirement

Given fiscal realities and limited funding, economic considerations are also important. It is assumed that the contractor who can demonstrate in the proposal that they can provide the stipulated maintenance at the required level of performance at the lowest cost will be awarded the contract. "Cost" should be more than the price of the contract. The overall life cycle costs that will be incurred over the life of the contract should be considered.

Notation

L	duration of the contract
T	preventive maintenance interval
σ	performance measure
$C(\sigma)$	maintenance cost incurred by the vendor

I(σ) outsourcer's revenue
W(σ) vendor's fee
R(σ) reliability corresponding to performance level σ
F(t) failure distribution function
f(t) failure density function associated with F(t)
MDT(T) mean expected down-time
$MTTR_f$ mean time to repair of corrective maintenance tasks
$MTTR_p$ mean time to repair of preventive maintenance tasks
MTBR mean time between replacement
C_h maintenance labour cost per hour
$C_p = MTTR_p \cdot C_h$ cost of preventive maintenance
$C_f = MTTR_f \cdot C_h$ cost of corrective maintenance
t transaction cost
e performance monitoring cost
Π_o outsourcer's profit
Π_v vendor's profit
p product marginal profit
Tc cycle time
Av (σ) availability of the system

5.6.5 The Model

The need for coordination arises each time two or more subjects with conflicting objectives are involved in the same economic opportunity. Assuming a rational behaviour, each subject pursues his own maximum utility objective, thus preventing the system to achieve the maximum global utility. In other words, by properly coordinating the outsourcing contract, the system can achieve the maximal profit possible. Then, with a proper contract the total profit can be split between the outsourcer and the subcontractor such that both parties may benefit of the higher global profit.

In order to achieve coordination a typical approach is to consider the "centralized" solution and the "decentralized" solution, analysing in the first case the global profit of the system, and in the second case the individual utilities of the contractors. The next step consists in modifying the contractors' utility function in order to align their strategies and achieve the maximum system profit. Once this analysis has been performed, coordination may be achieved by establishing a suitable contract which modifies the individual utilities by adopting revenue-sharing procedures.

To achieve coordination a contract must:

- achieve a system-optimal level; and
- arbitrarily split the profit between the contractors.

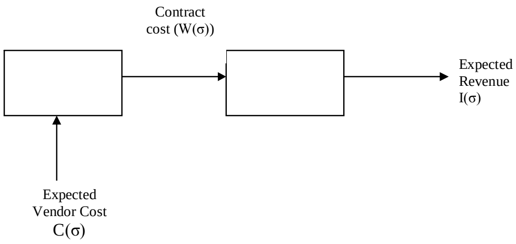
It obviously depends on the specific form of the contract, as it will be proven that the simple form of a fixed payment, will not induce the system to reach its optimal level.

In order to achieve coordination, a GS contract must be linked to a performance measure σ, and according to the performance level requested by the outsourcer the vendor should establish the corresponding reward W. Being L be the duration of the contract, C(σ) the maintenance cost incurred by the vendor, I(σ) the outsourcer's revenue corresponding to the performance level σ, the vendor and the outsourcer's profit functions are given by the following Equations (5.5) and (5.6):

$$\Pi_o(\sigma, p) = I(\sigma) - t - e - W(\sigma) \tag{5.5}$$

$$\Pi_v(\sigma, p) = W(\sigma) - C(\sigma) \tag{5.6}$$

Let us also assume that t (transaction costs) and e (monitoring costs) are fixed, we will, therefore, drop our references to these variables (Bryson et al, 1999, 2000, 2003). The model will be thus simplified as given in the Figure 5.8.



$$\Pi_o = I(\sigma) - W(\sigma)$$

$$\Pi_v = W(\sigma) - C(\sigma)$$

$$\Pi_{TOT} = R(\sigma) - C(\sigma)$$

Figure 5.8 Basic coordination scheme

A simple model for the outsourcer's revenue function is to consider the outsourcer's revenue related to the system availability *Av*. The application to a production plant which produces a product with marginal revenue *p* and cycle time *Tc* would thus be:

$$I(\sigma) = \frac{Uptime(\sigma)}{Tc}\, p = Av(\sigma)\frac{L}{Tc}\, p \tag{5.7}$$

On the other hand the profit of the vendor is related to his reward corresponding to the performance level σ and the related maintenance cost C(σ). The cost for the vendor ultimately depends upon the maintenance policy adopted. The utility of the vendor increases as maintenance costs decrease, hence the establishment of an effective maintenance policy becomes a crucial issue in such contracts.

5.6.6 Global Service Contracts with Preventive Maintenance Policies

In order to give an explicit formulation of the above equations, an assumption must be made for the maintenance policy adopted by the vendor. In the present paper the maintenance policy considered is a standard preventive maintenance policy with perfect repairs as described above. In such case the availability *(Av (σ))* of the system is related to the intrinsic fault probability function of the system and the average repair time necessary to perfectly replace the system condition "as good as new" when either a failure occurs (a corrective maintenance (CM) task is required) or a preventive maintenance (PM) is performed. The mean time to repair when a corrective or a preventive maintenance occurs are respectively: $MTTR_f$ $MTTR_p$. According to such considerations the expected revenue of the outsourcer as a function of the system availability (Rausand, and Høyland, 2003) is:

$$\begin{aligned}
MDT(T) &= \left[MTTR_p \int_T^{\infty} f(t)dt + MTTR_f \int_0^T f(t)dt \right] = \\
&= MTTR_f \cdot F(T) + MTTR_p \left[1 - F(T)\right] \\
MTBR(T) &= \int_0^T \left[1 - F(t)\right]dt + MTTR_p \int_T^{\infty} f(t)dt + MTTR_f \int_0^T f(t)dt = \\
&= \int_0^T \left[1 - F(t)\right]dt + MDT \\
Av(T) &= 1 - \frac{MDT(T)}{MTBR(T)} = \\
&= 1 - \frac{\left[MTTR_p \int_T^{\infty} f(t)dt + MTTR_f \int_0^T f(t)dt \right]}{\int_0^T \left[1 - F(t)\right]dt + MTTR_p \int_T^{\infty} f(t)dt + MTTR_f \int_0^T f(t)dt};
\end{aligned} \tag{5.8}$$

The outsourcer profit, function of the system availability is:

$$\Pi_o = I(\sigma) - W(\sigma) = Av(T)\frac{L}{Tc}p - W(\sigma) \tag{5.9}$$

$$\Pi_o = \left[1 - \frac{\left[MTTR_p\int_T^{\infty} f(t)dt + MTTR_f\int_0^T f(t)dt\right]}{\int_0^T[1-F(t)]dt + MTTR_p\int_T^{\infty} f(t)dt + MTTR_f\int_0^T f(t)dt}\right]\frac{L}{Tc}p - W(\sigma)$$

Which ultimately is a function of the intrinsic failure rate of the system, the preventive maintenance interval and the mean time to repair for corrective and preventive maintenance.

The vendor profit is related to the cost of the preventive maintenance policy, which again is a function of the intrinsic failure rate of the system, the preventive maintenance interval and the mean time to repair for corrective and preventive maintenance. The costs associated with failures of equipment are typically higher than costs associated to preventive maintenance. This implies that the optimal PM actions need to be determined through a proper trade-off between the CM and PM costs. For a preventive maintenance policy and a given interval T, the total cost of maintenance is:

$$C(T) = \frac{C_p}{T}R(T) + \frac{C_f}{T}[1 - R(T)] \tag{5.10}$$

Being C_p the intervention cost of preventive maintenance and C_f the intervention cost of the corrective maintenance, the vendor's profit function is given by the Equation (5.11):

$$\Pi_v = W(\sigma) - \left(\frac{C_p}{T}R(T) + \frac{C_f}{T}[1 - R(T)]\right)L \tag{5.11}$$

Which is a function of the reward, the intrinsic failure rate of the system, the preventive maintenance interval and the cost of a corrective and a preventive maintenance action.

In order to exploit the opportunities for coordination, the system profit must be determined.

$$\Pi_{tot} = \Pi_o + \Pi_v = I(\sigma) - C(\sigma) \tag{5.12}$$

$$\Pi_{tot} = \left[1 - \frac{\left[MTTR_p \int_T^{\infty} f(t)dt + MTTR_f \int_0^T f(t)dt\right]}{\int_0^T [1 - F(t)]dt + MTTR_p \int_T^{\infty} f(t)dt + MTTR_f \int_0^T f(t)dt}\right] \frac{L}{Tc} p + \\ - \left[\frac{C_p}{T} R(T) + \frac{C_f}{T}[1 - R(T)]\right] L \tag{5.13}$$

Vendor-Outsourcer coordination is achieved when global system profit is maximized. It can be easily seen that a simple fixed fee contract does not allow achieving coordination. If in fact W(σ) is a constant, and both the vendor or the outsourcer pursue a strategy to maximize their own personal profit function, the outsourcer profit is maximized when the following condition occurs:

$$\Pi_o^* \Rightarrow \frac{d}{dT}\left(1 - \frac{\left[MTTR_p \int_T^{\infty} f(t)dt + MTTR_f \int_0^T f(t)dt\right]}{\int_0^T [1 - F(t)]dt + MTTR_p \int_T^{\infty} f(t)dt + MTTR_f \int_0^T f(t)dt} \frac{L}{Tc} p - W\right) = 0 \\ \frac{d}{dT}\left(1 - \frac{\left[MTTR_p \int_T^{\infty} f(t)dt + MTTR_f \int_0^T f(t)dt\right]}{\int_0^T [1 - F(t)]dt + MTTR_p \int_T^{\infty} f(t)dt + MTTR_f \int_0^T f(t)dt}\right) = 0 \tag{5.14}$$

While the vendor profit is maximum when:

$$\Pi_v^* \Rightarrow \frac{d}{dT}\left[W - \left(\frac{C_p}{T} R(T) + \frac{C_f}{T}[1 - R(T)]\right)\right] = 0 \\ \frac{d}{dT}\left(\frac{C_p}{T} R(T) + \frac{C_f}{T}[1 - R(T)]\right) = 0 \tag{5.15}$$

While the Outsourcer pursues a maximum availability objective, the vendor pursues a minimum cost objective. If in a fixed price contract the outsourcer pays a fee W for performing at level σ*, but the vendor actually performs at level σ < σ*, then in the absence of any penalty the vendor increases his profit by (C(σ)-

C(σ*)). Even increasing the value of W (i.e. the outsourcers raises the vendor's reward) will not have a positive effect upon the global system performance since it has no effect upon the optimal profit point of the vendor. Coordination hence cannot be achieved unless a proper revenue sharing contract is established which modifies the individual profit function of the vendor and the outsourcer. In order to achieve coordination hence a fixed fee contract cannot be employed, and proper incentive/penalty costs must be established as a function of the performance level achieved. A typical linear penalty may hence be in the following form:

$$W(\sigma) = k - a(\sigma^* - \sigma) \tag{5.16}$$

Where k = constant fee, a = penalty rate, σ* = penalty threshold.

In the contract considered if σ* = minimum availability allowed by the outsourcer:

$$\begin{aligned} \Pi_o &= I(\sigma) - W(\sigma) = Av(T)\frac{L}{Tc}p - k - a\left[Av(T) - Av^*\right] = \\ &= Av(T)\left[\frac{L}{Tc}p - a\right] + aAv^* - k \end{aligned} \tag{5.17}$$

And by assuming:

$$\frac{L}{T_c}p = a \tag{5.18}$$

We achieve:

$$\Pi_o = aAv^* - k = const \tag{5.19}$$

Thus the total profit is:

$$\Pi_{Tot} = \Pi_o + \Pi_v = \Pi_v + const \tag{5.20}$$

In such case the vendor profit becomes an affine function of the total profit, hence, by maximizing his profit, the vendor will maximize total system profit. The outsourcer profit share is given by k. Thus, by adopting a linear penalty function and by defining the penalty rate according to Equation (5.18) system coordination is achieved and profit can be arbitrarily shared.

5.6.7 Numerical Application

In this paragraph a numerical application is proposed. The system failure has been modelled as a Weibull function with α=1000 and β=3,5. The cost of the planned maintenance task is C_p = € 4000, the cost of the unplanned maintenance is C_f = € 7000, L/Tc*p=100, $MTTR_f$= 50 h $MTTR_p$=20 h. The total maintenance cost per unit time is given in Figure 5.9.

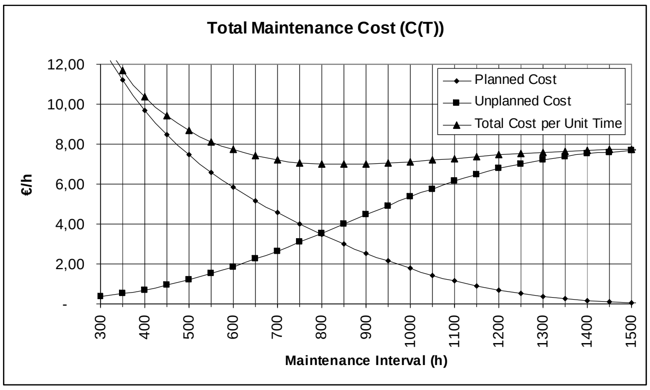


Figure 5.9 Vendor's total maintenance cost per unit time

The T* that achieves minimum maintenance cost is approx. 850 h with a total maintenance cost of 6,99 €/h.

The vendor profit function is:

$$\Pi_v = W(\sigma) - C(\sigma) = W - \left[\frac{C_p}{T} e^{-\left[\frac{T}{\alpha}\right]^\beta} + \frac{C_f}{T} \left(1 - e^{-\left[\frac{T}{\alpha}\right]^\beta} \right) \right] \tag{5.21}$$

The system availability is:

$$Av(T) = 1 - \frac{\left[MTTR_p \left(e^{-\left[\frac{T}{\alpha}\right]^{\beta}} \right) + MTTR_f \left(1 - e^{-\left[\frac{T}{\alpha}\right]^{\beta}} \right) \right]}{\int_0^T e^{-\left[\frac{t}{\alpha}\right]^{\beta}} dt + MTTR_f \left(1 - e^{-\left[\frac{T}{\alpha}\right]^{\beta}} \right) + MTTR_p \left(e^{-\left[\frac{T}{\alpha}\right]^{\beta}} \right)} \quad (5.22)$$

The total revenue obtained by the outsourcer is:

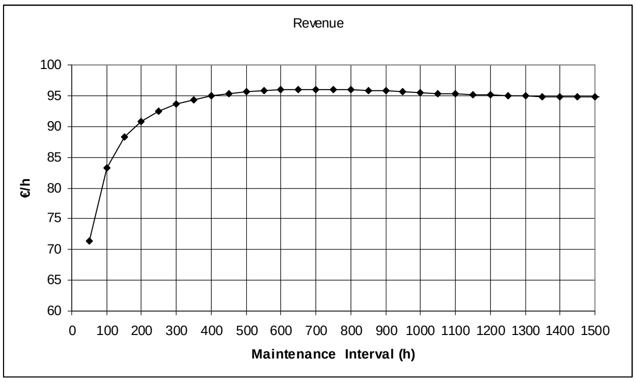


Figure 5.10 Outsourcer's total revenue per unit time

The T* that achieves maximum availability is approx. 700 h with a maximum revenue of 95,99 €/h. With a fixed fee contract with W=50 €/h the profit functions obtained are given in Figure 5.11:

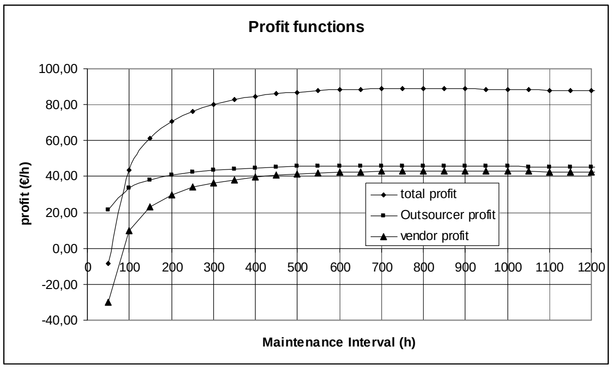


Figure 5.11 Profit Functions

The un-coordinated solution scheme is given in the following Table 5.10, where solution 1 corresponds to maximum outsourcer's profit, solution 2 corresponds to maximum vendor profit, and solution 3 corresponds to maximum global profit. With a linear penalty function contract, by defining: a = 100 and k = 50, and σ* = 0,9591 the outsourcer's profit becomes constant, and consequently the total profit is an affine function of the vendor profit. The maintenance interval that achieves maximum vendor's profit will consequently ensure the achievement of total system profit also. The k parameter on the other hand will define the revenue sharing level. The coordinated solution is given in Table 5.11:

Table 5.10 Optimal profits per hour (€/h)- un-coordinated solution

T*	Av	Total	Vendor	Outsourcer
700	0,9599	88,78	45,99	42,79
800	0,9591	88,90	45,83	43,01
850	0,9583	88,89	45,96	42,92

Table 5.11 Optimal profits per hour – coordinated solution

T*	Av	Total (€/h)	Vendor (€/h)	Outsourcer (€/h)
800	0,9591	88,90	42,91	45,99

5.6.8 Conclusion

In the present paper the opportunities of coordination in a GS maintenance contract have been investigated. The methodology proposed is based on the calculation of the total expected maintenance cost and total expected revenue. The maintenance cost is incurred by the vendor, while the revenue is obtained by the outsourcer. The model consists in the calculation and comparison of the individual (decentralized) and the global (centralized) profit functions. The proposed model proves that coordination among the vendor and the outsourcer is possible in maintenance global service contracts provided that penalties and/or incentives related to a performance measure are considered. In the numerical application proposed the performance measure adopted is the system availability. The obtained results prove that establishment of proper contract parameters such as a linear penalty rate, fixed fee and performance penalty threshold allows the achievement of system coordination.

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