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A Review of Maintenance Management Models: Application For The Clinic And Hospital Environment

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ABSTRACT : *Due to the particular characteristics of hospital environments, it is necessary to carefully select the maintenance management model to be implemented in a health institution. This model must guarantee not only the availability of medical technology but also residual risk management and patient safety. This article is focused on a general review about the maintenance process and its management models through time and analyses in a particular way its impact in the hospital sector. This review will classify the evolution of the maintenance function through time according to its historical context. It will summarize earlier literature review papers related to maintenance management. Moreover, it examines the impact of maintenance models within the literature regarding the clinic-hospital environment.*

We can find a number of papers about the application of a strategy for hospital maintenance management, independently of its orientation. Among the models reported in the literature for maintenance management, it was detected that only seven had risk orientation or criticality of the assets. These models could be the most adequate for clinical and hospital environment. Nevertheless, it was also identified that none of these models were aimed at maximizing the safety of physiologically impaired people. This highlights the need to develop a model that integrates the hospital maintenance management, the medical technology residual risk management and patient safety, which must nowadays be an aim to achieve by biomedical engineers. The paper provides an organized and structured literature review and identifies gaps from the perspective of research and practice. It is useful for biomedical engineers, maintenance managers or other professionals related directly or indirectly with hospital technology management or hospital facility management.

KEYWORDS*: Clinic-Hospital environment, Maintenance management, Maintenance model, Medical technology, Patient safety, Risk management.*

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I. INTRODUCTION

In the historical development of maintenance, it was proposed that some practices were considered the best like, steps or sequences of activities or models to manage the maintenance function (Fernández & Márquez, 2012; Pintelon & Van, 2013). In this sense, different terms are frequently used to describe models, methods, techniques, systems, types, tasks, philosophies, or strategies, to refer to the administration or management of maintenance function; in this work, the term model was used. In this way, it can be used to implement a high-quality model to drive maintenance activities and can be embedded in the general management system of the organization. Over time, it has become a research topic and a fundamental question to identify the effectiveness and efficiency of maintenance management and to fulfil enterprise objectives.

De Groote (1995) views maintenance as an integral part of an organization's long-term profitability, and which has increasingly become part of a total performance approach. Moubray (1977) defines maintenance as the execution of activities, which ensure physical assets continue to do what their users want them to do. However Tsang et al (1999) look at maintenance as the routine and recurring process of keeping a particular asset or machine, in its normal operating condition so that it can deliver its expected performance or services. Moreover, in the Oxford Dictionary maintenance is defined as the process of preserving a condition or situation or the state of being preserved. Finally in IEC 60300-3-14:2004 application guide - maintenance and maintenance support; maintenance is defined as follows: the combination of all technical, administrative and managerial actions during the lifecycle of an asset intended to retain it in, or restore it to a state in which it can perform the required function. (IEC, 2004)(De-Groote, 1995)(Moubray, 1997)(Tsang, Jardine, & Kolodny, 1999)

Summarizing, there are many ways to define the maintenance function according to the authors that investigate this topic. That reflects that maintenance has become a complex process to manage, to which special attention should be paid. Therefore, this article focuses on a literature review about the maintenance process and its management models through time and analysis, in a particular way, its impact in the hospital sector.

II. MAINTENANCE FUNCTION. ORIGIN AND EVOLUTION ACCORDING TO THE HISTORICAL CONTEXT.

Maintenance progress allows to distinguish several evolutionary generations, in relation to the different objectives of the productive or service areas over time (Gutiérrez, 2006; Pérez, Cárdenas, Rodríguez, & Cruz, 2000). Fig. 1 shows maintenance evolution and the productive or services area, taking into account the approach and its main objective according to its historical context. Let us carry out a brief analysis of each stage.

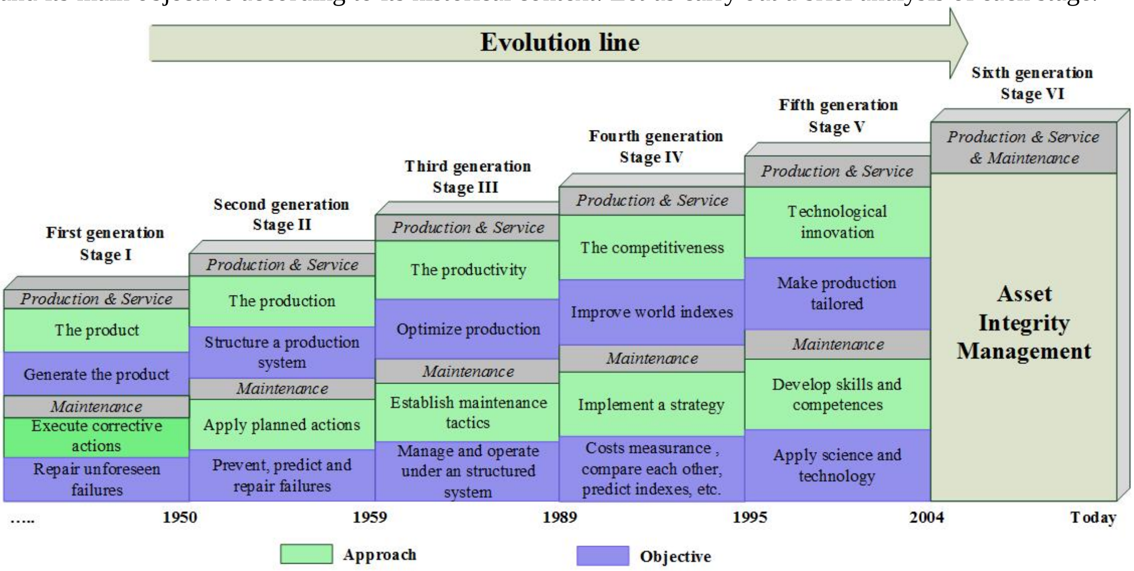

Figure 1: Approach and objectives of the maintenance and productive areas over the time.
Source: Own elaboration**.**

The priority of the production or service areas in stage I is the product while the maintenance area focuses on repair of unforeseen events (Barber, 1967; Metcalf, 1944; Newbrough, 1974; Reed, 1967). In this stage, it appears the primary elements required to maintain the assets are elements such as work orders, general tools, spare parts and a maintenance warehouse. It also shows the first information that is later constituted in the databases and then in information systems; then the techniques and technologies of the company in particular are developed; in general, it establishes the requirement for managing the maintenance function (Sacristán, 1996). The goal of stage II is to solve sudden stops, so the maintenance department begins to develop actions of prevention or prediction of failures. In this stage, techniques and technologies specific to prevention and prediction are implemented, such as: maintenance routines, preventive plans, technical measurements, state condition assessment, non-destructive tests, among others; creating in this way the asset's operational control (Galán & Alfonzo, 2016; Oliva, Arellano, López, & Soler, 2009; Viveros, Kristjanpoller, Barbera, & Crespo, 2013).

Once the companies have reached maturity in the real and conceptual management of maintenance actions, they begin to adopt a structure for a sequential, logical and organized development in order to gestate and operate maintenance under an organized system or maintenance tactic. In stage III the maintenance tactics are implemented, among them: Total Productive Maintenance (TPM), Reliability-centered maintenance (RMC), Total quality maintenance (TQMain), Evidence-based asset management (EBAM), Time-based maintenance (TBM), Computerized maintenance management system (CMMS), etc., in sequential and historical order (Z. Chen, Maiti, & Agapiou, 2017; Galán, Alfonso, & Duque, 2014; B. Jonge, RuudTeunter, & TiedoTinga, 2017; Modgil & Sharma, 2016; Pramod, Devadasan, Muthu, Jagathyraj, & Dhakshina, 2006; E. J. J. Ruijters, Guck, Drolenga, & Stoelinga, 2016). Stage IV is reached when companies have adequately developed the previous levels. In this stage, companies are interested in measuring results and knowing how well they do their work, which is why they begin to establish their own maintenance systems such as life cycle cost analysis (LCC). It is characteristic of this stage that the measurement systems implemented are under international parameters, to compare themselves with similar or different companies to establish the level of success reached, in general, they try to control all the executed actions (Goyal, Pabla, Dhami, & Lachhwani, 2017; Macchi, Márquez, Holgado, Fumagalli, & Martínez, 2009; Pui, Bhandari, Arzaghi, Abbassi, & VikramGaraniya, 2017; Sabri, Sulaiman, Ahmad, & Tang, 2015).

Stage V is characterized by the development of skills and competence in all maintenance staff; it is also dependent on all of the previous stages. At this level the FMECA (Failure Modes, Effects and Criticality Analysis), RCFA (Root Cause Failure Analysis), and RPN (Risk priority number) strategies are consolidated. The company is strengthened and develops skills and competence in whole or some of the topics initiated in the previous stages (Chemweno, Pintelon, Horenbeek, & Muchiri, 2015; Espinosa & Salinas, 2010; E. Ruijters, Guck, Noort, & Stoelinga, 2016; Selim, Yunusoglu, & Balaman, 2016; Sellappan, Nagarajan, & Palanikumar, 2015).

The difference between assets and liabilities is that conceptually the first one is associated with the production of wealth, while the second refers to investment or expenses. Under this premise, maintenance is influenced in terms of how to visualize the assets' use. The evolution towards the sixth generation "Assets Integrity Management", has different ways of being reached (Amadi-Echendu et al., 2010; Dunning, 2006; Kilsby, Remenyte-Prescott, & Andrews, 2017; Murthy, Atrens, & Eccleston, 2002; Palencia, 2007). It focuses on obtaining lower costs, lower labor requirements, reduce the planned repair and maintenance times (increased in operational time), as well as eliminating or reducing the logistics time required for maintenance and / or production.

III. ANALYSIS OF MAINTENANCE MANAGEMENT MODELS REPORTED IN THE LITERATURE

The review to identify the various maintenance models within the literature includes a group of preliminary studies. The first review report on maintenance models dates from 1976 in a study entitled "A survey of maintenance models: the control and surveillance of deteriorating systems" (Pierskalla & Voelker, 1976). The focus is on work appearing since the 1965 survey, "Maintenance Policies for Stochastically Failing Equipment: A Survey" by John McCall and the 1965 book, The Mathematical Theory of Reliability, by Richard Barlow and Frank Proschan (Barlow & Proschan, 1996; McCall, 1965). The survey includes models, which involve an optimal decision to procure, inspect, and repair and/or replace a unit subject to deterioration in service. Subsequently, Dekker (1996) and Stoneham (1998) publish two reviews on models or strategies for maintenance management. In 1996, Dekker reviews the applications of maintenance optimization models and discusses it future prospects. Two years later Stoneham characterized the most used maintenance models up to that date, among which stand out TPM, RCM and CBM. In a critical analysis at the beginning of the 21st century, Sherwin (2000) reviews the general models for maintenance management from a strategic viewpoint to consider maintenance as a "contributor to benefits" instead of "a necessary evil".

A few years later, in a review to identify different maintenance strategies, Mostafa (2004) and Garg et al. (2006) list a group of strategies for maintenance management. The papers finds, among other things, that important issues in maintenance management range from various optimization models, maintenance techniques, scheduling, and information systems etc., within each category the authors have been identified different gaps. Moreover, they provide a review of a large number of papers in this field and suggests a classification into various areas and sub areas. Fraser et al. (2015) perform a literature review, first with the aim to identify and categorize, the various maintenance management models, and second, to determine the depth of empirical evidence for the popular models in real-world applications (Fraser, Hvolby, & Tseng, 2015). Finally, Yousefli et al. (2017) propose a paper to categorize the literature and to adopt a hierarchy review according to maintenance management functions in hospital buildings.

Table I provides a summary of the earlier literature review papers that are related to the maintenance management model.

Table I Summary of the literature review papers related with the maintenance management

Source: Own elaboration.

Author	Year	Title	Publisher
William P. Pierskalla John A. Voelker	1976	A survey of maintenance models: the control and surveillance of deteriorating systems	Naval Research Logistics Quarterly
Rommert Dekker	1996	Applications of maintenance optimization models: a review and analysis	Reliability Engineering & System Safety
D. Stoneham	1998	The Maintenance Management and Technology Handbook	Elsevier Advanced Technology
David Sherwin	2000	A review of overall models for maintenance management	Journal of Quality in Maintenance Engineering
S. Mostafa	2004	Implementation of proactive maintenance in the Egyptian glass company	Journal of Quality in Maintenance Engineering
Amik Garg S.G. Deshmukh	2006	Maintenance management: literature review and directions	Journal of Quality in Maintenance Engineering

Kym Fraser Hans Henrik Hvolby Tzu Liang Tseng	2015	Maintenance management models: a study of the published literature to identify empirical evidence: A greater practical focus is needed	International Journal of Quality & Reliability Management
Zahra Yousefli Fuzhan Nasiri Osama Moselhi	2017	Healthcare facilities maintenance management: a literature review	Journal of Facilities Management

Twenty-seven maintenance management models were identified and were named in different ways with particular characteristics and practical utility. Except Pierskalla and Voelker review from 1976, with a reactive approach according to the period, it is possible to highlight that five of the identified models were listed in all the reviews, so it can be considered as the most relevant model reported in the literature for maintenance management. These models according to the fulfilled review are corrective maintenance (CM), preventive maintenance (PM), total productive maintenance (TPM), reliability-centred maintenance (RCM), and condition-based maintenance (CBM).

Additionally, authors continue searching for the most suitable model for maintenance management in their business (Campos, Fernández, Díaz, & Márquez, 2010; Gupta & Mishra, 2016; Hassanain, Froese, & Vanier, 2001; Lavy & Shohet, 2009; Márquez, León, Fernández, Márquez, & Campos, 2009; Pramod et al., 2006; Shafiee, 2015; Viveros, Stegmaier, Kristjanpoller, Barbera, & Crespo, 2013; C. H. Wang & Hwang, 2004). However, after reviewing the proposed models, it can be verified that theoretical bases form part of the most relevant models with an emphasis on informatics, so they will not be taken into account as new models, but as a specialization of existing models.

Table II summarizes the models identified in the literature, including its focus, the application environment and some examples of implementation in recent years, according to their historical context.

Table II: Maintenance management models**.**

Source: Own elaboration.

First generation: Before 1950	**Approach: Execute corrective actions**		**Objective: Repair unforeseen failures**
Model	**Main focus**	**Application**	**Evidences**
Corrective maintenance (CM)	Failures correction to return the asset immediately to its functionality condition.	Applicable to any work environment. It must be implemented together with a proactive action.	(M. Ben-Daya, U. Kumar, & D. N. P. Murthy, 2016; Y. Wang, Deng, Wu, Wang, & Xiong, 2014)
Breakdown, Reactive maintenance or Failure-Based Maintenance (FBM)	The action is performed after the asset fails. It can be more expensive than preventive maintenance.	Applicable to any work environment. It must be implemented together with a proactive action.	(Hauw, Wan, & Shahara, 2017; B. Jonge et al., 2017)
Campaign maintenance	Similar to Breakdown maintenance.	Commonly used when maintenance restrictions have no priority	(Stoneham, 1998)
Second generation: Between 1950 and 1959	**Approach: Apply planned actions**	**Objective: Prevent, predict and repair failures**	
Run-to-failure model Or Run-to-destruction model	Reactive approach. The asset is normally used until it fails, then it is discarded or a corrective action is executed	For assets that do not represent security risks in case of failure, assets with a minimum impact on production. Applicable when the repair cost is less than the maintenance cost.	(Salah, Osman, & Hosny, 2018; Stoneham, 1998**)**
Proactive maintenance	Philosophy focused on reducing the total maintenance required and optimizing the useful life of the asset	Applicable to environments where can be implement risk control strategies	(Canito et al., 2017; Ferreira et al., 2017; Mostafa, 2004)
Preventive maintenance (PM) Or Scheduled maintenance	Maintenance frequency is conditioned by the time, production volume and asset condition. Performed regularly on an asset to decrease the probability of failure	Applicable to assets with preventable failure modes, and assets with a probability of failure that increases with time or use.	(Chang, 2014; Maleki & Yang, 2017; Ni, Gu, & Jin, 2015; Sarker & Faiz, 2016; Sheu, Chang, Chen, & Zhang, 2015)
Predictive maintenance (PdM)	Maintenance is carried out when necessary instead scheduling intervention frequency.	Applicable to assets with a critical operational function. Assets with predesirable failure modes cost-effectively with regular monitoring	(M. Carnero, 2006; McKone & Weiss, 2002)

Third generation: Between 1960 and 1989	**Approach: Establish maintenance tactics**		**Objective: Manage and operate under an structured system**
Model	**Main focus**	**Application**	**Evidences**
Reliability-Centred Maintenance (RCM)	Corporate level maintenance strategy for optimization purposes. It allows determining the maintenance requirements of the assets according to their operating context.	For facilities with critical assets (those that can fail frequently or have large consequences of failures) such as airlines, power plants, oil industries, etc.	(Guck, Spel, & Stoelinga, 2015; Piasson, Bíscaro, Leão, & SanchesMantovani, 2016; E. Ruijters et al., 2016; Salah et al., 2018; Yssaad & Abene, 2015)
Total productive maintenance (TPM)	An asset management philosophy of whole company that integrates all business aspects (operators, materials, quality, energy, security, etc.) with maintenance operations.	Industrial and service environments where it is required to demonstrate operational requirements. Companies that implement quality management systems, risk management system, good practices (GxP), etc.	(Ahmad, Hossen, & Ali, 2018; Cavallone, Magno, & Zucchi, 2017; L. Chen & Meng, 2011; Jain, Bhatti, & Singh, 2014; Manjunatha, Srinivas, & Ramachandra, 2018; Poduval, Pramod, & P., 2015)
Total quality maintenance (TQMain)	Achieve and maintaining high overall asset effectiveness to improve manufacturing processes and produce quality products without interruption.	Similar to TPM	(Al-Najjar & Algabroun, 2018; Modgil & Sharma, 2016; Yang, Tavner, Crabtree, Feng, & Qiu, 2014)
Evidence-based asset management (EBAM)	It is the technique of making the right decisions and optimizing asset management processes with the best information available and with clearly defined decision criteria.	Applicable to companies which has implemented a computerized maintenance management system (CMMS)	(Campbell & Reyes-Picknell, 2015; Z. Chen et al., 2017; Delaney & Barton, 2015; Guo, Berkshire, Fulton, & Hermanson, 2017)
Time-based maintenance (TBM)	Maintenance activity based on time	Applicable in environments where developed a preventive maintenance strategies and predictive maintenance.	(B. Jonge et al., 2017; B. d. Jonge, Dijkstra, & Romeijnders, 2015; Kim, Ahn, & Yeo, 2016; Wenbin Wang, 2012)

Model	Main focus	Application	Evidences
Computerized maintenance management system (CMMS)	Designed to store, retrieve and analyze information, through computer applications.	Applicable to any work environment, where you need to handle large volumes of information.	(M. C. Carnero, 2015; Galán et al., 2014; Galán & Alfonzo, 2016; Hernández-Cedillo, Mejía-Rodríguez, & Dorantes-Méndez, 2017)
Fourth generation: Between 1981 and 1995		**Approach: Implement a strategy**	**Objective: Costs measurance , compare each other, predict indexes, etc.**
Outsourcing model	The transfer of the maintenance program of the companies to third parties in order to improve maintenance results and reduce costs	Applicable to any work environment. It must be implemented together with a proactive and reactive action.	(Manning, Larsen, & Bharati, 2015; Sabri et al., 2015; Spooner, Cape, & Summerfield, 2017)
Condition-based maintenance (CBM)	Based on assets monitoring and detection to determine vital alerts of imminent failure and decide the type of action to be carried out at each moment	Applicable in any environment where you can monitor and control analysis tools such as: vibration, infrared, ultrasonic, acoustic test, oil analysis, electrical test among others.	(Do, Voisin, Levrat, & Lung, 2015; Engeler, Treyer, Zogg, Wegener, & Kunz, 2016; Goyal et al., 2017; Keizer, P.Flapper, & H.Teunter, 2017; Su, Núñez, Baldi, & Schutter, 2016)
Condition monitoring	Similar to the CBM where the condition monitoring of the selected equipment is undertaken to detect potential failures	The same applications as CMB, with emphasis on operational performance.	(Caesarendra et al., 2016; Carroll, May, McDonald, & McMillan, 2015; Moghaddass & Ertekin, 2018; Ramirez, Muñoz, & Marquez, 2017; Yan, Chen, & Mukhopadhyay, 2017)
Risk-based maintenance (RBM)	Prioritize maintenance resources towards the assets that carry the greatest risk in case of failure. It is a methodology to determine the most economical use of maintenance resources.	Suitable for any work environment (equipment and operating systems).	(Bhandari, Arzaghi, Abbassi, Garaniya, & Khan, 2016; Jamshidi, Rahimi, Ait-kadi, & Ruiz, 2015; Pui et al., 2017; Ruparathna, Hewage, & Sadiq, 2018)

Model	Main focus	Application	Evidences
Value-driven maintenance planning (VDM)	It is a philosophy to optimize the value derived from maintenance at a given time. The decision to perform maintenance at any time is based on the cost / benefit analysis	Applicable to competitive environments in the market, where operations do not imply a high risk. Service companies, basic products factories, etc.	(Ali-Marttila et al., 2016; Khorshidi, Gunawan, & Ibrahim, 2016; Macchi et al., 2009; Rosqvist, Laakso, & Reunanen, 2009)
Fifth generation: Between 1996 and 2003		**Approach: Develop skills and competences**	**Objective: Apply science and technology**
Effectiveness-centred maintenance	Built on the philosophy of "doing the things correctly" instead of "doing the things right". It is based on the RCM model	Applicable to the environments where the RCM model can be developed	(Andriulo, Arleo, Carlo, Gnonia, & MarioTucci, 2015; Pun, Chin, Chow, & Lau, 2002)
Age-based maintenance	Apply tasks and maintenance intervals to assets, depending on their operating time. Control of the degradation time of a component	Mechanical and structural systems, hydraulic structures, engine monitoring, etc.	(Huynh, Castro, Barros, & Bérenguer, 2012; Shafiee & Finkelstein, 2015; Shafiee, Patriksson, & Chukova, 2016)
Availability-based maintenance (ABM)	The maintenance method based on availability. It is a version of Reliability-Centred Maintenance	The same applications as RCM	(Alaswad, Cassady, Pohl, & Li, 2017; Carroll et al., 2015; Qiu, Cui, & Gao, 2017)
Prognosis Help Management (PHM)	Evaluate the system based on data of its current condition or status within its life cycle, determine the occurrence mode and development of failures and, ultimately, mitigate system risks	Applicable to the environments where the CBM model can be developed	(Agarwal, Lybeck, Pham, Rusaw, & Bickford, 2015; Atamuradov, Medjaher, Dersin, Lamoureux, & Zerhouni, 2017; Goodman, 2015; Lei & Sandborn, 2016; Vogl, Weiss, & Helu, 2016; Wan, Fu, Li, & Zhao, 2016)

Model	Main focus	Application	Evidences
E-maintenance	Combines computerized maintenance system with Internet and electronic collaboration services	Applicable in companies providing services. Companies with high development in information and communications infrastructure	(M. Ben-Daya, U. Kumar, & D. N. Murthy, 2016; Guillén, Crespo, Gómez, & Sanz, 2016; Levrat, Iung, & Marquez, 2008)
Virtual maintenance model	Focused on the life cycle of the asset (conception, design, operation and withdrawal)	Applicable to the aeronautical industry, military training and modern vehicles	(Jenab, Moslehpour, & Khoury, 2016; Rao, Xu, Jing, Zhang, & Zhao, 2017; Sun, Shi, Xie, Sun, & Jia, 2016; Wei Wang, Zhang, & Feng, 2017)
Sixth generation: Since 2004 – Nowadays		**Approach: Tangible and intangible assets**	**Objective: Asset integrity management**
Terotechnology model	Focused on the life cycle of the system	Applicable to industrial maintenance.	(Czaplicki, 2008; Ibrahim & Brack, 2004; Palencia, 2007; Samanta & Sarkar, 2004)
Strategic maintenance management	A global business perspective based on TPM and RCM.	Applicable to the environments where the TPM and RCM models can be developed	(Alessandro, Malcolm, & Jiju, 2013; Baidya, Dey, Ghosh, & Petridis, 2018; Ginter, Duncan, & Swayne, 2018; Murthy et al., 2002; Shohet & Nobili, 2017)
Maintenance training model	An organizational philosophy that involves all workers, plant, equipment and support infrastructure	Applicable to the environments where the TPM model can be developed	(Song, Zhang, Li, & Wang, 2017; Worobey, Pearlman, Dyson-Hudson, & Boninger, 2016; Xu, Wang, & Ma, 2016)

IV. MAINTENANCE MANAGEMENT. APPLICATION TO THE CLINIC-HOSPITAL FACILITY

The demand for healthcare services and facilities is ever increasing in the twenty-first century owing to population growth, increased life expectancies and elevated standards of life. Nowadays, asset, risk and maintenance management are three types of management that are heavily related to each other. Moreover, all three of them are frequently encountered in asset intensive industries around the world. Unfortunately, this relationship has come late to the hospital environment.

As mentioned in the introduction section, maintenance is the combination of all technical, administrative and managerial actions during the lifecycle of an asset intended to retain it in, or restore it to a state in which it can perform the required function (IEC, 2004).

Applied to the hospital environment this definition is inappropriate. It requires the addition to the definition, a maintenance management model that includes risk management and patient safety. Therefore, this has forced hospital entities to record, document and analyze data and practices in a structured way and to use a consistent and transparent method for analysis (Ali & Wan-Mohamad, 2009; Galán, 2017; Mwanza & Mbohwa, 2015). Risk management does not mean that risks are deliberately accepted to meet the business objectives. The task is to identify risks within the entire process to implement appropriate measures to manage (control) these risks. In the hospital environment, this process is known as residual risk management and is aimed at maximizing the safety of patients and workers in a hospital entity (ISO, 2007; Lueddemann, Sahin, Pfeiffer, & Lueth, 2016; Rezaei, Yarmohammadian, Haghshenas, Fallah, & Ferdosi, 2018).

From the beginning of this century, scientific production has increased on the topic of hospital technological administration. There is a growing interest on the part of biomedical engineers to find a strategy or model applicable to the hospital environment (Canaway, Bismark, Dunt, & Kelaher, 2017; Ezziane et al., 2012; Lam, 2007; Mahfoud, Barkany, & Biyaali, 2016; Melo, 2016; Mutia, Kihiu, & Maranga, 2012; Støre-Valen, Larssen, & Bjørberg, 2014).

In a research proposal, Shohet, Leibovich, and Bar (2003) propose that biomedical engineers, as well as facility managers, should find new ways to improve the comfort, safety, energy consumption and cost effectiveness of the buildings they manage and operate. To develop this goal, quantitative management indicators for the examination of hospital buildings' performance and budgeting of their maintenance activities need to be taken into account. Other authors raise the need to develop a quantitative integrated health-care facility management model. Koning et al (2006) combine and apply different strategies to remain competitive, cost efficient, and up-to-date in a healthcare center. The article outlines a methodology and presents examples to illustrate how principles of Lean Thinking and Six Sigma can be combined to provide an effective framework for producing systematic innovation efforts in a healthcare center.

Lee and Kwak (2011) shows the relevance of the DKM (distributed knowledge management) model in a case study of a distributed decision support system (DDSS) in health care administration in the US. Sumet et al. (2012), use a knowledge management (KM) model as a tool to improve the quality of service in a hemodialysis unit. The paper focuses on intervention that applied KM to staff providing care for patients with hemodialysis to improve care and outcomes. Taghipour, Banjevic and Jardine (2001) present a multi-criteria decision-making model to prioritize medical devices according to their criticality, as a maintenance management strategy. Devices with lower criticality scores can be assigned a lower priority in a maintenance management program. However, those with higher scores should be investigated in detail to find the reasons for their higher criticality, and appropriate actions, such as 'preventive maintenance', 'user training', 'redesigning the device', etc., should be taken.

Franceschini et al. (2003) describes a proposal of a new approach for managing outsourcing processes. The model, which can be easily adapted to different application fields, has been conceived with the main aim of managing strategic decisions, economic factors and human resources. Shohet (2004) developed a quantitative model to integrate different domains related to facilities management (FM). The proposed model is divided into three main phases that deal with the five main FM domains. He asserted that all of the FM practices in hospitals could be outsourced. Alzaben et al. (2014) identified a means to improve maintenance operations in Saudi hospitals through the development of a new framework incorporating aspects of three important maintenance management concepts as suitable options to aid healthcare facility management. These options are Total Preventive Maintenance (TPM), Reliability Centred Maintenance (RCM) and Reliability Centred Failure Analysis (RCFA).

Straub and Van Mossel (2007) suggested a performance-based contract mechanism used to select an outsourcing contractor. To be selected, a contractor must propose their choice of maintenance strategies considering the future scenarios of the hospital in terms of services and requirements as well as the user satisfaction issues related to maintenance activities. Liu, Hotchkiss and Bose (2008) review the research literature on the effectiveness of contracting-out of primary health care services and its impact on both programme and health systems performance in low- and middle-income countries. Straub (2009) developed a calculation model was that calculates the net present value of the direct (product) and indirect (transaction) costs at project level for a competitive maintenance tendering approach and for performance-based maintenance contracts. The findings show that performance-based maintenance contracts reduce both direct and indirect costs compared to a competitive tendering approach. Bana e Costa et al. (2012) proposes a multi-criteria model for auditing a Predictive Maintenance Programme (PMP) developed and implemented in the General Hospital of Ciudad Real (GHCR) in Spain. The model has a two-level structure, with top level auditing areas specified by second level auditing criteria on which the performance of the PMP should be appraised. Ikediashi and Ekanem (2015) purpose a paper to extend the body of knowledge on health care facilities management (FM) by investigating the extent to which public hospitals in Nigeria have fared in terms of outsourced FM services.

On the other hand, Shohet and Nobili (2016) developed a performance-based model for clinic facilities by integrating eight KPIs into an enterprise resource planning (ERP) system for the maintenance of public clinic facilities. Jandali and Sweis (2018), identify and assess the factors affecting maintenance management performance of hospital buildings in Amman, Jordan. The analysis proved that 14 items representing four factors had significant effect on maintenance management performance and a new framework was established. Additionally, the results showed that Amman's hospitals were found to be in an average condition and maintenance management practices were assessed to be efficient.

Summarizing, due to the particular characteristics of hospital environments it is necessary to carefully select the maintenance management model to be implemented in a health institution. This model must guarantee not only the availability of medical technology but also the residual risk management and patient safety. Among the models reported in the literature for maintenance management analyzed in the previous section, it was detected that only seven had risk orientation or criticality of the assets and could be the most adequate for clinical and hospital environment. These models are predictive maintenance (PdM), reliability-centred maintenance (RCM), risk-based maintenance (RBM), availability-based maintenance (ABM), effectiveness-centred maintenance (ECM), time-based maintenance (TBM) and strategic maintenance management. Nevertheless, it was also identified that none of these models were aimed at maximizing the safety of physiologically impaired people.

Table III summarizes the maintenance management models that should been applied to hospital environments. It summarizes the number of articles found in the literature for each model with industrial applications (I) vs number of articles with an application in the hospital environment (H), from 2000 to 2017. The search was carried out in the main databases that publish research related with maintenance function and only included the model name in the title, abstract, and keywords of published articles.

Table III Number of papers related with the maintenance management model reported on the specialty literature
Source: Own elaboration.

BD / **Model**	EbscoHost	Emerald	Science Direct	Scopus	Springer	Web of Science	**Total**
PdM	75/1	26/0	13/1	356/1	47/1	262/3	**719/7**
RCM	183/0	15/0	27/1	50/0	10/0	225/0	**510/1**
RBM	105/2	5/0	62/2	13/0	7/0	72/1	**264/5**
ABM	23/0	2/0	13/0	9/0	0/0	6/0	**53/0**
ECM	0/0	1/0	14/0	0/0	0/0	7/0	**22/0**
TBM	59/0	4/0	6/0	9/0	1/0	9/0	**88/0**
SMM	18/2	14/1	18/0	126/1	2/0	3/0	**181/4**
Total	**463/5**	**67/1**	**153/4**	**563/2**	**67/1**	**584/4**	**1897/17**

As can be seen from Table III, the databases produced a total of 1897 articles with industrial application and only 16 with a direct application to the hospital environment; including as a search criteria the model name in the title, abstract, and keywords of published articles. If the search is extended with the maintenance management models, independently of the risk orientation, we can find a number of research articles about the application of any strategy for hospital maintenance management. This highlights the need to develop a model that integrates the hospital maintenance management, the medical technology residual risk management and patient safety, which must be nowadays be an aim to achieve by biomedical engineers.

V. CONCLUSIONS

Maintenance management has flourished as a science along the time but its impact on decision making within organizations is limited so far. Considering maintenance as an applied research field and maintenance management being of strategic importance for any type of organization, it offers a detailed overview of an area, which has not been given the strategic attention by business managers in the previous years. Specialized literature on maintenance models was reviewed, considering a large amount of papers published in the main databases that publish research related within maintenance function in a period of 2000 to 2017. The information recovered about the of maintenance management models will permit practitioners to reconsider the way to manage the maintenance function, especially in a clinic-hospital environment.

According to the literature review, there is very limited research on identification, evaluation and application of maintenance management models in a hospital environment. The literature is even more limited in the case of analysis and risk management associated with the maintenance function in hospitals.

Finally, improvement of the performance of the maintenance function in healthcare facilities not only leads to reduced cost and resource efficiency gains but also elevates the satisfaction of patients by increasing the quality and reliability of services. Therefore, designing a maintenance model that integrates maintenance management, risk management and patient safety, is the new challenge that biomedical engineers must face nowadays.

VI. BIBLIOGRAPHY

Agarwal, V., Lybeck, N., Pham, B. T., Rusaw, R., & Bickford, R. (2015). Prognostic and health management of active assets in nuclear power plants. *International Journal of Prognostics and Health Management, 6*(Special issue), 1-17.

Ahmad, N., Hossen, J., & Ali, S. M. (2018). Improvement of overall equipment efficiency of ring frame through total productive maintenance: a textile case. *The International Journal of Advanced Manufacturing Technology, 94*(1-4), 239–256. doi: http://doi.org/10.1007/s00170-017-0783-2

Al-Najjar, B., & Algabroun, H. (2018). *A Model for Increasing Effectiveness and Profitability of Maintenance Performance: A Case Study.* Paper presented at the Engineering Asset Management.

Alaswad, S., Cassady, R., Pohl, E., & Li, X. (2017). A model of system limiting availability under imperfect maintenance. *Journal of Quality in Maintenance Engineering, 23*(4), 415-436. doi: http://doi.org/10.1108/JQME-06-2016-0024

Alessandro, L., Malcolm, B., & Jiju, A. (2013). Applications of Lean Six Sigma in an Irish hospital. *Leadership in Health Services, 26*(4), 322-337. doi: http://doi.org/10.1108/LHS-01-2012-0002

Ali-Marttila, M., Marttonen-Arola, S., Ylä-Kujala, A., Ukko, J., Rantala, T., Sinkkonen, T., . . . Kärri, T. (2016). *Stagewise Process Towards Collaborative and Value-Driven Decisions in Maintenance Networks.* Paper presented at the Proceedings of the 10th World Congress on Engineering Asset Management (WCEAM 2015), Lecture Notes in Mechanical Engineering. Springer, Cham.

Ali, M., & Wan-Mohamad, W. M. N.-B. (2009). Audit assessment of the facilities maintenance management in a public hospital in Malaysia. *Journal of Facilities Management, 7*(2), 142-158. doi: http://dx.doi.org/10.1108/14725960910952523

Alzaben, H., McCollin, C., & Eugene, L. (2014). Maintenance planning in a Saudi Arabian hospital. *Safety and Reliability, 34*(2), 25-40. doi: http://doi.org/10.1080/09617353.2014.11691004

Amadi-Echendu, J. E., Willett, R., Brown, K., Hope, T., Lee, J., Mathew, J., . . . Yang, B.-S. (2010). *What Is Engineering Asset Management?* Paper presented at the Definitions, concepts and scope of engineering asset management.

Andriulo, S., Arleo, M. A., Carlo, F. d., Gnonia, M. G., & MarioTucci. (2015). Effectiveness of maintenance approaches for High Reliability Organizations. *IFAC-PapersOnLine, 48*(3), 466-471. doi: http://doi.org/10.1016/j.ifacol.2015.06.125

Atamuradov, V., Medjaher, K., Dersin, P., Lamoureux, B., & Zerhouni, N. (2017). Prognostics and Health Management for Maintenance Practitioners - Review, Implementation and Tools Evaluation. *International Journal of Prognostics and Health Management, 8*(Special Issue on Railways & Mass Transportation), 1-31.

Baidya, R., Dey, P. K., Ghosh, S. K., & Petridis, K. (2018). Strategic maintenance technique selection using combined quality function deployment, the analytic hierarchy process and the benefit of doubt approach. *The International Journal of Advanced Manufacturing Technology, 94*(1-4), 31–44. doi: http://doi.org/10.1007/s00170-016-9540-1

Barlow, R., & Proschan, F. (1996). *The mathematical theory of reliability* (Vol. 7). New York: Siam.

Ben-Daya, M., Kumar, U., & Murthy, D. N. (2016). *Computerized Maintenance Management Systems and e-Maintenance.* Paper presented at the Introduction to Maintenance Engineering: Modeling, Optimization, and Management, John Wiley & Sons, Ltd, Chichester, UK.

Ben-Daya, M., Kumar, U., & Murthy, D. N. P. (2016). *Introduction to maintenance engineering: modelling, optimization and management.* Hoboken, United States: John Wiley & Sons.

Bhandari, J., Arzaghi, E., Abbassi, R., Garaniya, V., & Khan, F. (2016). Dynamic risk-based maintenance for offshore processing facility. *Process Safety Progress, 35*(4), 399-406. doi: http://doi.org/10.1002/prs.11829

Caesarendra, W., Kosasih, B., KietTieu, A., Zhu, H., .Moodie, C. A. S., & Zhu, Q. (2016). Acoustic emission-based condition monitoring methods: Review and application for low speed slew bearing. *Mechanical Systems and Signal Processing, 72-73*, 134-159. doi: http://doi.org/10.1016/j.ymssp.2015.10.020

Campbell, J. D., & Reyes-Picknell, j. V. (2015). *Uptime: Strategies for Excellence in Maintenance Management* (Third Edition ed.): CRC Press.

Campos, M. A. L., Fernández, J. F. G., Díaz, V. G., & Márquez, A. C. (2010). *A new maintenance management model expressed in UML.* London,: Taylor & Francis Group.

Canaway, R., Bismark, M., Dunt, D., & Kelaher, M. (2017). Medical directors' perspectives on strengthening hospital quality and safety. *Journal of Health Organization and Management, 31*(7/8), 696-712. doi: http://doi.org/10.1108/JHOM-05-2017-0109

Canito, A., Fernandes, M., Conceição, L., Praça, I., Santos, M., Rato, R., . . . Marreiros, G. (2017). *An Architecture for Proactive Maintenance in the Machinery Industry.* Paper presented at the Ambient Intelligence– Software and Applications – 8th International Symposium on Ambient Intelligence (ISAmI 2017).

Carnero, M. (2006). An evaluation system of the setting up of predictive maintenance programmes. *Reliability Engineering and System Safety, 91*(8), 945-963. doi: http://doi.org/10.1016/j.ress.2005.09.003

Carnero, M. C. (2015). Auditing model for the introduction of computerised maintenance management system. *Production Planning and Control, 1*(1), 17-41. doi: http://doi.org/10.1504/IJDS.2015.069049

Carroll, J., May, A., McDonald, A., & McMillan, D. (2015). *Availability improvements from condition monitoring systems and performance based maintenance contracts.* Paper presented at the European Wind Energy Association (EWEA) Offshore.

Cavallone, M., Magno, F., & Zucchi, A. (2017). Improving service quality in healthcare organisations through geomarketing statistical tools. *The TQM Journal, 29*(5), 690-704. doi: http://doi.org/10.1108/TQM-12-2016-0104

Costa, C. A. B. e., Carnero, M. C., & Oliveira, M. D. (2012). A multi-criteria model for auditing a Predictive Maintenance Programme. *European Journal of Operational Research, 217*(2), 381-393. doi: http://dx.doi.org/10.1016/j.ejor.2011.09.019

Czaplicki, J. M. (2008). Terotechnology versus Exploitation Theory–some remarks. *Scientific Problems of Machines Operation and Maintenance, 43*(2), 45-58.

Chang, C.-C. (2014). Optimum preventive maintenance policies for systems subject to random working times, replacement, and minimal repair. *Computers & Industrial Engineering, 67*, 185-194. doi: http://doi.org/10.1016/j.cie.2013.11.011

Chemweno, P., Pintelon, L., Horenbeek, A. V., & Muchiri, P. (2015). Development of a risk assessment selection methodology for asset maintenance decision making: An analytic network process (ANP) approach. *International Journal of Production Economics, 170*, 663-676. doi: http://dx.doi.org/10.1016/j.ijpe.2015.03.017

Chen, L., & Meng, B. (2011). How to apply TPM in equipment management for Chinese enterprises. *Chinese Business Review, 10*(2), 137-145.

Chen, Z., Maiti, S., & Agapiou, A. (2017). *Evidence-based safety management in building refurbishment*. Paper presented at the Proceedings of the Doctoral Workshop in Building Asset Management, Association of Researchers in Construction Management (ARCOM), Glasgow, UK.

Dekker, R. (1996). Applications of maintenance optimization models: a review and analysis. *Reliability Engineering & System Safety, 51*(3), 229-240. doi: http://dx.doi.org/10.1016/0951-8320(95)00076-3

Delaney, G. P., & Barton, M. B. (2015). Evidence-based estimates of the demand for radiotherapy. *Clinical Oncology, 27*(2), 70-76. doi: http://dx.doi.org/10.1016/j.clon.2014.10.005

Do, P., Voisin, A., Levrat, E., & Lung, B. (2015). A proactive condition-based maintenance strategy with both perfect and imperfect maintenance actions. *Reliability Engineering & System Safety, 133*, 2-32. doi: http://doi.org/10.1016/j.ress.2014.08.011

Dunning, J. H. (2006). Towards a new paradigm of development: implications for the determinants of international business. *Transnational corporations, 15*(1), 173-227.

Engeler, M., Treyer, D., Zogg, D., Wegener, K., & Kunz, A. (2016). Condition-based Maintenance: Model vs. Statistics a Performance Comparison. *Procedia CIRP, 57*, 253-258. doi: http://doi.org/10.1016/j.procir.2016.11.044

Espinosa, F. F., & Salinas, G. E. (2010). Evaluación de la madurez de la función mantenimiento para implementar innovaciones en su gestión. *Información Tecnológica, 21*(3), 3-12. doi: http://dx.doi.org/10.4067/S0718-07642010000300002

Ezziane, Z., Maruthappu, M., Gawn, L., Thompson, E. A., Athanasiou, T., & Warren, O. J. (2012). Building effective clinical teams in healthcare. *Journal of Health Organization and Management, 26*(4), 428-436. doi: http://doi.org/10.1108/14777261211251508

Fernández, J. F. G., & Márquez, A. C. (2012). *Maintenance Management in Network Utilities : Framework and Practical Implementation*. London: Springer.

Ferreira, L. L., Albano, M., Silva, J., Martinho, D., Marreiros, G., Orio, G. d., . . . Ferreira, H. (2017). *A pilot for proactive maintenance in industry 4.0*. Paper presented at the Factory Communication Systems (WFCS).

Franceschini, F., Galetto, M., Pignatelli, A., & Varetto, M. (2003). Outsourcing: guidelines for a structured approach. *Benchmarking: An International Journal, 10*(3), 246-260. doi: http://dx.doi.org/10.1108/14635770310477771

Fraser, K., Hvolby, H. H., & Tseng, T. L. (2015). Maintenance management models: a study of the published literature to identify empirical evidence: A greater practical focus is needed. *International Journal of Quality & Reliability Management, 32*(6), 635-664. doi: http://dx.doi.org/10.1108/IJQRM-11-2013-0185

Galán, M. H. (2017). Management audit applied to the maintenance department in hospital facilities. *Ingeniería Mecánica, 20*(3), 152-159.

Galán, M. H., Alfonso, Y. D., & Duque, A. A. (2014). Sistema Automatizado para la Gestión del Mantenimiento. *INGE@ UAN-Tendencias en la Ingeniería, 4*(8), 48-54.

Galán, M. H., & Alfonzo, Y. D. (2016). Methodology and implementation of maintenance management program. *Revista Ingniería Industrial, 37*(1).

Garg, A., & Deshmukh, S. G. (2006). Maintenance management: literature review and directions. *Journal of Quality in Maintenance Engineering, 12*(3), 205-238. doi: http://dx.doi.org/10.1108/13552510610685075

Ginter, P. M., Duncan, W. J., & Swayne, L. E. (2018). *The Strategic Management of Healthcare Organizations*. John Wiley & Sons.

Goodman, D. (2015). *Expanding the boundaries of test and diagnostics: Prognostics and Health Management (PHM) for complex systems*. Paper presented at the Test Symposium (ETS), 2015 20th IEEE European, Cluj-Napoca.

Goyal, D., Pabla, B. S., Dhami, S. S., & Lachhwani, K. (2017). Optimization of condition-based maintenance using soft computing. Neural Computing and Applications. *Neural Computing and Applications, 28*(Suppl 1), 829–844. doi: http://dx.doi.org/10.1007/s00521-016-2377-6

Guck, D., Spel, J., & Stoelinga, M. (2015). *DFTCalc: Reliability Centered Maintenance via Fault Tree Analysis*. Paper presented at the Formal Methods and Software Engineering. Lecture Notes in Computer Science, Springer, Cham.

Guillén, A. J., Crespo, A., Gómez, J. F., & Sanz, M. D. (2016). A framework for effective management of condition based maintenance programs in the context of industrial development of E-Maintenance strategies. *Computers in Industry, 82*(1), 170-185. doi: http://doi.org/10.1016/j.compind.2016.07.003

Guo, R., Berkshire, S. D., Fulton, L. V., & Hermanson, P. M. (2017). Use of evidence-based management in healthcare administration decision-making. *Leadership in Health Services, 30*(3), 330-342. doi: http://doi.org/10.1108/LHS-07-2016-0033

Gupta, G., & Mishra, R. P. (2016). A SWOT analysis of reliability centered maintenance framework. *Journal of Quality in Maintenance Engineering, 22*(2), 130-145. doi: http://dx.doi.org/10.1108/JQME-01-2015-0002

Gutiérrez, L. A. M. (2006). *Mantenimieto estratégicos para empresas de servicios o industriaeles: Enfoque sistémico Kantiano* (1 ed.).

Hassanain, M., Froese, T., & Vanier, D. (2001). Development of a maintenance management model based on IAI standards. *Artificial Intelligence in Engineering, 15*(1), 177–193. doi: http://doi.org/10.1016/S0954-1810(01)00015-2

Hauw, S. T., Wan, M. W. H., & Shahara, D. S. (2017). *Spreadsheet simulation-based optimization for personnel capacity requirement in breakdown maintenance*. Paper presented at the MATEC Web of Conferences, EDP Sciences.

Hernández-Cedillo, C., Mejía-Rodríguez, A. R., & Dorantes-Méndez, G. (2017). *Diseño e Implementación de un Sistema Computarizado para la Gestión de Equipo Médico* Paper presented at the XXXIX Congreso Nacional de Ingeniería Biomédica

Huynh, K. T., Castro, I., Barros, A., & Bérenguer, C. (2012). Modeling age-based maintenance strategies with minimal repairs for systems subject to competing failure modes due to degradation and shocks. *European Journal of Operational Research, 218*(1), 140-151. doi: http://doi.org/10.1016/j.ejor.2011.10.025

Ibrahim, M. Y., & Brack, C. (2004). *New concept and implementation of inter-continental flexible training of terotechnology and life cycle costs*. Paper presented at the Industrial Technology, 2004. IEEE ICIT'04. 2004 IEEE International Conference on, Hammamet, Tunisia, Tunisia

IEC. (2004). *60300-3-14 Application guide - Maintenance and maintenance support*

Ikediashi, D., & Ekanem, A. M. (2015). Outsourcing of facilities management (FM) services in public hospitals: A study on Nigeria's perspective. *Journal of Facilities Management, 13*(1), 85-102. doi: http://dx.doi.org/10.1108/JFM-06-2014-0017

ISO. (2007). *14971 Risk management for medical devices-"Application of Risk Management to Medical Devices"*.

Jain, A., Bhatti, R., & Singh, H. (2014). Total productive maintenance (TPM) implementation practice: A literature review and directions. *International Journal of Lean Six Sigma, 5*(3), 293-323. doi: http://doi.org/10.1108/IJLSS-06-2013-0032
Jamshidi, A., Rahimi, S. A., Ait-kadi, D., & Ruiz, A. (2015). A comprehensive fuzzy risk-based maintenance framework for prioritization of medical devices. *Applied Soft Computing, 32*, 322-334. doi: http://doi.org/10.1016/j.asoc.2015.03.054
Jandali, D., & Sweis, R. (2018). Assessment of factors affecting maintenance management of hospital buildings in Jordan. *Journal of Quality in Maintenance Engineering, 24*(1), 37-60. doi: http://doi.org/10.1108/JQME-12-2016-0074
Jenab, K., Moslehpour, S., & Khoury, S. (2016). Virtual Maintenance, Reality, and Systems: A Review. *International Journal of Electrical and Computer Engineering, 6*(6), 2698-2707. doi: http://doi.org/10.11591/ijece.v6i6.11468
Jonge, B., RuudTeunter, & TiedoTinga. (2017). The influence of practical factors on the benefits of condition-based maintenance over time-based maintenance. *Reliability Engineering & System Safety, 158*(1), 21-30. doi: http://dx.doi.org/10.1016/j.ress.2016.10.002
Jonge, B. d., Dijkstra, A. S., & Romeijnders, W. (2015). Cost benefits of postponing time-based maintenance under lifetime distribution uncertainty. *Reliability Engineering & System Safety, 140*, 15-21. doi: http://doi.org/10.1016/j.ress.2015.03.027
Keizer, M. C. A. O., P.Flapper, S. D., & H.Teunter, R. (2017). Condition-based maintenance policies for systems with multiple dependent components: A review. *European Journal of Operational Research, 261*(2), 405-420. doi: http://doi.org/10.1016/j.ejor.2017.02.044
Khorshidi, H. A., Gunawan, I., & Ibrahim, M. Y. (2016). A value-driven approach for optimizing reliability-redundancy allocation problem in multi-state weighted k-out-of-n system. *Journal of Manufacturing Systems, 40*(parte 1), 54-62. doi: http://doi.org/10.1016/j.jmsy.2016.06.002
Kilsby, P., Remenyte-Prescott, R., & Andrews, J. (2017). A modelling approach for railway overhead line equipment asset management. *Reliability Engineering & System Safety, 168*, 326-337. doi: http://dx.doi.org/10.1016/j.ress.2017.02.012
Kim, J., Ahn, Y., & Yeo, H. (2016). A comparative study of time-based maintenance and condition-based maintenance for optimal choice of maintenance policy. *Structure and Infrastructure Engineering, 12*(12), 1525-1536. doi: http://doi.org/10.1080/15732479.2016.1149871
Koning, H., Verver, J. P., Heuvel, J., & Bisgaard, S. (2006). Lean Six Sigma in Healthcare. *Journal for Healthcare Quality, 28*(2), 4-11. doi: http://dx.doi.org/10.1111/j.1945-1474.2006.tb00596.x
Lam, Y. (2007). A geometric process maintenance model with preventive repair. *European Journal of Operational Research, 182*(2), 806-819. doi: http://dx.doi.org/10.1016/j.ejor.2006.08.054
Lavy, S., & Shohet, I. M. (2007). Computer-Aided Healthcare Facility Management *Journal of Computing in Civil Engineering, 21*(5), 363-372. doi: http://dx.doi.org/10.1061/(ASCE)0887-3801(2007)21:5(363)
Lavy, S., & Shohet, I. M. (2009). Integrated healthcare facilities maintenance management model: case studies. *Facilities, 27*(3-4), 107-119. doi: http://dx.doi.org/10.1108/02632770910933134
Lei, X., & Sandborn, P. A. (2016). PHM-Based Wind Turbine Maintenance Optimization Using Real Options. *International Journal of Prognostics and Health Management, 1*(1), 1-14.
Levrat, E., Iung, B., & Marquez, A. C. (2008). E-maintenance: review and conceptual framework. *Production Planning and Control, 19*(4), 408-429. doi: http://doi.org/10.1080/09537280802062571
Liu, X., Hotchkiss, D. R., & Bose, S. (2008). The effectiveness of contracting-out primary health care services in developing countries: a review of the evidence *Health Policy and Planning, 23*(1), 1–13. doi: http://dx.doi.org/10.1093/heapol/czm042
Lueddemann, T., Sahin, S., Pfeiffer, J., & Lueth, T. C. (2016). *Experimental evaluation of a novel ISO 14971 risk management software for medical devices.* Paper presented at the System Integration (SII), 2016 IEEE/SICE International Symposium on, Sapporo.
Macchi, M., Márquez, A. C., Holgado, M., Fumagalli, L., & Martínez, L. B. (2009). Value-driven engineering of E-maintenance platforms. *Journal of Manufacturing Technology Management, 25*(4), 568-598. doi: http://dx.doi.org/10.1108/JMTM-04-2013-0039
Mahfoud, H., Barkany, A. E., & Biyaali, A. E. (2016). Preventive Maintenance Optimization in Healthcare Domain: Status of Research and Perspective. *Journal of Quality and Reliability Engineering, 1*(1), 2-10. doi: http://dx.doi.org/10.1155/2016/5314312
Maleki, H., & Yang, Y. (2017). An uncertain programming model for preventive maintenance scheduling. *Grey Systems: Theory and Application, 7*(1), 111-122. doi: http://doi.org/10.1108/GS-07-2016-0015
Manjunatha, B., Srinivas, T. R., & Ramachandra, C. G. (2018). *Implementation of total productive maintenance (TPM) to increase overall equipment efficiency of an hotel industry.* Paper presented at the International Conference on Research in Mechanical Engineering Sciences (RiMES 2017), MATEC Web Conf.
Manning, S., Larsen, M. M., & Bharati, P. (2015). Global delivery models: The role of talent, speed and time zones in the global outsourcing industry. *Journal of International Business Studies, 46*(7), 850–877. doi: http://doi.org/10.1057/jibs.2015.14
Márquez, A. C., León, P. M. d., Fernández, J. F. G., Márquez, C. P., & Campos, M. L. (2009). The maintenance management framework: A practical view to maintenance management. *Journal of Quality in Maintenance Engineering, 15*(2), 167-178. doi: http://dx.doi.org/10.1108/13552510910961110
McCall, J. J. (1965). Maintenance Policies for Stochastically Failing Equipment: A Survey. *Management science, 11*(2), 493 - 524 doi: http://dx.doi.org/10.1287/mnsc.11.5.493
McKone, K., & Weiss, E. (2002). Guidelines for implementing predictive maintenance. *Production and Operations Management, 11*(2), 109-124.
Melin, A., & Granath, J. Å. (2004). Patient focused healthcare: an important concept for provision and management of space and services to the healthcare sector. *Facilities, 22*(11/12), 284-289. doi: http://dx.doi.org/10.1108/02632770410561277
Melo, S. (2016). The impact of accreditation on healthcare quality improvement: a qualitative case study. *Journal of Health Organization and Management, 30*(8), 1242-1258. doi: http://doi.org/10.1108/JHOM-01-2016-0021
Modgil, S., & Sharma, S. (2016). Total productive maintenance, total quality management and operational performance: An empirical study of Indian pharmaceutical industry. *Journal of Quality in Maintenance Engineering, 22*(4), 353-377. doi: http://dx.doi.org/10.1108/JQME-10-2015-0048
Moghaddass, R., & Ertekin, Ş. (2018). Joint optimization of ordering and maintenance with condition monitoring data. *Annals of Operations Research*, 1–40. doi: http://doi.org/10.1007/s10479-017-2745-3
Mostafa, S. (2004). Implementation of proactive maintenance in the Egyptian glass company. *Journal of Quality in Maintenance Engineering, 10*(2), 107-122. doi: http://dx.doi.org/10.1108/13552510410539187
Murthy, D., Atrens, A., & Eccleston, J. (2002). Strategic maintenance management. *Journal of Quality in Maintenance Engineering, 8*(4), 287-305. doi: http://dx.doi.org/10.1108/13552510210448504
Mutia, D., Kihiu, J., & Maranga, S. (2012). Maintenance Management of Medical Equipment in Hospitals. *Industrial Engineering Letters, 2*(3), 9-19.
Mwanza, B. G., & Mbohwa, C. (2015). An Assessment of the Effectiveness of Equipment Maintenance Practices in Public Hospitals. *Procedia Manufacturing, 4*, 307-314. doi: http://dx.doi.org/10.1016/j.promfg.2015.11.045

Ni, J., Gu, X., & Jin, X. (2015). Preventive maintenance opportunities for large production systems. *CIRP Annals, 64*(1), 447-450. doi: http://doi.org/10.1016/j.cirp.2015.04.127
Palencia, O. G. (2007). Optimización integral del mantenimiento: hacia la terotecnología de clase mundial. *Revista Clepsidra, 3*(4), 59-70. doi: http://dx.doi.org/10.26564/19001355.268
Pedersen, M. K., & HolmLarsen, M. (2001). Distributed knowledge management based on product state models — the case of decision support in health care administration. *Decision Support Systems, 31*(1), 139-158. doi: http://doi.org/10.1016/S0167-9236(00)00124-X
Pérez, E. N., Cárdenas, O. T., Rodríguez, J. A., & Cruz, E. H. (2000). *Gestión e Ingeniería Integral del mantenimiento*: Centros de Estudios Innovación y Mantenimiento.
Piasson, D., Bíscaro, A. A. P., Leão, F. B., & SanchesMantovani, J. R. (2016). A new approach for reliability-centered maintenance programs in electric power distribution systems based on a multiobjective genetic algorithm. *Electric Power Systems Research, 137*, 41-50. doi: http://doi.org/10.1016/j.epsr.2016.03.040
Pierskalla, W. P., & Voelker, J. A. (1976). A survey of maintenance models: The control and surveillance of deteriorating systems. *Naval Research Logistics Quarterly, 23*(3), 353–388. doi: http://dx.doi.org/10.1002/nav.3800230302
Pintelon, L., & Van, P. F. (2013). *Asset management. The maintenance perspective*. Leuven, Belgium: Acco.
Poduval, P. S., Pramod, V. R., & P., J. R. V. (2015). Interpretive Structural Modeling (ISM) and its application in analyzing factors inhibiting implementation of Total Productive Maintenance (TPM). *International Journal of Quality & Reliability Management, 32*(3), 308-331. doi: http://doi.org/10.1108/IJQRM-06-2013-0090
Pramod, V., Devadasan, S., Muthu, S., Jagathyraj, V., & Dhakshina, G. (2006). Integrating TPM and QFD for improving quality in maintenance engineering. *Journal of Quality in Maintenance Engineering, 12*(2), 1355–2511. doi: http://dx.doi.org/10.1108/13552510610667174
Pui, G., Bhandari, J., Arzaghi, E., Abbassi, R., & VikramGaraniya. (2017). Risk-based maintenance of offshore managed pressure drilling (MPD) operation. *Journal of Petroleum Science and Engineering, 159*, 513-521. doi: http://dx.doi.org/10.1016/j.petrol.2017.09.066
Pun, K., Chin, K., Chow, M., & Lau, H. (2002). An effectiveness-centered approach to maintenance management: a case study. *Journal of Quality in Maintenance Engineering, 8*(4), 346-368.
Qiu, Q., Cui, L., & Gao, H. (2017). Availability and maintenance modelling for systems subject to multiple failure modes. *Computers and Industrial Engineering, 108*(C), 192-198. doi: http://doi.org/10.1016/j.cie.2017.04.028
Ramirez, I. S., Muñoz, C. Q. G., & Marquez, F. P. G. (2017). *A Condition Monitoring System for Blades of Wind Turbine Maintenance Management.* Paper presented at the Proceedings of the Tenth International Conference on Management Science and Engineering Management Springer, Singapore.
Rao, Y., Xu, B.-l., Jing, T., Zhang, F., & Zhao, X.-y. (2017). The Current Status and Future Perspectives of Virtual Maintenance. *Procedia Computer Science, 107*, 58-63. doi: http://doi.org/10.1016/j.procs.2017.03.056
Rezaei, F., Yarmohammadian, M. H., Haghshenas, A., Fallah, A., & Ferdosi, M. (2018). Revised risk priority number in failure mode and effects analysis model from the perspective of healthcare system. *International Journal of Preventive Medicine, 9*(1), 1-7.
Rosqvist, T., Laakso, K., & Reunanen, M. (2009). Value-driven maintenance planning for a production plant. *Reliability Engineering & System Safety, 94*(1), 97-110. doi: http://doi.org/10.1016/j.ress.2007.03.018
Ruijters, E., Guck, D., Noort, M. v., & Stoelinga, M. (2016). *Reliability-centered maintenance of the electrically insulated railway joint via fault tree analysis: a practical experience report.* Paper presented at the Dependable Systems and Networks (DSN), 2016 46th Annual IEEE/IFIP International Conference on.
Ruijters, E. J. J., Guck, D., Drolenga, P., & Stoelinga, M. I. A. (2016). *Fault maintenance trees: Reliability centered maintenance via statistical model checking.* Paper presented at the Proceedings of the IEEE 62nd Annual Reliability and Maintainability Symposium, RAMS IEEE.
Ruparathna, R., Hewage, K., & Sadiq, R. (2018). Multi-period maintenance planning for public buildings: A risk based approach for climate conscious operation. *Journal of Cleaner Production, 170*(1), 1338-1353. doi: http://doi.org/10.1016/j.jclepro.2017.09.178
Sabri, S. M., Sulaiman, R., Ahmad, A., & Tang, A. Y. (2015). A comparative study on it outsourcing models for Malaysian SMEs e-business transformation. *ARPN Journal of Engineering and Applied Sciences, 10*(23), 17863-17870.
Salah, M., Osman, H., & Hosny, O. (2018). Performance-Based Reliability-Centered Maintenance Planning for Hospital Facilities. *Journal of Performance of Constructed Facilities, 23*(1), 04017113. doi: http://dx.doi.org/10.1061/(ASCE)CF.1943-5509.0001112
Samanta, B., & Sarkar, B. (2004). La terotecnología para una ventaja competitiva *Ingeniería y gestión de mantenimiento: una nueva visión del mantenimiento, 1*(37), 27-32.
Sarker, B. R., & Faiz, T. I. (2016). Minimizing maintenance cost for offshore wind turbines following multi-level opportunistic preventive strategy. *Renewable Energy, 85*, 104-113. doi: http://doi.org/10.1016/j.renene.2015.06.030
Selim, H., Yunusoglu, M. G., & Balaman, Ş. Y. (2016). A dynamic maintenance planning framework based on fuzzy TOPSIS and FMEA: application in an international food company. *Quality and Reliability Engineering International, 32*(3), 795-804. doi: http://dx.doi.org/10.1002/qre.1791
Sellappan, N., Nagarajan, D., & Palanikumar, K. (2015). Evaluation of risk priority number (RPN) in design failure modes and effects analysis (DFMEA) using factor analysis. *International Journal of Applied Engineering Research, 10*(14), 34194-34198.
Shafiee, M. (2015). Maintenance strategy selection problem: an MCDM overview. *Journal of Quality in Maintenance Engineering, 21*(4), 378-402. doi: http://dx.doi.org/10.1108/JQME-09-2013-0063
Shafiee, M., & Finkelstein, M. (2015). Shafiee, M., & Finkelstein, M. (2015). An optimal age-based group maintenance policy for multi-unit degrading systems. *Reliability Engineering and System Safety, 134*, 230-238. doi: http://doi.org/10.1016/j.ress.2014.09.016
Shafiee, M., Patriksson, M., & Chukova, S. (2016). An optimal age–usage maintenance strategy containing a failure penalty for application to railway tracks *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 230*(2), 407-417. doi: http://doi.org/10.1177/0954409714543337
Sherwin, D. (2000). A review of overall models for maintenance management. *Journal of Quality in Maintenance Engineering, 6*(3), 138-164. doi: http://dx.doi.org/10.1108/13552510010341171
Sheu, S.-H., Chang, C.-C., Chen, Y.-L., & Zhang, Z. G. (2015). Optimal preventive maintenance and repair policies for multi-state systems. *Reliability Engineering & System Safety, 140*, 78-87. doi: http://doi.org/10.1016/j.ress.2015.03.029
Shohet, I. M., Lavy-Leibovich, S., & Bar-On, D. (2003). Integrated maintenance monitoring of hospital buildings. *Construction Management and Economics, 21*(2), 219-228. doi: http://dx.doi.org/10.1080/0144619032000079734
Shohet, I. M., & Nobili, L. (2016). Enterprise resource planning system for performance-based-maintenance of clinics. *Automation in Construction, 65*, 33-41. doi: http://dx.doi.org/10.1016/j.autcon.2016.01.008
Shohet, I. M., & Nobili, L. (2017). Application of key performance indicators for maintenance management of clinics facilities. *International Journal of Strategic Property Management, 21*(1), 58-71. doi: http://doi.org/10.3846/1648715X.2016.1245684

Song, Q., Zhang, J., Li, C., & Wang, Z. (2017). *Application of Virtual Simulation Technology in Maintenance Training.* Paper presented at the International Conference on Technologies for E-Learning and Digital Entertainment.
Spooner, N., Cape, S., & Summerfield, S. (2017). Outsourcing strategies in bioanalysis. *Bioanalysis, 9*(15), 112 115 –112 116. doi: http://doi.org/10.4155/bio-2017-4986
Stoneham, D. (1998). *The Maintenance Management and Technology Handbook* (1st ed.). Oxford: Elsevier Advanced Technology.
Støre-Valen, M., Larssen, A. K., & Bjørberg, S. (2014). Buildings' impact on effective hospital services: The means of the property management role in Norwegian hospitals. *Journal of Health Organization and Management, 28*(3), 386-404. doi: http://doi.org/10.1108/JHOM-08-2012-0150
Straub, A. (2009). Cost savings from performance-based maintenance contracting. *International Journal of Strategic Property Management, 13*(3), 205-217.
Straub, A., & Van-Mossel, H. J. (2007). Contractor selection for performance-based maintenance partnerships. *International Journal of Strategic Property Management, 11*(2), 65-76. doi: http://dx.doi.org/10.1080/1648715X.2007.9637561
Su, Z., Núñez, A., Baldi, S., & Schutter, B. D. (2016). *Model Predictive Control for rail condition-based maintenance: A multilevel approach.* Paper presented at the Intelligent Transportation Systems (ITSC), 2016 IEEE 19th International Conference on. IEEE.
Sumet, S., Suwannapong, N., Howteerakul, N., & Thammarat, C. (2012). Knowledge management model for quality improvement in the hemodialysis unit of a non-profit private hospital, Bangkok, Thailand. *Leadership in Health Services, 25*(4), 306-317. doi: https://doi.org/10.1108/17511871211268946
Sun, H., Shi, F., Xie, Y., Sun, J., & Jia, L. (2016). *Research and Implementation of Scene Effect Based on Particle System in Virtual Maintenance Platform.* Paper presented at the International Conference on Human Centered Computing.
Taghipour, S., Banjevic, D., & Jardine, A. K. (2011). Prioritization of medical equipment for maintenance decisions. *Journal of the Operational Research Society, 62*(9), 1666–1687. doi: http://dx.doi.org/10.1057/jors.2010.106
Viveros, P., Stegmaier, R., Kristjanpoller, F., Barbera, L., & Crespo, A. (2013). Propuesta de un modelo de gestión de mantenimiento y sus principales herramientas de apoyo. *Ingeniare. Revista chilena de ingeniería, 21*(1), 125-138.
Vogl, G. W., Weiss, B. A., & Helu, M. (2016). A review of diagnostic and prognostic capabilities and best practices for manufacturing. *Journal of Intelligent Manufacturing, 1*(1), 1-17. doi: http://doi.org/10.1007/s10845-016-1228-8
Wan, B., Fu, G., Li, Y., & Zhao, Y. (2016). Research on a Defects Detection Method in the Ferrite Phase Shifter Cementing Process Based on a Multi-Sensor Prognostic and Health Management (PHM) System. *Sensors, 16*(8), 1263. doi: http://doi.org/10.3390/s16081263
Wang, C. H., & Hwang, S. L. (2004). A stochastic maintenance management model with recovery factor. *Journal of Quality in Maintenance Engineering, 10*(2), 154-165. doi: http://dx.doi.org/10.1108/13552510410539222
Wang, W. (2012). An overview of the recent advances in delay-time-based maintenance modelling. *Reliability Engineering & System Safety, 106*, 165-178. doi: http://doi.org/10.1016/j.ress.2012.04.004
Wang, W., Zhang, W., & Feng, W. (2017). *The Research of Maintainability Analysis Based on Immersive Virtual Maintenance Technology.* Paper presented at the Advances in Human Factors in Simulation and Modeling.
Wang, Y., Deng, C., Wu, J., Wang, Y., & Xiong, Y. (2014). A corrective maintenance scheme for engineering equipment. *Engineering Failure Analysis, 36*, 269-283. doi: http://dx.doi.org/10.1016/j.engfailanal.2013.10.006
Worobey, L., Pearlman, J., Dyson-Hudson, T., & Boninger, M. (2016). Clinician Competency with Wheelchair Maintenance and the Efficacy of a Wheelchair Maintenance Training Program. *Archives of Physical Medicine and Rehabilitation, 97*(10), e55. doi: http://dx.doi.org/10.1016/j.apmr.2016.08.165
Xu, L., Wang, S., & Ma, Y. L. (2016). *The Design and Realization of Virtual Maintenance and Training System of Certain Type of Tank.* Paper presented at the Engineering Asset Management.
Yan, R., Chen, X., & Mukhopadhyay, S. C. (2017). *Structural Health Monitoring* (Vol. 26). Springer International Publishing AG.
Yang, W., Tavner, P. J., Crabtree, C. J., Feng, Y., & Qiu, Y. (2014). Wind turbine condition monitoring: technical and commercial challenges. *WIND ENERGY, 17*(1), 673–693. doi: http://dx.doi.org/10.1002/we.1508
Yousefli, Z., Nasiri, F., & Moselhi, O. (2017). Healthcare facilities maintenance management: a literature review. *Journal of Facilities Management, 15*(4), 352-375. doi: http://dx.doi.org/10.1108/JFM-10-2016-0040
Yssaad, B., & Abene, A. (2015). Rational Reliability Centered Maintenance Optimization for power distribution systems. *International Journal of Electrical Power & Energy Systems, 73*, 350-360. doi: http://doi.org/10.1016/j.ijepes.2015.05.015

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