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Janusz SZPYTKO, Yorlandys Salgado DUARTE
AGH University of Science and Technology (Akademia Górniczo-Hutnicza)

MAINTENANCE STRATEGIES OVERLOOK FOR DEVICES UNDER OPERATION

Analiza strategii obsługiwania urządzeń w procesie eksploatacji

Abstract: *An updated systematization of maintenance strategies based on selected transport device exploitation parameters, working in continuous process was presented. The presented framework provides guidelines of assessment methods and an evolution of the way-of-thinking and technological changes in the modern industry related with the maintenance strategies. The paper present also a holistic discussion about the maintenance strategies applicability on overhead operating cranes.*

Keywords: maintenance, devices, learning management systems

Streszczenie: *Zaprezentowano zmodyfikowaną metodę obsługiwania eksploatowanych w sposób ciągły środków transportowych z wykorzystaniem ich wybranych parametrów eksploatacyjnych. Przykładem zastosowania jest wybrana klasa środków transportu technologicznego: suwnice pomostowe. Przedstawiono metody oceny oraz ewolucji sposobu myślenia i zmian technologicznych we współczesnym przemyśle związanych ze strategiami utrzymania.*

Słowa kluczowe: proces obsługiwania, urządzenia, systemy uczące się

1. Introduction

The word evolution in the context of maintenance strategies, simply means the gradual development of maintenance strategies. However, words like evolution in maintenance should not be confused with evolution of maintenance. While the former has to do with thinking about how practices, technologies and techniques had changed over the years and chronicling that journey, the later has to do with the relationship between the evolution and maintenance. Maintenance has been around as long as humans have existed. From the routine sharpening of man's earliest spears and tools to the repair work needed for modern technologies, our tools and machines have needed upkeep and repair. As a profession and as a corporate practice, maintenance has evolved considerably in the last 50 years.

As a profession, maintenance is not just the domain of tradespeople. It also includes engineers and planners to manage maintenance practice. In world-class companies, maintenance is now seen as an integral part of business operations because it can have a significant impact on corporate profitability. Over the last 50 years, the techniques for performing maintenance have also significantly changed. While maintenance used to be reactive to breakdown, maintenance in world-class companies is now an activity that is much more proactive, because plant and equipment, however well designed, will not remain safe or reliable if it is not maintained.

Examples of a good adaptation to the today's maintenance requirements, even knowing that the design is well achieved are the overhead cranes, reason why the discussion revolves around this particular case of devices. The cranes are playing the crucial role in many critical industrial processes, especially in steel plants, power plants, shipyards, aircraft plants; and transport processes of loads with large dimensions, large loading capacity and dangerous properties are majority supported by cooperating cranes as an important element in the technological processes.

The paper discusses the evolution of maintenance strategies from different perspectives, taking in account different knowledge areas and focusing on transport devices under exploitation, our case, cranes.

The paper aim is to systematize the evolution of maintenance strategies focusing on overhead travelling cranes under operation, as a study case example (allowing to limit the search to obtain a concrete point of view) depending on the context to illustrate the evolution with selected citations (references). In addition, we cite and describe a formal model under construction, oriented to overhead crane illustrating a current approach and summarizing today efforts in this field.

2. Maintenance generations

As a discussion starting point, in the reference [3], the authors summarized the generations of maintenance practice since World War 2. These generations are reproduced below but they are augmented short-related discussions.

The early generation had a focus on corrective maintenance with some basic routine maintenance such as lubrication. From that starting line, subsequent generations of maintenance professionals have added more and more proactive maintenance elements to their maintenance strategy.

First generation 1940–1955

- Fix it when it broke – *If it is not broken, do not fix it* is an adage that has been repeated for decades. However, this is not a viable approach in today's plants, especially when it comes to asset-intensive industries and smart factories.
- Basic and Routine maintenance – *routine maintenance*, which is the basic maintenance strategy, refers to any maintenance task that is done on a planned and ongoing basis to identify and prevent problems before they result in equipment failure. Some common routine maintenance includes regular inspections or service work.
- Corrective maintenance – This involve any task that corrects a problem with an asset and returns it to proper working order. Corrective maintenance tasks can be both planned and unplanned. There are three situations for corrective maintenance to occurs: When an issue is detected through condition monitoring? When a routine nspection uncovers a potential fault? When a piece of equipment breaks down?

Well-designed overhead cranes begin mass production in Germany in 1910. After this year, almost all the manufacturing processes worldwide introduce the selected device as a support for the production process. References [5, 7, 8] are examples of first-generation maintenance strategies applied in manufacturing and continuous production plants, in which overhead cranes are involved as a critical supports system. During this period, any complex simulation or mathematical model was used to support the making-decision process, only strong empirical experience coming from daily work (like daily checking routine for example, workers with experience) was used to create inspection routines scheduling. Currently in the modern industry, similar strategies are applied when the system or component is not critical (change the light lamp of the desktop office).

The main contribution during this period of time related to maintenance strategies is the empirical knowledge of the daily work.

Second Generation 1955–1975

- Planned preventative maintenance (PM) - Preventive maintenance (or preventative maintenance) is maintenance that is regularly performed on a piece of equipment to lessen the likelihood of it failing. It is performed while the equipment is still working so that it does not break down unexpectedly. In terms of the complexity of this maintenance strategy, it falls between reactive (or run-to-failure) maintenance and predictive maintenance.

- Time-based maintenance (TBM) - is maintenance performed on equipment based on a calendar schedule. This means that time is the maintenance trigger for this type of maintenance. TBM is planned maintenance, as it must be scheduled in advance. This means that it can be used with both predictive maintenance and preventative maintenance.
- System for planning and controlling work.

The second-generation maintenance strategies branch is strongly associate with standards generated by manufacturers and supporting by the American Society of Mechanical Engineers (ASME). In the case of overhead cranes, standards like ASME B30.2, ASME B30.10, ASME B30.16, ASME B30.17, ASME B30.20 define the inspection cycle as well as the possible maintenance to be performed.

The common recommendations that come from the standards are the typical *Frequent Inspections*: Visual examinations by the operator or other designated personnel. Depending on the service, this may be: (a) normal service -monthly, (b) heavy service -weekly to monthly and (c) severe service -daily to weekly.

Inspections usually focus on exploitations parameters related to moving parts: (1) operation time -operating mechanisms (2) overload sensors -limit devices (3) load swing -control systems (4) conditions of position controls -brakes, performing *Operational Tests*: (a) lifting and lowering, (b) trolley travel, (c) bridge travel, (d) hoist-limit devices; and the last but not least, the *Load Test*. All these inspections take time, reason why, in generally, the standards propose the *Availability* indicator to analyze the cycle life of the overhead crane. Usually, previous standards referred are used in the current industry as a contract between manufacturers and customers, in order to guarantee the useful life of the crane under exploitation.

During this time, the main contribution related with maintenance strategies is the creation of standard procedures for inspecting the condition of the overhead crane based on accumulated historical knowledge.

Third Generation 1975–2000

- Condition-based maintenance (CBM) - is a maintenance strategy that monitors the actual condition of an asset to decide what maintenance needs to be done. CBM dictates that maintenance should only be performed when certain indicators show signs of decreasing performance or upcoming failure. Checking a machine for these indicators may include non-invasive measurements, visual inspection, performance data and scheduled tests. Condition data can then be gathered at certain intervals, or continuously (as is done when a machine has internal sensors). Condition-based maintenance can be applied to mission critical and non-mission critical assets. Unlike in planned maintenance (PM), where maintenance is performed based upon predefined scheduled intervals, condition-based maintenance is performed only after a decrease in the condition of the equipment has been observed. Compared

with preventive maintenance, this increases the time between maintenance repairs, because maintenance is done on an as-needed basis.
- Reliability - centered maintenance.
- Computer aided maintenance management and information system.
- Workforce multi-skilling and team working.
- Proactive and strategic thinking.

The third branch storage the maintenance strategies methodological roots for all the techniques used in practice into the modern industry and resulting its main contribution. During this period, the industry reaches high levels of maturity and maintenance scheduling is well defined as an optimization problem based on maintenance condition. As an example, the maintenance scheduling general problem, can be decomposed essentially by hierarchical levels, holistic objective (referring to global or integrated strategies) or multi-objectives (referring to decentralized strategies), and optimization criteria, cost, reliability, or hybrid approach.

Examples are cost-holistic [1], cost-multi-objectives sequential [6] and holistic-reliability approach [13]. For any of the cases, the problem is to find the best scheduled maintenance sequence of actions for each component considered in the system. Generally, the objectives and restrictions depend on the individual system requirements, but, as a consensus, the optimization problem is defined as a multi-criteria combinatorial problem of non-linear objective functions with constrains.

Depending on the approach selected to resolve the maintenance scheduling problem, the volume of initial information required, the number of models constrains, and the complex mathematical formulations are issues to consider. These three dimensions above sometimes define the approach to be used. Multi-objectives approach introduces constrains and modeling challenges but is closer to the system needs. Holistic-objective approach sometimes do not represent all the system requirements. Cost-objective approach required high information levels and assumptions to standardize the selection criteria. Reliability-objective approach is not well accepted and understood by the industry. In conclusion, the approach selection depends largely on the characteristics of the system under analysis and implementation requirements.

The reason we are talking about maintenance strategies in general is because overhead cranes systems are impacted in the same way by the former definition. But, even the maturity and the well-defined optimization models in this generation, the limited number of applications highlights a transient problem caused by an inadequate organization of the problems by the owners of the problem and a lack of training in the formation of engineers. In fact, traditional engineering education during this generation focuses on system design rather than maintenance [9].

This limitation results in many arguments against models and in favor of more qualitative approaches such as RCM and TPM or other approaches such as condition monitoring. However, it is a fact that optimization models can offer much more than qualitative approaches, but at the cost of increased complexity and specificity.

Strong rejections to the use of models in this generation are the data available to be used by the models, in order to guarantee a reliable decision [9], reason why, models are more pertinent in the next generation given the development of the communication systems.

Current Generation 2000+

- Risk-based inspection.
- Risk-based maintenance.
- Risk-based life assessment.
- Reliability-centered maintenance.
- Condition based monitoring.
- Computer aided maintenance management and information system.

The difference between the current branch and the previous one is mainly technology advances in the communication systems. Therefore, all the previous concepts related with maintenance strategies has been shaped, leveraging on the exponential increase in the power of the IT tools, sensors, embedded systems, IoT, able to generate and analyze plenty of data. As an example, concepts like Digital Twins [15, 17], Closed Loop Engineering [4, 12], e-Maintenance [11] had a huge impact in the previous methodological problems defined and the overhead crane systems cited are examples of digital industry adaptation.

Looking at the references cited on overhead cranes so far in each generation, we can openly say that the evolution of maintenance strategies in overhead cranes as a study case follows the human way-of-thinking and the technological changes over time, starting with the empirical knowledge during the daily work (experience), then formalization of procedures, seeking to store accumulated knowledge for the next generation (standards), then improvements through mathematical solutions, seeking to optimize the process with different approaches (modelling) and, in the last step, updating existing methods with the robust communication systems and IT solutions that emerge every day.

As a summary, fig. 1 describes the tree of general methodological strategies related to the evolution of maintenance shaped to the case study of overhead cranes analyzed, and each branch of the tree is impacted by the history of maintenance strategies (way of thinking, technology, communication system, modelling) but the branch conceptually remain stable.

On the other hand, and just before we close this section, it is necessary to say that the discussion of the todays maintenance related papers focuses on two main points: promoting well-organized data collection and analysis and automatic approach (machine learning) to take advantage of the potential of optimization methods [10] and the role of simulation-based maintenance operations optimization approach [2] as successfully applied approaches to maintenance operations (taking advantage of the current computation capacity). However, even knowing that both start of art proposals are new starting points for future discussions, going through the research of the new starting points, the methodological basis remain the same (each branch of the tree remains stable) as well as the conclusion found in this paper because in both papers cited the maintenance strategies are generally categorized by the tree proposed in this paper.

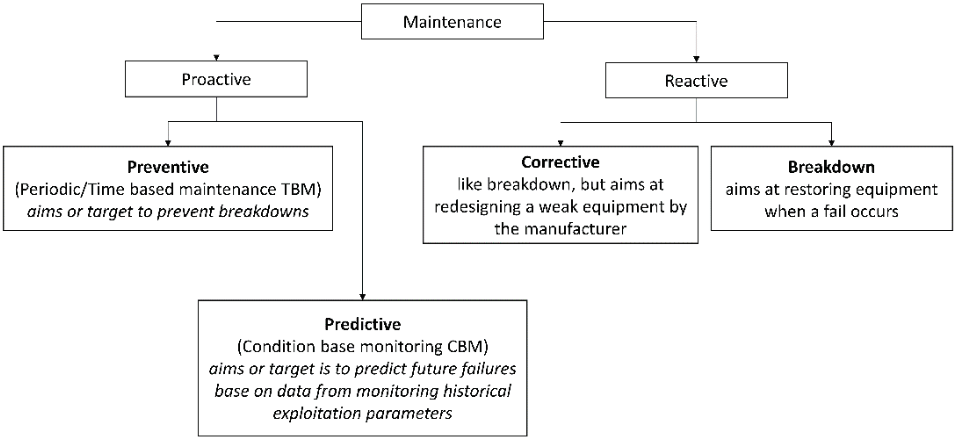

Fig. 1. Simplified summary of Maintenance Strategies

In the following sections, given the current state of the discussion, we add new points of view and new remarks separated from different perspectives. The idea is to introduce other arguments that usually go in parallel with the evolution of maintenance, but at the same time impact on its development, such as: maintenance practice improvements, data analysis, maintenance engineering education and practical applications.

3. Improvements in maintenance practice

Planned preventative maintenance was the first to be added to the practices of the first maintenance generation. Then, with new technology and developments in failure theory, predictive maintenance was also included in world-class maintenance activities. With these new maintenance activities came new strategies for applying them to the workplace. The most dominant of these was Reliability Centered Maintenance, which was developed for the aircraft maintenance industry and the rapidly adopted by other industries too. These new strategies provided a structure for determining which maintenance activities should be used, and when. Most recently, the maintenance profession has begun to consider the total cost of asset ownership as being within its jurisdiction. Ideas such as Evidence Based Asset management, Risk-Based maintenance, and Total Productive Maintenance, have contributed to this. In the reference [14], the authors also put forward a similar idea of maintenance progression. They suggest phrases that are representative of the status of maintenance within a company. For the early generation, maintenance was a “necessary evil”. This relationship had evolved significantly for the most recent generation where maintenance is a “co-operative partnership”.

4. Achieving world-class maintenance practice

Unfortunately for many companies, the fact is that their maintenance is still seen as a "necessary evil". For those companies, their maintenance has not stayed in touch with world-class maintenance practice. To progress, one of the first steps is to change the corporate culture so that maintenance is a co-operative partnership that can significantly contribute to profitability and customer satisfaction. The maintenance department itself will have to up-skill and adopt new practices before the corporate culture will change to view maintenance as the important business function that it is. For the maintenance department, up-skilling will mean new techniques are learnt to predict and prevent equipment failures. The new practices will include a more involved relationship with the production and management teams as well as adopting software tools that will facilitate a world-class maintenance practice as we illustrate in the fig. 2.

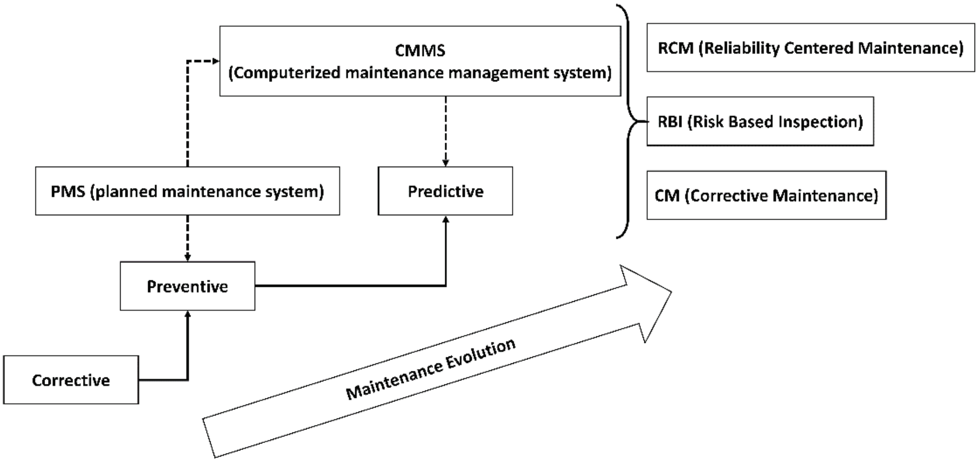

Fig. 2. Maintenance evolution in practice

5. With great data comes great opportunity

The types of maintenance we have discussed can be effective, but uptime can reach 98% when businesses begin to incorporate data into their maintenance strategies. With good data, a company can start to pinpoint why equipment failed, which provides an opportunity to intervene before failure in the future. The focus shifts from repairing to improving.

The goal for every organization should be to optimize its assets. Machines are getting smarter, finding patterns in data, and extrapolating generalizations from those patterns. Advanced strategies such as predictive forecasting and reliability-centered maintenance require a constant stream of data to improve equipment availability. The completeness, accuracy, and integrity of data becomes critical.

Maintenance is being recognized as an area in which companies need to invest, rather than a cost to be reduced. To fully exploit the oceans of data generated by today's assets, one of those investments should be an Enterprise Asset Management system (EAM). And integrating it with your Enterprise Resource Planning (ERP) system as well as your Manufacturing Execution system (MES) should be a top priority. This type of initiative is iterative and typically includes learning and continuous process improvement over a long period, so setting the right expectations among stakeholders is important.

6. Maintenance engineering

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

Maintenance, and hence maintenance engineering, is increasing in importance due to rising amounts of equipment, systems, machineries, and infrastructure. Since the Industrial Revolution, devices, equipment, machinery, and structures have grown increasingly complex, requiring a host of personnel, vocations and related systems needed to maintain them. Prior to 2006, the United States spent approximately US$300 billion annually on plant maintenance and operations alone. Maintenance is to ensure a unit is fit for its purpose, with maximum availability at minimum costs.

Maintenance engineer's description

A maintenance engineer should possess significant knowledge of statistics, probability, and logistics, and additionally in the fundamentals of the operation of the equipment and machinery he or she is responsible for. A maintenance engineer should also possess high interpersonal, communication, and management skills, as well as the ability to make decisions quickly.

Typical responsibilities include:

- Assure optimization for the maintenance of organization structure.
- Analysis of repetitive equipment failures.
- Estimation of maintenance costs and evaluation of alternatives.
- Forecasting of spare parts.
- Assessing the needs for equipment replacements and establish replacement programs as at when due.
- Application of scheduling and project management principles to replacement programs.
- Assessing required maintenance tools and skills for efficient maintenance of equipment.
- Assessing required skills for maintenance personnel.

- Reviewing personnel transfers to and from maintenance organizations.
- Assessing and reporting safety hazards associated with maintenance of equipment.

Maintenance engineering education

Institutions across the world have recognized the need for maintenance engineering. Maintenance engineers usually hold a degree in Mechanical Engineering, Industrial Engineering, or other engineering disciplines. In recent years specialized bachelor and master courses have developed. The bachelor's degree program in Maintenance Engineering at the German-Jordanian University in Amman is addressing the need, as well as the Bachelor Programme in Maintenance Engineering at Lulea University of Technology. With an increased demand for Chartered Engineers, The University of Central Lancashire in United Kingdom has developed a MSc in Maintenance Engineering currently under accreditation with the Institution of Engineering and Technology and a Top-up Bachelor of Engineering with honors degree for technicians holding a Higher National Diploma and seeking a progression in their professional career.

Maintenance Manager

As maintenance management evolved, so did the job of the maintenance manager. Clearly maintenance management is no longer a pure technical function. Business economics (cost-benefit considerations) and business context (how important are the installations in question? what are the functional requirements? etc.) play an important role. A good maintenance manager needs to have a technical background in order to have an eye for the "big picture" and not lose any aspect out of sight. Nowadays, the decisions expected from the maintenance manager are complex and sometimes can have far reaching consequences. He/she is (partly) responsible for operational, tactical, and strategical aspects of the company's maintenance management. This involves the final responsibility for operational decisions like the planning of the maintenance jobs and tactical decisions concerning the long-term maintenance policy to be adopted. More recently, maintenance managers are also consulted in strategic decisions, e.g. purchases of new installations, design choices, personnel policy.

7. Application in practice: study case of overhead cranes

Once the evolution of the maintenance strategies, improvements over time and the importance of maintenance in today's systems are discussed, we present, as an example, a real overhead crane system under exploitation for more than 30 years, discussing the maintenance oriented perspective of the human way-of-thinking and the technological changes in the form of an evolutionary timeline: empirical knowledge during the daily work, formalization of procedures, improvements through mathematical solutions and updating existing methods with the robust communication systems and IT solutions. The study case is a hot rolling mills system of a steel plant with critical overhead cranes operating with hazard conditions and continuous operation under national polish regulations. The example is fully described in the reference [16] and is a typical example that merge two current state-of-art [2, 10] (simulation-oriented approach and automatic or programmatic decision-making process), the methodological basis described above in this paper and the effort of several institutions and researchers to discuss about maintenance, because the paper cited [16] belongs to the proceedings of the 4th IFAC Workshop on Advanced Maintenance Engineering, Services and Technologies, Cambridge, 2020, recent global meeting related to challenges in the field of maintenance.

All systems operating on a continuous basis, as well as supporting systems, their main function is to be available. The overhead cranes system analyzed works on continuous basis and may be unavailable for two main reasons: *repair time caused by random failures* in the components of the crane and *maintenance process*. In this particular case, all the operational cranes are under polish national regulations (Poz. 2176 and Dz. U. 2019 poz. 667). Mandatory regulations establish a frequency inspection for each characteristic crane, and the maintenance process is reduced to a checklist that follows all these rules. Depending of the checklist, the workers (maintenance team) can perform some maintenance tasks based on the results.

At this point in the description, the first two steps in the timeline are evident: *empirical knowledge during the daily work* and *formalization of procedures*. The polish national regulation (Poz. 2176 and Dz. U. 2019 poz. 667) is strongly related to ASME standards and has been applied and updated for 30 years. In this particular system, the procedures are well-stablished, the standards define the frequency and checklist, but they are not enough to decide *when* the maintenance should be performed (maintenance scheduling).

The human decision-making process behind of the maintenance scheduling management process is the coordination of components maintenance and/or replacement that make up the system but maintaining holistic and/or clustering objectives defined by the decision makers. Coordination itself can be an complex problem and humanly dreadful to find a faster optimal solution, mathematically speaking is a nondeterministic polynomial time NP-complete problem, therefore, listing all possible operational scenarios to make a coherent coordination in order to find the best scenario is difficult, reason why, computational modeling are pertinent in this case (*improvements through mathematical solutions*). There may be cases where the dimension of the system is not large and the experience is applied prevailing a sustainable solution, but it is necessary to emphasize that it is not always the optimal one.

Going forward, the analyzed system collects by SCADA (**S**upervisory **C**ontrol **A**nd **D**ata **A**cquisition) and SAP (**S**ystems, **A**pplications & **P**roducts in Data Processing) systems, historical information available related with the maintenance management process: historical degradation data, previous planned process, system structure, etc. At this point, two well-stablished IT tools for collecting and managing data and processes stand out, but the IT tools were created to monitor the work of the workers and not to improve the maintenance process, however, it has all the information necessary to improve the process. Therefore, the next two steps in the timeline: *improvements through mathematical* *solutions* and *updating existing methods with the robust communication systems and IT solutions* are presented together, in order to show how, using the historical information collected by the SCADA and SAP systems and with an accurate mathematical solution, it is possible to coordinate the maintenance scheduling process and, at the same time, close the discussion on the evolution of maintenance strategies applied in a study case.

As a wide description, based on SCADA and SAP system information, specially, historical degradation data, planned frequency maintenance standards, system structure, nominal exploitation parameters, is possible use an exploitation efficiency system (see Figure 3) based on risk management to simulate the same maintenance process performed in the time real, but in this case, an optimization algorithm chooses the best maintenance schedule, and provides a faster and optimal feedback to the entity manager as a closed-loop system.

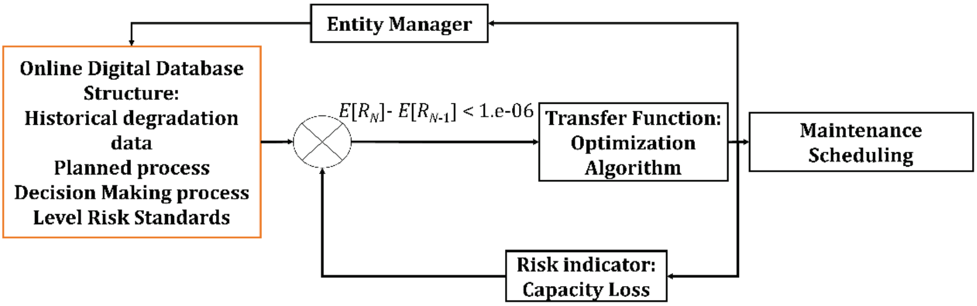

Fig. 3. Risk-based Exploitation Efficiency System

Knowing the general idea of the solution proposed in the reference [10], the mathematical model behind is a stochastic no-linear optimization model with bounded constraint that evaluates a risk global-system behaviour indicator based on Monte Carlo simulations. The model objective is to minimize the expected value $E[R]$ of the convolution function, between the overhead cranes loading system capacity distribution function of the steel plant (LC, loading capacity) impacted by maintenance scheduling (TTM, time to maintenance, TDM, time duration maintenance), defined as X, and the necessary load capacity distribution function of the production line, defined as Y. The model is defined below:

$$\min\{E[R]\} \tag{1}$$

where:

$$\begin{array}{lcl} R & \rightarrow & f(X,Y) \\ X & \rightarrow & f(t, LC_i, \ldots) \\ LC_i & \rightarrow & f(t, TTM_{i,k\neq 1}, TDM_{i,k}, x, \ldots) \quad \text{with} \quad x = TTM_{i,1} \end{array}$$

subject to:

$$0 < TTM_{i,1} < \text{Simulation Window} - (TTM_{i,1} + TTM_{i,k\neq 1} + TDM_{i,k})$$

The general description above shown a clear contribution in the last two steps in the timeline: *improvements through mathematical solutions* and *updating existing methods with the robust communication systems and IT solutions*. Examples like the one presented (Reliability Centered Maintenance) can be found in the literature. To close the discussion, we can say that the maintenance strategies are constantly updated with IT tools looking for more proactive solutions, but the fundamentals of the strategies remain constant. The study case presented summarizes some of the efforts made to improve the maintenance process.

8. Conclusions

The brief discussion across the paper about maintenance strategies highlight the following conclusion related. Maintenance strategies: proactive (preventive and predictive) and reactive (corrective and breakdown), conceptually remains stable (way of doing is without many changes). The process of degradation is inherent in the technical system; therefore, control risk management and maintenance scheduling processes are increasingly relevant and the human decision-making process behind is a target to improve.

The impacted by way of man thinking, used technology (software and hardware), communication technology and systems, as well as today used digital modeling tools and after the results implementation in practice strategies, are strongly guided by the individual system requirements (application environment), but the fundamentals of the maintenance strategies remain stable. The study case presented as an example, illustrate clearly the evolutionary timeline of the maintenance strategies: empirical knowledge during the daily work, formalization of procedures, improvements through mathematical solutions and updating existing methods with the robust communication systems and IT solutions.

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