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Digital Integrated Maintenance Technology for Cooperative Cranes

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***Abstract*—The paper presents the final stage and shape of an integrated digital technology created to support cooperative overhead cranes maintenance strategies. The technology involves online self-analysis layers for parameter calibration and data processing, measurement of dependencies on degradation data with copula approach, simulation-based risk modeling with implemented variance reduction techniques and well-established heuristic algorithms to solve maintenance scheduling optimization with implemented parallel computing. The tool is a compilation of efforts that aims a robust and comprehensive contribution in the field of informatic technologies. The paper describes the overview architecture and relationship between all the research involved to reach at the final tool.**

***Keywords*—Digital Twins, Maintenance, Risk Assessment**

I. INTRODUCTION

Today continuous process industry is highly automated, and every system involved in each process is made up of a large number of components. Due to the complexity and size of the system, coordination of operation and maintenance is a constant challenge, especially the decision-making behind these two processes. One way to compensate these challenges is to use new methodologies and technological features to create comprehensive tools that achieve fast and smart coordination, even in extremely complex system.

Digital Twins concept is a framework that unites system engineering methodology and technology by proposing five-dimensions as pillars for building solutions and tools in modern industry. This concept provides clear guidelines for describing each key component in an engineering solution. Conceptually, the five dimensions are: *physical object*, *virtual counterpart*, *connection*, *data*, and *services*. Therefore, each study case must define each of these dimensions.

This contribution intends to describe the final stage and shape of a digital integrated maintenance technology using the Digital Twins framework.

That said, the remaining sections of this document are organized as follows: first, a definition of the Digital Twins five dimensions applied to the technology under study, then a description of all the variables and functional connections involved in the architecture of the digital platform. At the same time, during the descriptions, we show the links to previous research. Then we describe future works and next steps from a research point of view, ending the paper with the conclusions section.

II. DIGITAL PLATFORM

A. Physical object

The platform proposed in this paper was created with the intention of improving the maintenance coordination of a real running process, resulting in another contribution in the transition to the digital industry. Practical examples like the one presented are common when a process is well known and can be replaced and optimized by smart software. Particularly, the proposed solution (integrated maintenance technology) is focused on supporting the maintenance department strategies of a steel plant, which has the role of managing this process in cooperative overhead cranes. Maintenance strategies is the research subject here because it continues to be a permanent need in the industry, as discussed in reference [15].

The technology is a tool oriented to assess risks holistically at the system level (cooperative overhead crane system or set of overhead cranes). The selection of the approach is an agreement with the maintenance department and is connected in some way to the system characteristics, while there may be other approaches such as cost-based experiences [2] or using two levels [4]. The technology, as a whole, practically and methodologically introduces notable improvements in the process under study and is supported by previous solutions applied in other cases with similar problems [5], [11] and [16].

In this paper, the *physical object* is the coordination of maintenance strategies for a set of overhead cranes in a steel plant.

B. Virtual counterpart

The integrated maintenance technology is made up of layers, separated into three functional blocks: Processed Data, Risk Model and Maintenance Scheduling. The integrated digital platform architecture is shown in Figure 1, as well as the connection between the functional blocks. The functions that make up blocks are separated and encapsulated by independent layers to ensure flexibility, and all are robustly implemented in Matrix Laboratory (MATLAB).

In the proposed technology, Risk Model and Maintenance Scheduling functional blocks together form the *virtual counterpart*.

The parameters and variables needed to run the Risk Model are transferred from a database to the Risk Model with an independent layer, once the data has been processed by the block Processed Data (in our case the *connection* dimension of the Digital Twins framework), along with the configuration selected by the user (maintenance department manager).

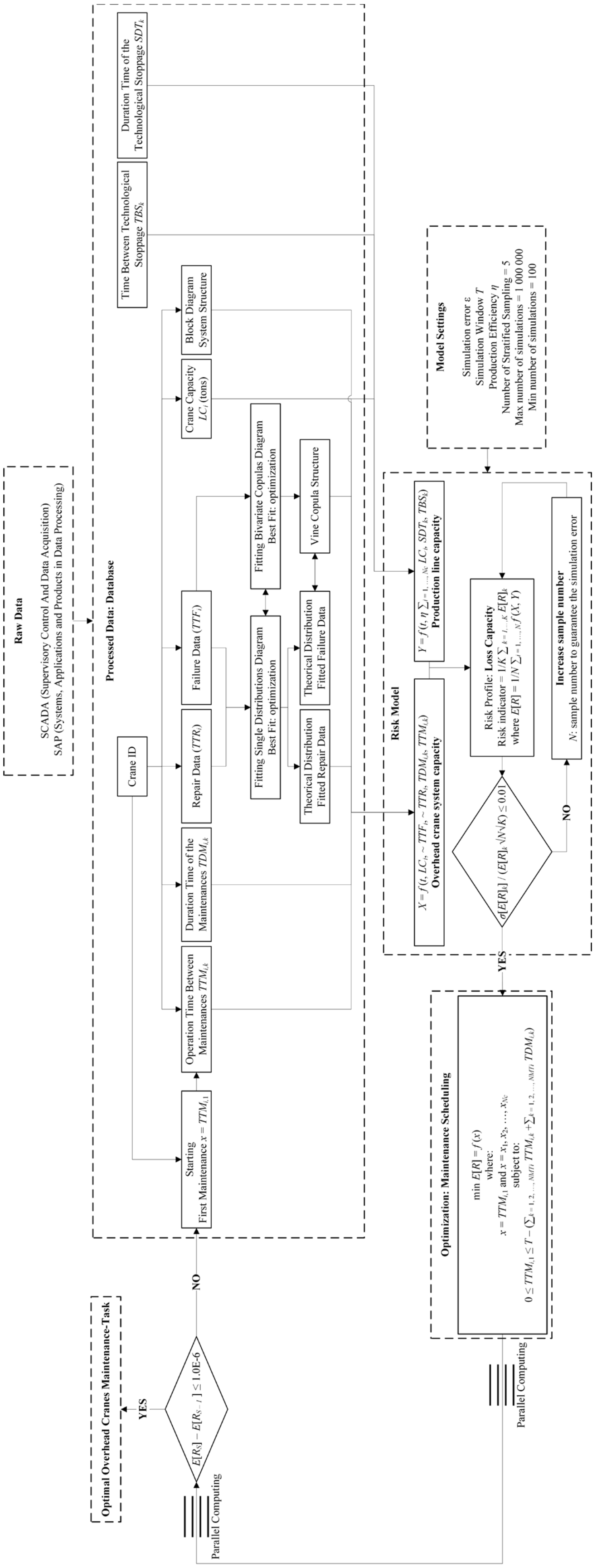

Fig. 1. Digital Paltform Architecture.

Fig. 2. The output of the Risk Model is an indicator (Loss Capacity) that measures the potential losses in tons in the steel plant due to the unavailability of overhead cranes. The reasons why overhead cranes may be unavailable are unexpected failures and scheduled maintenance. Previous studies prove that the model is well-defined even when the variable data changes over time. The sensitivity analysis performed to address this conclusion is discussed in the contribution [18].

The method implemented to estimate the risk indicator (a convolution product between the system capacity and system requirements) is the Monte Carlo method. We select a simulation method because it is the only reasonable way to construct the compound distribution of the system, combination of the stochastic time-to-failure (*TTF*) and time-to-repair (*TTR*) concatenation of each crane through the series-parallel block diagram.

Based on previous experience, e.g., contributions [3], [6], [10] and [14], we can say that simulation approaches allow us to achieve memorable results because they introduce modelling flexibility by considering functional and random variables.

Even using a simulation method, the time needed to estimate the indicator is quite fast because we implemented variance reduction techniques (stratification in our case) to reduce the variance of the estimator and reduce the time. The performance of the model before and after applying the variance reduction technique is analyzed in the contribution [17]. The method has simulation error control, and the estimation is always accurate for any scenario in which it is evaluated.

One of the inputs to the Risk Model is the maintenance lifecycle of each crane under consideration. The graphical representation of maintenance over time depends on the starting time of the maintenance cycle. This variable can be fixed or variable in the Risk Model. This relationship defines the connection between the Risk Model and the Maintenance Scheduling routine. Leaving the starting time of each i (index referring to each crane) lifecycle maintenance time-to-maintenance $TTM_{1,i}$ free as a variable allows a heuristic optimization algorithm to search for the best scheduling maintenance for the system using the Loss Capacity indicator to discriminate the combination with lowest risk for the system, therefore, as a solution we get a risk oriented coordinated maintenance scheduling. The optimization flow diagram is presented in [12] and the convergence of the optimization model is fully discussed in the contribution [21].

The implemented optimization routine is a heuristic method as we pointed out above, but thanks to parallel computing, the candidate scenarios are evaluated independently and the time to reach the final solution is also quite fast for this type of algorithm, knowing that it is dependent on the computer power. The improvements introduced by the parallel computing are discussed in the contribution [17].

The connection between the user (maintenance department manager) and the three functional blocks composing the technology is a dynamic window that visualizes the performance of the Risk Model (risk indicator convergence, empirical histogram of the risk indicator, stochastic convolution between the system capacity and system requirements) and plots the graphical representation of the maintenance scheduling.

C. Connection

The Processed Data block plays an important role and is the most complex block because it provides the Risk Model with all the variables and parameters needed to assess the selected scenario or regime. Therefore, the output of Processed Data is a database with all the inputs of the Risk Model. The Processed Data functional block is the *connection* dimension between the *data* and the *virtual counterpart* in the proposed technology.

Now, we describe the overview of the connection between these two blocks (Processed Data and Risk Model) by listing the input variables and parameters of the Risk Model and the processes involved:

- Crane ID

The crane ID is filtered from the Supervisory Control And Data Acquisition (SCADA) system and stored in the database.

- Crane Capacity LC_i (tons).

The crane capacity is filtered from the SCADA system and stored in the database.

- Block diagram of the system structure.

The system block diagram is constructed using information from the Systems, Applications & Products in Data Processing (SAP) system, where the cranes in the same section of the production line are considered in series and cranes in different sections are considered in parallel. A filtered location code from the SAP system is used to determine the series-parallel block diagram of the system. This practice is common in the field of reliability engineering and in our case, we adopted the methodology, knowing that it has been successfully applied in previous experiences [1].

- Simulation window *T*.

The simulation window is a parameter set by the user of the digital platform (manager in our case). Usually, the window can vary between one week and one year, and by default the tool sets this parameter to one year.

- Theoretical distribution fitted to failure data of each crane considered / Theoretical distribution fitted to repair data of each crane considered.

Complexity arises at this stage. The platform works online, therefore, each time a scenario is evaluated, the following process is executed: For each crane *i*, we filter from the SCADA system the historical Failure Data ($TTF_{i,k}$) and Repair Data ($TTR_{i,k}$) and applying the formal fit selection flow diagram presented in [13] and validated in [19], we select the best statistical theoretical distribution based on the Akaike Information Criterion (AIC) criterion. The diagram is applied independently to $TTF_{i,k}$ and $TTR_{i,k}$ variables.

- Maintenance lifecycle of each crane considered (operation time between maintenance $TTM_{i,k}$ and duration time of the maintenance $TDM_{i,k}$).

Each crane has associated a lifecycle maintenance provided by the manufacturer and international crane-related standards. The raw information is stored in the SAP system of the steel company, and an independent layer filters and moves the information from the SAP system to the database using a unique crane ID.

- Degradation dependency structure of the crane system.

In order to measure the dependencies between crane degradation data, i.e., cranes working under the same regime, cranes with same capacities, etc., we selected the vine-copula approach. We decided to introduce the copula approach into the model because it is flexible enough to capture both dependent and independent functional conditions. The decision is accompanied by the analysis of the relationship between the copula approach and the conditional expected value (Loss Capacity) in reference [20] and how it is finally introduced into the model in contribution [23] by generating dependent random structures. This practice was even tested with previous case studies, specifically gantry cranes in a container terminal, as we described in reference [9].

The process to measure the dependencies is complex, and like the fitting process, this layer is also executed each time a scenario is evaluated. The overview of the process is as follows: For each pairwise cranes considered in the system, i.e., Crane 1 – Crane 2, we filter from the SCADA system the historical Failure Data and apply the formal selection flow diagram presented and validated in [22], then we select the best statistical copula distribution for each pairwise cranes combination in the considered system based on the AIC criterion. Then applying a two-step selection process, we search for local concatenations of copulas using the AIC criterion, and then once the best local selections are found (local minimum), the final dependency structure is the option with minimum AIC criterion, resulting this option in the global selection step (global minimum).

- Information related with the production line (time between technological stoppage TBS_k, and duration of the technological stoppage SDT_k).

In the SAP system is stored the planification of the production line. Then, an independent layer captures and transfers the information to the database created for maintenance strategies purposes.

D. Data

The proposed technology is made to work without human intervention in the most sensitive steps of the model to avoid human errors and to select decisions at all times based on data collected by professional systems. SCADA and SAP systems are the main sources of raw information used by the proposed tool and together they form the *data* dimension. Both systems have different functions and were created for different purposes, so an intermediate database (digital *connection*) was created for maintenance purposes to filter and process the information needed for the platform.

E. Services

The tool is easy to understand, and by looking at a global indicator, the manager (user of the tool) can evaluate the performance of decisions and at the same time improve the decision-making by changing parameters and variables in the model. Thanks to the implemented tool, it is possible to analyze various scenarios and regimes in the modelled system, it is possible predict and analyze potential decisions, and always, as a main result, the tool provides the best risk-oriented maintenance scheduling scenario for the input setting and regime selected by the user.

The features and flexibilities of the technology define the services dimension in the Digital Twins framework.

The process of building such a tool is not easy because it is necessary to consider all potential scenarios to be evaluated. Moreover, it takes time to redesign the tool in order to achieve the ultimate goal of the contribution. Regardless of the above, a previous experience in this field allows us to travel in a suitable way, for instance, a similar situation happened with the contribution [7]. This reference initializes the journey of the contributions, then, the analysis of the interrelation with other system resulted in the contribution [8], and then the final shape of the proposal was published in [16] under the guidance of the digital twins concepts.

Having described all the dimensions, we introduce the future work, from the research point of view, related to the proposed technology.

III. Achivements and Future Work

The proposed technology is a unique engineering solution; therefore, comparisons are difficult. At this point, after all the validation and modelling tests performed, the tool is ready to be applied in practice in the steel plant. Once the economic achievements related to the introduction of the technology are known, a new contribution will discuss the results.

IV. Conclusions

The paper summarizes the effort of two years of work to create a technology oriented to solve a specific problem, but during the journey memorable methodological and technological goals have been achieved, leaving a bunch of papers describing how a running system can be improved by means of digital technologies.

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