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OPERATIONS DYNAMICS OF GAS CENTRIFUGAL COMPRESSOR: PROCESS, HEALTH AND PERFORMANCE INDICATORS

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ABSTRACT

Emerging technologies of Industry 4.0 have introduced novel ways of perceiving maintenance management, which has developed from being perceived as a “necessary evil” to become proactive with a holistic focusing on entire systems rather than single machines from Maintenance 3.0. In this context, the industry has begun to really appreciate the unique opportunities followed by system dynamics and simulation tools capabilities of representing the real world. However, maintenance management and performance are complex aspects of asset’s operation that is difficult to justify because of its multiple inherent trade-offs. Although the majority are unanimous when it comes to the expected impact maintenance plays on company profitability, this is in most cases challenging to determine and quantify. Moreover, relevant literature is considered as limited, especially with regards to impact simulation of Maintenance 4.0. Therefore, this paper focuses on the supportive function system dynamics, and modeling and simulation tools can be of help to assess behavior and predicting the future outcome of Maintenance 4.0 in the era of Industry 4.0. This includes developing a conceptualized model that enables simulating the future expected behavior i.e. (un)availability and cost by implementing such maintenance system. In this context, a centrifugal compressor with the function of exporting gas to Europe is applied as a case study.

Keywords: Industry 4.0 Architecture, System Dynamics, Maintenance Management, Impact Simulation

NONMENCLATURE

Abbreviations

RCM	Reliability centered maintenance
CBM	Condition-based maintenance
TPM	Total productive maintenance
O&M	Operation and maintenance
O&G	Oil and gas
IoT	Internet of things
CPS	Cyber-physical system
PM	Preventive maintenance
RUL	Remaining useful life
OEE	Overall equipment efficiency
HSE	Health, safety and environment

1. INTRODUCTION

The perception of maintenance management has been highly influenced by several technological developments and evolved in from being a “necessary evil”, “technical matter”, “cost-cutting contributor”, “profit contributor” until it today is perceived as a “cooperative partnership” that can potentially add value to the business [1]. Moreover, maintenance strategies have developed rapidly over the last three industrial revolutions from being reactive, preventive, predictive and finally to become proactive and holistic (focus on entire system rather than single machine) [2]. Those strategic changes lead to several maintenance programs e.g. reliability centered maintenance (RCM), condition based maintenance (CBM), and total productive maintenance (TPM) [1].

Maintenance is often associated with high cost allocated in the phase of an asset’s operation and maintenance (O&M). In fact, the cost of maintenance is determined as sector dependent and varies all from 15 to 70 percent of total production cost [3-5]. Moreover, several authors state that maintenance management is often attributed to poor planning and decision support resulting into inefficiency and waste of both cost and resources [5-9]. However, maintenance management and performance are complex aspects of asset's operation that is difficult to justify because of its multiple inherent trade-offs. Therefore, the expected or estimated impact of maintenance is often challenging to determine and quantify. Nevertheless, several literature are in fact unanimous when it comes to the expected impact maintenance plays on company profitability, supporting current perception of maintenance as a "cooperative partnership" [2, 10-14].

The importance of facilitating simulating the expected impacts of emerging technologies in the context of Industry 4.0 and its associated concepts has never been as important as it is today. It exists a great optimism of what the expected impact Industry 4.0 will bring to the oil and gas sector (O&G). [15] states that predictive maintenance and operations optimization are the two main technologies that will have the highest industrial and societal impacts in this specific sector, by e.g. reducing maintenance costs by 20% and operational downtime by 5% (mainly due to predictive maintenance). However, nowadays, only one single percent of data originating from 30 000 sensors located on a traditional oil rig is exploited. Moreover, this single percentage is in most cases utilized with regards to control and detection of operational anomalies [16] and not for optimization and prediction in which [15] highlights as the most beneficial impact. Moreover, as the cumulative maintenance expenditures concerning offshore installations with design life of 30 years can reach up to £2 Billion (and often more, as life-extending measures are commonly adopted to enable operating such facilities over its designed lifetime) [17], there exist a great potential of reducing the associated cost by £400 Million (given that a 20% reduction in maintenance cost as presented by [15] is reasonable). Hence, the potential impacts of adopting an intelligent maintenance system in Industry 4.0 is considered as tremendous. However, estimating these specific impacts of predictive maintenance and operations optimization require techniques with growing complexity and capabilities. Therefore, simulation is considered as the key enabling technology as highlighted by [18] that may facilitate forecasting impacts of e.g. intelligent maintenance in Industry 4.0 in the context of predictive maintenance and operations optimization.

Several studies have adopted the methodology of system dynamics and investigated the opportunities of developing a model that enables simulating the impact of maintenance or internet of things (IoT) with respect to output variables such as e.g. companies' availability, cost and profit [16, 19-28]. Regardless, the authors identify two research gaps: (1) none of the existing models enables simulating the causal relationship that is present in the maintenance phase of a centrifugal compressor applied to export gas in the O&G industry, and (2) none of existing literature facilitate simulation of intelligent maintenance architecture based on Industry 4.0 requirements. Hence, the purpose of this paper aims to develop a conceptualized model that enables simulating both the behavior of the associated compression system applied in gas export and the expected impacts introduced through the implementation of an intelligent maintenance system, by adopting the methodology of systems dynamics and simulation.

The remainder of this paper is organized as follows. Section 2 presents some relevant theory regarding process modeling and industrial simulation. Then, the case study of the centrifugal gas export compressors is investigated in section 3. Section 4 is dedicated to the presentation of the conceptualized model developed in which enables simulating the behavior of the case study and the expected impact of implementing intelligent maintenance in the era of Industry 4.0. At last, section 5 provides some concluding remarks.

2. PPROCESS MODELING & INDUSTRIAL SIMULATION

Industry 4.0 and associated emerging technologies of cyber-physical systems (CPS), internet of things (IoT), big data, and cloud computing (including diagnosis and prognosis) are expected to play a vital role in companies future competitiveness and sustainability. However, determining the future benefits of adopting such technologies is of vital importance. Therefore, model-based representations i.e. process modeling and industrial simulation approaches e.g. system dynamics have become a highly embraced tool with its growing complexity and capabilities [28]. This includes tools such as e.g. discrete event simulation (e.g. Arena), system dynamics (e.g. Vensim), and multi simulation methods (e.g. Anylogic and Numerus (Nova)), which all are frequently applied by industries to facilitate modeling and simulation of complex processes to perceive their nonlinear characteristics, either in the phase of early design, O&M, or late in decommissioning. The benefit of adopting process modeling and industrial simulation relates to its unique way of representing scenarios that are as close as possible to the real world. In this process, causal relationships are investigated and described in details, yielding an understanding of the system behavior.

The literature describes the application of process modeling and industrial simulation in order to enhance asset operation. This is especially interesting i.e. maintenance and its impact on companies' availability, cost, and profit. In this context, some of the most well-known simulation models are presented in Table 1, considering their associated influencing variables, rates, and estimated benefits. Moreover, these well-known models constitute a supportive function when developing the conceptualized model presented in this paper. In fact, the model of [19] is especially interesting by its classification of failures (critical, degraded, and incipient) and its description of detection rate w.r.t sensor technology and maintenance management.

In this paper, the authors intend to adopt the approach of system dynamics to investigate and describe the case study and successively aid developing a model that enables simulating the causal relationship(s) associated with the operation of the case study.

3. CASE STUDY

The case study in this investigation is a compression system with the primary function of enabling transporting sales gas (processed natural gas) through subsea pipelines by dynamically compressing it from 62 to 185 barg – thus, decisive as it determines whether the end users receive their booked gas or not. The compression system comprises four identical compressor trains, which each includes an electric motor, gearbox, and two centrifugal compressors arranged in series. In operation, three out of the four compressor trains are in operation and sharing loads. Hence, one train is at any time functioning as redundancy in cold standby [29, 30].

Table 1: Summary of the five most well-known simulation models.

	Influencing variables	**Rates**	**Estimated benefits**
Linneusson et al. [31]	- Number of repair workers and maintenance engineers - Goal and fraction of preventive maintenance (PM) and CBM based on root cause analysis - Inspection interval - Scheduled and unscheduled repairs - Backlog of PM and CBM - Equipment health	- Take down and break down rate - Mean time to failure	- Availability - Maintenance cost - Acc. maintenance budget margin - Acc. company result
Jambekar [32]	- Throughput pressure - Planned throughput - PM	- Equipment and labor force utilization - Breakdown	- Process quality - Process reliability
Zuashkiani, et al. [33]	- Resource shift to reactive maintenance - Production - No. of repairmen allocated to reactive maintenance - No. of repairmen left to proactive maintenance - Reactive maintenance - Collateral damage	- Accumulated defects - Breakdown - Downtime due to proactive maintenance - Pressure on production - Take down rate for proactive maintenance - Downtime due to reactive maintenance - No equipment time for PM	- Plant OEE
Honkanen [34]	- Working components - Components that are either failing soon, under repair, or have failed due to aging and infant life. - Working and failing components to be CBM maintained. - Components under maintenance	- (Net, Effective and Total) operating time - (Net) availability - (Scheduled) downtime - Speed and defect losses - Work start rates of repair, PM work, and CBM work.	- Availability - Performance - Quality
Jokinen et al. [19]	- Spare part management - Maintenance management (e.g. target and active tasks related to preventive and corrective maintenance)	- Time - Increased degradation with time - New components and worn out components - Failures (incipient, degraded, and critical)	- Availability - Maintenance cost

Moreover, each compressor train includes 45 sensor signals related to condition monitoring: 26 sensor signals of vibration displacement in X- and Y-axis, 18 sensor signals monitoring the temperature of the bearings, and one single sensor signal that monitors vibration in terms of velocity. The data generated by the different sensors are in most cases exploited through trending. Therefore, it is of interest to investigate the behavior of the respective compression system (as a decisive part of the transportation system) and how a potential implementation of an intelligent maintenance system in the era of Industry 4.0 may impact the operation/ transportation in terms of availability and cost. To do so, the methodology of system dynamics including modeling and simulation is adopted.

In order to manage developing a simulation model that allows simulating the expected impacts, several processes must be studied at first, which are summarized in Table 2.

1. Gas production/compression scenario (normal loading, seasonal demand): The need for gas compression is highly dependent on the season as the consumers mainly utilize the gas for heating and cooking at households (in addition to industrial consumption). Thus, end-user demand is peaking at winter-season when the need for heating is at its greatest. From a maintenance perspective, this will obviously play an important role when it comes to planning as a specific action will affect the operational (un)availability differently.

2. Planned maintenance scenario (planned schedule timeline): Equipment vendor usually provides customers with recommendations of preventive maintenance action throughout the equipment's life cycle. These are often based on either time in operation or numbers of cycles. Clearly, this will have an impact on planned unavailability and maintenance cost, and must, therefore be considered in the context of intelligent maintenance and maintenance decision support (maintenance optimization).

3. Failure growth scenarios: The occurrence of symptoms of failure, or even failure, rises demand for necessary future action. The (symptom of) failure will impact the operation differently based on its characteristics i.e. location, size, and severity. This is highly associated with maintenance management and the application of condition monitoring technologies including sensor technology, diagnosis, prognosis, which determines detection stage and thereby the degradation criticality, and the urgency for repair along with its cost.

4. Fault detection scenario: The introduction of Industry 4.0 has brought novel opportunities in maintenance management, especially considering cloud computing including diagnosis and prognosis. In more detail, Maintenance 4.0 differentiates from Maintenance 3.0 by moving its focus from the traditional enterprise level to become more holistic comprising the asset-level and between asset and enterprise-level. Therefore, it is of interest to simulate the difference between three monitoring scenarios in terms of impact: (1) compressor without condition monitoring system, (2) compressor with condition monitoring system (Maintenance 3.0), and (3) compressor with Maintenance 4.0. In this context, it is expected that the detection rate related to condition monitoring increases and the cost related to the level of repair is reducing, respectively.

5. Fault prevention scenario (by the control system): The objective of intelligent maintenance is to enhance right maintenance to be executed at the right time. This could e.g. include performing temporary maintenance actions or measures that extend the remaining useful life (RUL) estimate, which enables delaying the need to execute the required maintenance action from the diagnosis – thus, gaining opportunistic benefits. This comprises, for instance, the ability to plan the maintenance work for next opportunistic interval e.g. low production season or no-production days. Additionally, preventing the needs for corrective maintenance, which is commonly known as costly in comparison to other maintenance strategies.

6. Fault prevention scenario (by maintenance action): Accurate health assessments (diagnosis) and RUL estimations enable developing detailed work orders including spare part management, required human resources, and expected execution time. This improves the maintenance supportability and enhances the maintenance action's successfulness ensuring that the right maintenance action is conducted.

7. Maintenance performance: It is clear that execution of diagnosis will pose a beneficial impact of the maintenance performance since it enables assessing the current health status of the equipment and by this pinpoint the exact degradation mechanism. Thus, if the diagnosis e.g. reveals degradation of outer racing of a roller bearing, the maintenance personnel can plan down to the smallest details on how to maintain this in the best way. Hence, enhancing the performance of the maintenance action that is measurable through e.g. the mean-time-to-repair (MTTR) estimate.

8. Spare Part Management: The capabilities of prognostics is expected to impact the cost of inventory since it reduces the need for having spare parts in stock as it is possible to forecast at what time the different spare parts are required in advance.

Table 2: Summary of related case study scenarios with potential estimated impacts.

Scenarios Affecting Transportation	**Potential Estiamted Impact**
Gas production/compression scenario (normal loading, seasonal demand)	Availability, performance
Planned maintenance scenario	Planned unavailabiliy, planned maintenance cost
Failure growth scenario	Saving losses (unplanned maintenance cost, cost related to the level of repair (since the fault was detected before the whole system was damaged, etc.)
Fault prevention scenario	Gain opportunistic benefits e.g. able to plan the maintenance work for next opportunistic interval e.g. low production season or no-production days.
Maintenance performance scenario	Operational availability and unavailability (e.g. MTTR), cost of inventory, required human resources.
Spare part management scenario	Cost of inventory

4. The Conceptualized Model

The prime objective of implementing intelligent maintenance architecture based on Industry 4.0 is to facilitate optimizing existing maintenance schedule. Although, the definition of "optimization" [35] can be interpreted ambiguously, it is in this context referred to as the mathematical concept that determines the optimal solution to a function comprising several different input and output variables such as e.g. gas price, cost, spare part management, operational (un)availability, and resources required and available. The most optimal solution based on the multiple variables is dependent on their weighting that may vary from time to time, under different circumstances. Resultantly, the optimization process shall ensure that the right maintenance takes place at the right time.

The conceptualized model developed to enable simulating this optimum maintenance action is based on maintenance theory from the literature review, systems dynamics (Vensim), the well-known simulation models presented in Table 1, and the scenarios extracted from the case study. As seen from the conceptualized model presented in Figure 1, it can be decomposed into four sub-models: (1) *production*, (2) *maintenance management*, (3) *CBM*, and (4) *equipment degradation*. In general, production (sub-model 1) is similar to any commodity, highly associated with the logic of supply and demand comprising variables such as e.g. politics, regulations, wealth, technology, population, and substitutes. Briefly, this is in turn determining the price of the commodity and thereby the revenue of the company. Moreover, the production is restricted by the availability of resources (hydrocarbons) and the associated overall equipment efficiency (OEE) that is governed by the specific maintenance management (sub-model 2). The most important content of maintenance management is to optimize the existing maintenance schedule. This includes detecting failures (diagnosis), predicting the future development of the degradation and its impact on the system (prognosis), in which enables developing a detailed maintenance plan that identifies the best opportunistic window to perform the required maintenance action that improves availability and thus minimizes unavailability.

CBM (sub-model 3) is all about monitoring performance and health data through sensor technology in order to detect, predict, and extend the RUL estimate by prolonging the time to when the specific maintenance action is required. In this context, failure modes are classified into critical, degraded, and incipient failure modes. Traditionally, critical failure modes are detectable through performance monitoring (variables related to the process such as e.g. pressure, temperature, and flow), while health parameters can improve the detection rate of critical failure modes and may even comprise certain degraded failure modes by combining performance and health parameters in terms of multivariate analyses of big data.

In order to detect degradation mechanisms early, awareness of equipment degradation (sub-model 4) affected by certain characteristics such as e.g. environment (weather and climate) and operation (rpm and loading) is of high importance as it is connected with the equipment's failure rate. Moreover, such awareness supports achieving an understanding of equipment behavior along with responding to the results from the diagnosis and prognosis by e.g. prolonging the time to required maintenance action.

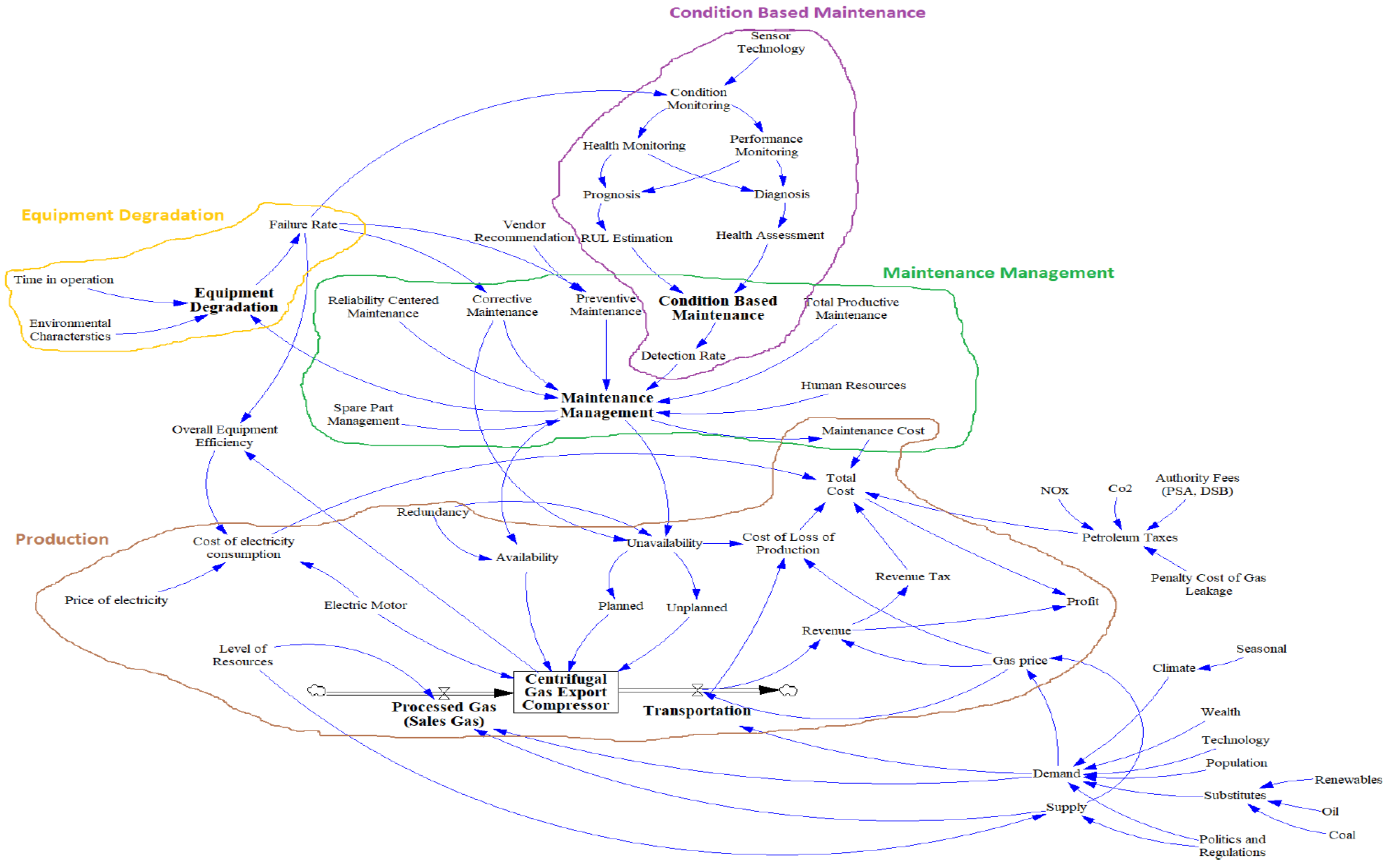

Figure 1: The conceptualized simulation model with associated sub-models.

In final, Figure 2 shows the three causal loops identified in the conceptual model, which is the basic benefit of systems dynamic to manage (balancing or reinforcement).

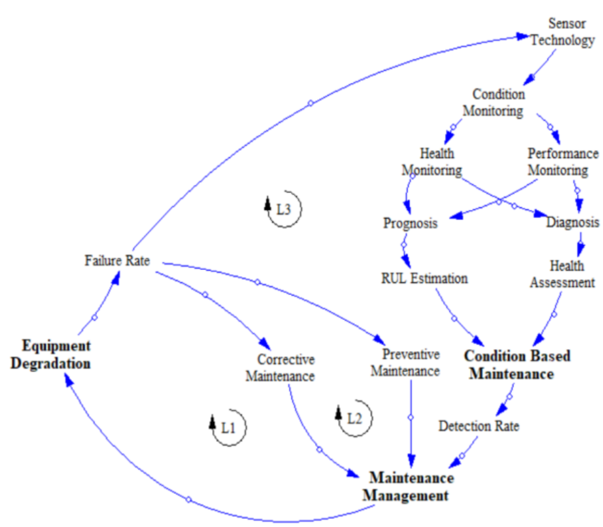

Figure 2: Three different causal loops demonstrated by the conceptualized simulation model.

To summarize, the conceptualized simulation model shows the interaction between the different maintenance strategies affecting maintenance management. Furthermore, this plays a vital role for the estimated impacts i.e. availability and cost efficiency (as shown in Figure 1). It is clear from Figure 2 that the causal loop of CBM (L3) yields the greatest impacts and thus the objective of maintenance management, and vice versa for the causal loop regarding corrective maintenance (L1). However, in order to estimate the specific impacts, the capabilities of detecting the different failure modes associated with the system through sensor technology (parameter monitoring) and data analyses (diagnosis and prognosis) must be investigated.

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5. CONCLUSION

Industry 4.0 and associated emerging technologies of CPS, IoT, big data, and cloud computing (including diagnosis and prognosis) are expected to play a key role in companies' future competitiveness and sustainability. However, determining these future benefits of adopting such technologies is of vital importance. Therefore, process modeling and industrial simulation approach e.g. system dynamics have become a highly embraced tool with its growing complexity and capabilities to facilitate perceiving nonlinear characteristics of complex processes.

Literature describes the importance of having a rigid maintenance management, which is reflected in associated impacts such as e.g. availability and cost estimations. Moreover, based on the growing complexities and capabilities of system dynamics, simulation is frequently adopted to estimate such impacts. However, maintenance management and performance are complex aspects of asset's operation that is difficult to justify because of its multiple inherent trade-offs. Although the majority are unanimous when it comes to the expected impact maintenance plays on company profitability, this is in most cases challenging to determine and quantify.

The conceptualized model developed in this paper demonstrates three causal relationships between different scenarios and its potential estimated impacts related to a case study concerning a centrifugal compressor that is applied to transport natural gas through subsea pipelines. The three causal loops (corrective maintenance, preventive maintenance, and CBM) are showing the importance of having rigid maintenance management and its impact on company availability and cost. However, in order to quantify these specific impacts, the capabilities of detecting the different failure modes associated with the system through sensor technology (parameter monitoring) and data analyses (diagnosis and prognosis) must be investigated. Moreover, it is expected that implementation of Maintenance 4.0 will not only aid for improved operational impacts i.e. availability and cost but also enhance the asset's health, safety and environment (HSE) aspects. This is described rather narrowly in the report. Nevertheless, HSE is of greatest importance but is excluded as it is challenging to quantify and simulate such intangible aspects of the operation.

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