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Enabling condition-based maintenance decisions with proactive event-driven computing

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ABSTRACT

Condition Based Maintenance (CBM) can take advantage of the emergence of Internet of Things (IoT) and the proactive event-driven computing paradigm for fully exploiting its capabilities by enabling proactive maintenance decisions ahead of time. In this paper, proactive event-driven computing is used as a lever in order to provide a holistic CBM approach along with an information system for generating proactive maintenance recommendations. Since the Detect and the Predict phases of the "Detect-Predict-Decide-Act" proactivity principle as applied to the CBM framework are well-studied fields in literature, the focus of the current research is on the Decide phase that is still an unexplored area. Therefore, in the context of this paper, the approach, contributing decision methods and technical specifications of an associated information system are defined and developed for this phase. The proposed approach is implemented in an information system, which is deployed and evaluated in the context of two real industrial scenarios in the area of oil and gas and automotive lighting equipment industries. The results of a comparative and a sensitivity evaluation analysis show that the proposed approach can enable industrial business transformation from a reactive to a proactive mode of operation, in order to eliminate maintenance-related losses and optimize business performance.

1. Introduction

The emergence of the Internet of Things (IoT) and the Industry 4.0 paradigm have paved the way for enhancing the monitoring capabilities of enterprises with the extensive use of physical and virtual sensors. Sensors generate a multitude of data that can be used for the identification of deviations with respect to normal operations. Taking advantage of the big data generated from a large amount of sensors requires the development of event monitoring and data processing systems that are able to handle real-time data in complex, dynamic environments in order to get meaningful insights about business performance. Sensor-generated data can be used to predict undesirable situations and hence enable engineers to decide and act proactively. Proactivity is leveraged with novel information technologies with the ability to mitigate the impact of undesired future events, or to exploit future opportunities [1]. Currently, the capabilities of proactive event-driven decision making have not been examined in manufacturing operations, due to several challenges associated to large scale enterprise environments as well as due to the lack of appropriate algorithms.

Maintenance operations are a major part of the total manufacturing costs. Studies show that approximately 60% of all the manufacturing equipment fails prematurely after the implementation of corrective maintenance actions [2]. Insufficient maintenance management can result in equipment deterioration and quality defects which correspond to financial losses due to delays, customer complaints, and purchasing of new equipment spare parts. For this reason, Condition Based Maintenance (CBM) is an evolving maintenance strategy in the last years. CBM aims to avoid unnecessary maintenance tasks by taking maintenance actions only when there is evidence of abnormal behaviors of a physical asset.

Automation of CBM decisions on the basis of real-time, sensor-enabled prognostic information is an unexplored area. Existing works regarding CBM applications have usually the following limitations: (i) they provide only a diagnostic or a prognostic output [3]; (ii) they rely on processing of batches of data and not on real-time, event-driven information [4]; (iii) in cases they provide recommendations, these

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refer typically to immediate action implementation, something that may not lead to an optimized performance because the expected loss may be minimized of the action is implemented some time into the future and before the occurrence of an equipment breakdown. The research objective of this paper is to pave the way towards the development of the next generation event-driven and proactive CBM approach that will take advantage of the recent advancements in proactive event-driven decision making for providing recommendations about best maintenance actions at the optimal time.

The rest of the paper is structured as follows: Section 2 reviews the literature on proactive event-driven computing and CBM. Section 3 presents the proposed approach and associated methods for proactive decision making in the context of CBM, while Section 4 presents the implementation of the proposed approach. The next two sections describe the application of the proposed approach by deploying the aforementioned system in a real industrial environment (Section 5) and show the evaluation results by presenting an extensive comparative and sensitivity analysis (Section 6). Finally, conclusions and directions of future work are discussed in Section 7.

2. Literature review

2.1. From sensing to proactive enterprise

'Sensing Enterprise' refers to the ability of the enterprise to process information captured by sensors and to provide added value insights [5]. It does that by taking advantage of IoT advances such as advanced sensor fusion, faster wireless connectivity and real-time predictive analytics. For this process, intelligent, interconnected and interoperable smart components and devices are required to analyze events and react on the basis of them [5]. Although sensing enterprises with high monitoring capabilities within their network and across different levels are a reality, the strategic value of data analysis can be increased by supporting data-driven decision making. Similar to the way that the events are driving reactivity in the sensing enterprise, predictions can drive proactivity, leading to increased situation awareness and decision making capabilities ahead of time. Proactive computing extends the reactive pattern known as 'Sense-and-Respond' [6] or 'Detect-and-Act' [7] to the proactivity principle consisting of four stages [1,8]:

- **Detect** events and situations
- **Predict** future undesired events
- **Decide** recommendations that are going to be provided
- **Act** by enacting the decision taken in order to adapt the operational system and by collecting feedback to improve the recommendations.

The evolution from responsive computing, in which processing is done in response to an explicit request, to reactive computing, in which processing is triggered in response to event, was achieved with the development of models and tools to express and execute reactive systems in an easy way [1]. A similar evolution is necessary for enabling pervasive use of proactive computing. The proactivity principle is enabled through the exploitation of IoT capabilities and the support of decision making with the implementation of real-time, event-driven information systems. Proactive decision making goes a step beyond the real-time predictive analytics by providing recommendations on the basis of predictions ahead of time.

2.2. Condition based maintenance

Maintenance is a key operation function and is related to all the processes of a manufacturing firm. It focuses not only on avoiding the equipment breakdown but also on improving business performance. Methods used for CBM can be classified in four categories [9]: (i) model-based, (ii) knowledge-based, (iii) data-driven and (iv) combination of them. CBM relies on diagnostic and prognostic models and uses them to support decisions about the appropriate maintenance actions based on the current and predicted health state of a manufacturing system based upon data gathered through condition monitoring [4]. The motivation of CBM is that the vast majority of equipment failures are preceded by certain signs, conditions, or indications that a failure is going to occur. New practices put failure prediction at the backbone of decision making for CBM with the development of appropriate e-maintenance information systems [10]. Moreover, there is an increasing interest on real-time CBM platforms in the context of IoT and Industry 4.0 [11–17].

To this end, CBM can take significant advantage of proactive computing in order to overcome challenges associated with its application in large scale, big data-based enterprise environments and with the lack of appropriate algorithms that can be embedded in an event streaming computational environment. Therefore, the "Detect-Predict-Decide-Act" proactivity principle can be mapped to the CBM framework in order to develop associated information systems and algorithms. Despite the significance of proactive maintenance decisions [18,10,9,3], their automation by providing CBM recommendations ahead of time in a real-time, event-driven environment still remains a challenge [10,19–21].

3. Proactive event-driven decision making for CBM

The proposed approach deals with proactive event-driven decision making for CBM. More specifically, its contribution consists of three main aspects: setting CBM in the context of proactivity, i.e. mapping the proactivity principle to the CBM framework (Section 3.1); (ii) focusing on the Decide phase of the proactivity principle and how it is implemented in the frame of CBM (Section 3.2); (iii) proposing proactive decision methods for CBM capable of being implemented in an event streaming computational environment (Section 3.3). The proposed approach forms the basis for the development of an event-driven architecture for proactive decision making and for an information system covering all the phases of the proactivity principle in the context of CBM.

3.1. CBM in the context of proactivity

This Section describes the proposed methodology for the development of an integrated information system that fully exploits the capabilities of proactive event-driven computing in the context of CBM. Each phase of the proposed methodology is further described below.

- **Detect**: The *Diagnosis* phase, which deals with signal processing, condition monitoring and health assessment, corresponds to the Detect phase of proactive event-driven computing and is implemented with a Complex Event Processing (CEP) engine [22]. The CEP engine performs operations on events in real-time by implementing an Event Processing Network (EPN) that consists of event producers, event processing agents and event consumers. The CEP engine detects unusual situations based on event data gathered from the appropriate condition monitoring sensors. The diagnostic output of this phase, i.e. the detection of an unusual situation, triggers the Predict phase.
- **Predict**: The Prognosis phase, corresponds to the Predict phase of proactive event-driven computing and includes a predictive analytics service, which enables the generation of real-time, event-driven predictions of future undesired events. This service can benefit from the large amount of research works in the prognostic phase of the CBM framework, that have been embedded in information systems and provide a prognostic output, such as the Remaining Useful Life (RUL) of some part of equipment, the Remaining Life Distribution (RLD), etc. So, when an undesired event (e.g. breakdown) is predicted to occur, the probability distribution function of its occurrence along with its parameters feed into the Decide phase.