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On a versatile scheduling concept of maintenance activities for increased availability of production resources

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Abstract

Manufacturing systems are making a shift towards intelligent and predictive Cyber Physical Systems (CPS) with enhanced sensing and communication capabilities. Current maintenance activities are based on predefined schedules, without considering the working state of the equipment and thus leading to over-maintained machinery. The cost related to the production process interruption and for dispatching maintenance personnel to restore the equipment to proper working conditions is high.
In this context, this study presents an extendable and re-usable scheduling approach supporting multiple heterogeneous inputs and outputs. Predictive maintenance indicators from the monitored equipment are used for scheduling maintenance operations in line with the existing schedule. A web-service architecture is adopted towards supporting highly different use-cases, such as equipment providers and/or manufacturers. The incorporation of maintenance activities to the production schedule may result in a reduction of maintenance breakdowns and thus increased productivity. The proposed approach has been applied to cases deriving from the automotive and steel production industries.

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Keywords: Maintenance; scheduling; web-services;

1 Introduction

The emergence of modern sensors, high-end computing devices and their constantly increasing interconnection hold the promise of increased automation reducing production costs and time.The preservation of industrial equipment in working condition is one of the key challenges a production system needs to handle. Maintenance activities involve the complete or partial interruption of the production process to restore the system to an acceptable operating condition. Consequently, this restore process may result in higher production downtime and increased operational costs.

Existing solutions are targeted to the owner's case and perspective. Moreover, existing implementation do not allow for easy extension or reconfiguration without interrupting the production system. Thus, most maintenance providers tend to assign resources to each of their costumer or each end-user has maintenance resources who remain idle most of the time.

Towards improving the efficiency of maintenance activities from the production perspective, appropriate planning is required so as not to interrupt the production or do so in a planned and non-interruptive way. The scheduling and execution of maintenance operations should consider:

- the availability of the machines used in production,

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- the time required for the maintenance activities to complete [1],
- the availability of maintenance personnel (specialized or shopfloor) and
- the production running and not running trade-off.

In this work, a maintenance-aware scheduling concept is presented. The proposed approach incorporates input data, as the outcome of a predictive maintenance Artificial Intelligence (AI) algorithm, adjusting the execution of maintenance operations according to the existing production schedule as well as to the availability of maintenance resources.

The proposed concept supports the scheduling of maintenance operations from an end-user and a maintenance provider perspective. In the first case, maintenance personnel are on premise. The production schedule is also an input and a maintenance aware schedule is generated with potential changes to the existing production schedule itself. Hence, production downtime due to maintenance activities, planned or unplanned, may be reduced. In the second case, specialized maintenance is needed. Thus, the maintenance plan of the provider is an input as well as the production plan of the end-user which in this case does not change. Maintenance operations are fitted to the production schedule according to the maintenance plan of the maintenance provider. As a result, the service cost for the provider can be reduced by improving the management of its maintenance resources through adequate planning and scheduling.

The discussed approach has been implemented in a software system based on a Microservices architecture for increased flexibility enabling interconnection with external systems and additional functionalities.

1.1 Literature review

Scheduling problems including maintenance activities may be represented by two larger groups. On the one hand, the literature is focused on “fixed” and “coordinated” models [2]. The first type includes pre-defined constraints such as the duration, starting and completing times. On the contrary, “coordinated” models are focused on simultaneously determining when each maintenance activity should be conducted and when each job should be processed.

The scheduling of manufacturing operations, which was traditionally based solely on Manufacturing Execution Systems (MES), cannot demonstrate increased flexibility and scalability to heterogeneous systems [3]. As manufacturing paradigms are making a shift towards cyber-physical systems [4], new scalable and distributed solutions are required for managing the production process efficiently. In this context, distributed software engineering architectures such as microservices can support scalable and distributed applications [5]. The current industry trends indicate a transition from Service-Oriented Architecture (SOA) to Microservices [6]. The decentralized concept of microservices provides the development teams with more agility and better offering to their clients. A microservices-based middleware for the digital factory is presented in [7] supporting various distributed software applications. Mourtzis et al. [8], developed an integrated system, under the Industry 4.0 concept, that incorporates data gathered from the monitored equipment and alters the maintenance schedule based on the available timeslots. Senra et al. [9] proposed a scheduling algorithm that considers the availability of equipment and technicians, as well as the related processing times. The proposed methodology has been validated under a case study but lacks in terms of online equipment monitoring as the maintenance activities have been already defined. A decision-making tool for production maintenance synchronization has been introduced in [10]. The proposed approach combines multiple criteria, such as product performance and component reliability and provides the optimal scheduling solution. The work presented in [11] has focused on providing the optimal solution to a flexible job shop scheduling problem based on incorporating a condition-based maintenance approach. However, it seems to lack in terms of general and versatile applicability since 1) the relevant monitored equipment is restricted to one kind of machine without the potential of implementing the developments to meet the requirements posed from other types of machines and 2) the overall production schedule hasn’t been considered on the generation of the new maintenance schedule.

The latest trends of research are focusing towards implementing and optimizing the outcome of predictive maintenance approaches. Liu et al. [12] has proposed a decision model to coordinate prognostic information as the outcome of predictive maintenance decisions with the available resources. Aiming at reducing the expected maintenance costs, the integrated model considers also the degradation model of the monitored machine. However, the applicability of the proposed method to machines of different type is in question. On the other hand, Asma Ladj et al. [13] proposed an integrated scheduling model that can be applied to a wider spectrum of machines. The proposed method deals with the permutation flow shop scheduling problem [14] with predictive maintenance activities considering maintenance cost optimization criteria. An operational pattern analysis that incorporates the collected data from industrial systems and uses a fast Fourier transform was adopted in [15] while sensor based degradation models for identifying the frequency of unexpected failures was used in [16]. A mixed integer programming model for scheduling the machines maintenance activities was proposed in [17]. The proposed study focused on flow-shop topology where machine could be maintained once during the planning horizon. The machines were able to switch between a nominal model and a degraded one allowing in this way to find the ultimate schedule of production operation. An operation-dependent maintenance scheduling method in flexible manufacturing systems has been proposed in [18]. The newly introduced methodology is based on a metaheuristic optimization where candidate solutions are evaluated through repeated discrete event simulations of the manufacturing system. Dynamic interactions though between the equipment condition and the operations are still open. Finally, Biondi et al. [19] presented an industrial framework for the integration of maintenance and production scheduling of process plants considering the degradation impacts of the plant unit. The proposed method was validated through computation models and each applicability under real industrial environments is still open.

1.2 The SERENA project

The work presented in this paper is part of the European research project SERENA. Purpose of the project is the development of solutions for truly connected production processes where all machinery data are accessible, allowing easier maintenance in case of unexpected events and minimization of costly production downtimes. This is envisioned to be achieved through the combination of existing solutions in predictive maintenance towards providing (1) advanced gateways for collecting sensor data and extracting meaningful information for the condition of the equipment; (2) AI methods for equipment health assessment, (3) hybrid predictive analytics; and (4) predictive maintenance and cloud-based communication framework.

2 Approach

In the presented study, the domain knowledge of the system or a work centre is comprised of the following key elements or classes:

1. Work centre: defining the physical place where a maintenance or production activity will take place, e.g. an assembly station. A work centre is linked to certain properties, such as geometrical characteristics of its physical layout, I/O streams, etc. The work centre element is closely coupled to its physical assets, such as equipment/machines/tools. The equipment of a work centre is used by resources, e.g. human operators, to execute a specific job.
2. Job: is the superset of the activities that take place in a certain period in the workstation. A job is comprised of tasks. Each job has a set of constraints, such as completion time, assembly sequence, bill of material, required tools, etc.
3. Resource: responsible for executing a task in a specific workstation. In this study, as resources are considered operators, robotic manipulators and mobile robots for logistic operations interacting with the work centre.

A separate element is considered for capturing and representing operator's feedback. Purpose of integrating this input is to enhance the effectiveness of the generated schedule from the operator's perspective, either related to a manufacturing or maintenance operation.

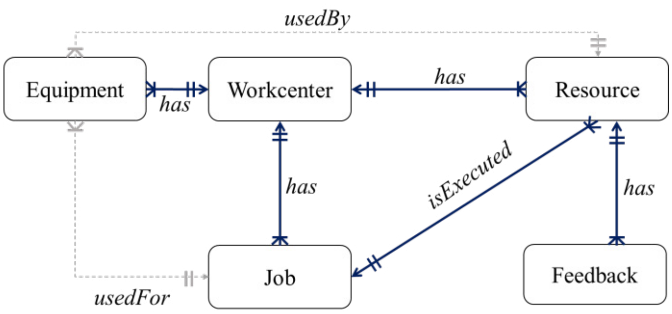

Fig. 1. Main scheduling entities relationships

A high-level Entity-Relationship representation of the data model is presented in Fig. 1.

The approach discussed in this study is based on a decision-making framework for selecting the production-wise appropriate time slot for assigning a maintenance activity to a suitable resource.

The scheduling framework receives as input a list of production and maintenance tasks to be carried out alongside with possible constraints depending on the characteristics and requirements of each facility. These constraints include among others information such as operation time, arrival and due date of the job. Next, the input information is evaluated out of a set of weighted criteria towards generating alternative schedules. The weights are estimated based on the production targets of each system, such as minimize cycle time, production cost, energy consumption or other.

Two implemented criteria are described below as an example.

1. The total time for the tasks' execution, Δ_R, is estimated as the sum of the completion time of the assignment tasks both to the human maintenance operator and the monitored equipment. This criterion is based on the following equation:

$$\Delta_R = \sum_{i=1}^{n} \Delta_E^i \qquad (1)$$

Where:

- Δ_E^i: execution time for a task i that is assigned to the human maintenance operator and the robot/rolling mill
- n: the total number of tasks that have been assigned to the selected resources

2. The overall cost of the selected resources, K_{total}, is estimated as the sum of the operating cost of each resource for each task. The equation describing the correlation is:

$$K_{total} = \sum_{j=1}^{N} K_R^j \qquad (2)$$

Where:

- K_R^j: operation cost of resource j that is responsible to perform each task
- N: the total number of resources

The result of the whole scheduling procedure includes the tasks which are assigned to specific resources, alongside with the correct timing and duration of the tasks. More importantly, the generated schedule includes both maintenance tasks best fitted to the existing production schedule. Depending on the criteria selected for the evaluation and their weights it is possible either to change the production schedule or keep it intact.

3 System Implementation

To evaluate the proposed approach, a Java web-based scheduling application was implemented using the Spring framework handling HTTP requests and responses.

The scheduling tool implements a generic multi-criteria algorithm to produce a series of task – resource assignments. Information about tasks, resources and other relevant information is retrieved from legacy and shopfloor systems through the appropriate connecting scripts. The design of the components that realize the scheduling application follows a client-server approach where most of the functionality resides on the server side and the client applications mainly support user interaction.

The aim for the scheduling tool is to receive information from various sources under various data formats. The preferred technic for designing the data handling mechanism is the Microservices architecture. The essence of the architecture is the deployment of the application as a sum of small, both in size but also in business logic, modular, independently deployed services. These services execute a specific process and communicate with each other with a well - defined communication protocol that depends on the needs of the application.

The usage of the Microservice architecture has been implemented in the scheduler data consuming Application Programming Interface (API) that stands between the scheduler and the data and information providers such as:

- Shop floor Systems
- Supervision Systems
- Safety Systems
- Legacy Systems

The various abovementioned systems and any other that could provide data can connect to the API through well - defined communication protocols, such as REpresentational State Transfer (REST), Message Queuing Telemetry Transport (MQTT) or other.

The API due to its lightweight nature that is provided by the Microservices Architecture can be rapidly deployed in Internet of Things (IoT) devices and containers.

The implementation of the API consists of the following components:

- Communication Traffic Handler is a component that manages the incoming traffic from the various sources and distributes them to the next component. Acts as a dispatcher server.
- Data and Information Normalization Handler is a component that normalizes all the various types of user info into JavaScript Object Notation (JSON) objects for the next component to manage the data
- Data Verification Handler is a component that verifies that the data that was transformed into JSON objects is in an appropriate format to be sent to the next component
- Entity Mapping Handler is a component that creates a mapping between JSON objects and Entities that are corresponding to the Database schema of the scheduler

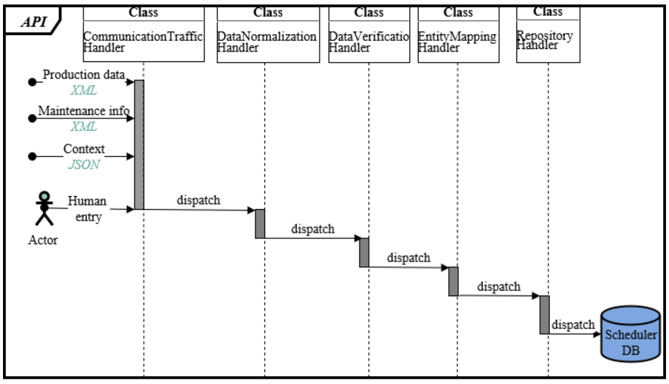

Fig. 2. Data consuming API sequence diagram

- Repository Handler is the component that creates the connection between the API and the Database of the scheduler and passes the info to the Database. Additionally, it can manage different schemas depending on the required schedule.

The technology behind the API is Java with Spring Boot, Spring Data Rest and Hibernate ORM. The communication between the components of the API is achieved with REST calls using JSON objects.

The input values are retrieved from a MySQL database by means of an Object Relational Mapping framework. This framework is used to match the values coming from the database to simple Entity classes (POJOs) inside the web application. The translation of these objects to the input XML format is achieved by using the JAXB library which provides the necessary mechanism to convert the Java objects into Extensible Markup Language (XML). The results are also in an XML format and contain a sequence of tasks assigned to specific resources. The high-level architecture of the implemented system is presented in Figure 3.

The implemented system supports the generation of a schedule in the case where specialized maintenance team is required and not. The classification is based on the user type authentication. For the implemented system the roles considered are a maintenance facility user and a factory user.

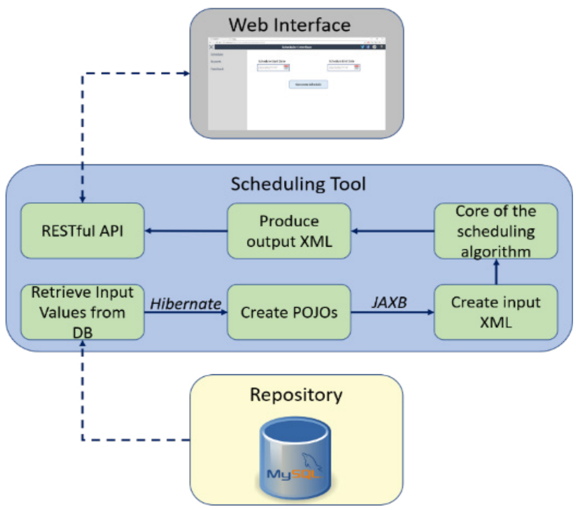

Fig. 3. High level system architecture

4 Case Study

In this section, two pilot case scenarios based on the two identified user types are described. The first, coming from the automotive industry, concern a case, where specialized maintenance personnel are required from the robot provider. In the second case, which is related to the steel parts production industry and focuses on monitoring a rolling mill machine, the maintenance activities can be carried out by the factory maintenance personnel.

4.1 Scheduling from the maintenance provider perspective

Regarding the automotive industry use case, after the identification of the maintenance need, the scheduling problem consists of identifying time slots for the maintenance activities to take place based on the following:

- existing production schedule of the customer and
- the maintenance team's availability,

under the constraint of the time horizon elapsed for the breakdown of the equipment and that the production schedule of the customer will remain intact.

The process begins with the maintenance provider which can also be the equipment provider, analyzing the machine data towards evaluating its condition. The condition of the equipment is evaluated in terms of Remaining Useful Life (RUL) of the equipment. The RUL result, indicating a potential failure within a specific period, is communicated to the customer. The customer/factory provides the availability based on the current production orders and planning for the maintenance provider to find a suitable timeslot for the suitable maintenance teams to provide support to the customer/factory. Thus, both sides combine their time and cost restrictions and the supplier communicates with the factory to provide the results of the whole procedure. The automotive industry use case includes two different resources; (1) the maintenance engineer and (2) the maintenance operator and 3 tasks corresponding to a maintenance activity to a robot. The maintenance engineer is further in charge of three other clients and must prioritize the work to be done in terms of time and cost. Also, the maintenance operator is changing shifts in case something urgent comes up. In this case, some time is needed for the replacement to take place. This scenario is applied to a workstation coming from the automotive industry operated by two robots with the purpose of assembling a hydraulic pump (Table 1).

Table 1. Task list of robotic use case

Resources	Job	Tasks
Racer Robot 7.1.4	Assembly of the hydraulic pump	Pick & Place
Racer Robot 7.1.4		Screwing
Maintenance Engineer	Maintenance of Belt Gates	Visual Inspection
Maintenance Operator		Check belts frequency after a run-in
		Replacement of part if needed

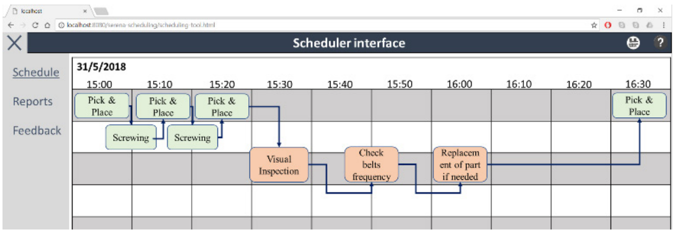

Fig. 4. Gantt chart visualisation for the first use case

This information is provided as inputs to the scheduling component which after evaluating the different criteria, generates the assignments to the resources. The results are visualized in a Gantt chart (Fig. 4). The orange blocks represent maintenance tasks while the green production activities.

4.2 Scheduling for the maintenance consumer

Concerning the steel parts production, the scheduling tool is focused on the factory side and the maintenance is assumed to be carried out by the shop floor personnel. In this case as well, the metric for the condition evaluation of the equipment is the RUL, which is received as input. The factory already has a maintenance plan with all the required information. Additionally, the schedule generation in this case includes the re-scheduling of the entire production and not just the fitting of maintenance tasks to the production plan, like the previous case.

In this scenario there are 11 resources considered. Each of them responsible for a specific task in the production line. The job to be carried out is the forming of the trailing arms. During this case a maintenance job is required in the rolling mill machine, including some actions to be taken (Table 2).

The generated schedule maintenance aware production schedule is presented in Fig. 5, where the grey blocks concern production tasks while the orange is for maintenance activities.

Table 2. Steel parts production case - Resources

Resources	Job	Tasks
Heating Machine	Forming of the Trailing Arms	Heating
Rolling Mill		Rolling
Stamping Press Machine		Eye-rolling
200t Press Machine		Forming
Stamping Press Machine		Hardening
6 Robots		Pick & Place
Rolling Mill	Maintenance of Gap Control Cylinders	Visual Inspection
		In-line shape measurement
		Monitoring of machine alignment
		Replacement of part if needed

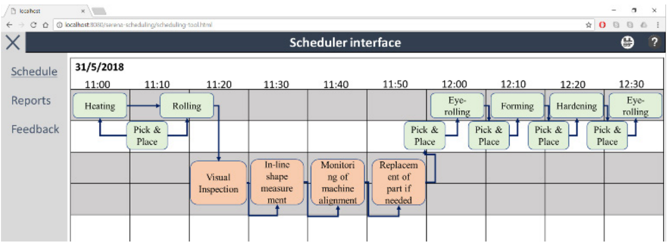

Fig. 5. Gantt chart visualisation for the second use case

5 Conclusions

The present approach and the discussed technologies show potential for versatile scheduling of maintenance operations. A software system has been implemented to test and validate the proposed approach in two different use cases, requiring connection to different components and with different inputs and requirements.

It should be noted that in the first case the maintenance activities were placed by the scheduler on a non-interrupting for the production timeslot leaving the initial production schedule as is, while in the second case the scheduler adapted the entire production schedule. This makes the scheduling approach and technologies used suitable for different users and environments. Moreover, the scheduling approach followed can reduce maintenance costs by appropriate maintenance planning and scheduling from the perspective of the end use and maintenance provider through the better utilization of their maintenance resources.

Future work should aim at utilizing the user's feedback and the correlation of the acquired data with meaningful information for the scheduler per case. This is foreseen to require additional implementations and extension of the presented data model to support context generation.

Foreseen challenges concern the evaluation of the effectiveness of the proposed approach for versatile environments and users, the integration of additional criteria as well as bringing the software component to a maturity level enabling their deployment and testing in normal working conditions.

Acknowledgements

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