# Cyber Physical System Based Proactive Collaborative Maintenance

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***Abstract*—The aim of the MANTIS project is to provide a proactive maintenance service platform architecture based on Cyber Physical Systems. The platform will allow estimating future performance, predicting and preventing imminent failures and scheduling proactive maintenance. Maintenance is an important element that creates added value in the business processes and it also creates new business models with a stronger service orientation. Physical systems and the environment they work in are continuously monitored by a range of intelligent sensors, resulting in massive amounts of data, which characterise the usage history, working condition, location, movement and other physical properties of the systems. These systems are part of a larger network of heterogeneous and collaborative systems (e.g. vehicle fleets) connected via robust communication mechanisms able to operate in challenging environments. MANTIS consists of distributed processing chains that efficiently transform raw data into knowledge, while minimising the need for bandwidth. Sophisticated distributed sensing and decision-making functions are performed at different levels collaboratively, ranging from local nodes to locally optimise performance, bandwidth and maintenance; to cloud-based platforms that integrate information from diverse systems and execute distributed processing and analytics algorithms for global decision-making.**

*Keywords*—*cyber physical systems; collaborative maintenance ecosystems; proactive maintenance; MANTIS*

## I. INTRODUCTION

The British Standards Institute (BSI) defines maintenance as a combination of all the technical and associated administrative activities required to keep equipment, installations and other physical assets in the desired operating condition or to restore them to this condition [1]. Meanwhile, the Maintenance Engineering Society of Australia (MESA) indicates that maintenance tends to achieve the required asset capabilities within an economic or business context [2]. Maintenance also includes the engineering decisions and associated actions that are necessary for the optimisation of specified equipment capability, i.e., the ability to perform a specified function within a range of performance levels that may relate to capacity, rate, quality, safety and responsiveness [3]. Similarly, [4] states that the objective of maintenance is in achieving the agreed output level and operating pattern at a minimum resource cost within the constraints of the system condition and safety. The desired production output is achieved through high availability, which is influenced by the equipment reliability and maintainability, and the maintenance supportability [5]. Finally, part of maintenance's responsibility is also in the technical systems' safety and in ensuring of good condition of the plant [6], [7].

### A. Maintenance trends

Predictive maintenance, also known as *online monitoring*, *condition-based maintenance*, or *risk-based maintenance*, has a long history. From the initial visual inspection, as the oldest method however still one of the most powerful and widely used, predictive maintenance evolved to automated methods, where advanced signal processing techniques, based on pattern recognition, neural networks, fuzzy logic, and data-driven empirical and physical modeling, are used [8].

Despite advances in predictive maintenance technologies, time-based and hands-on equipment maintenance is remains the norm in many industrial processes. Nowadays, nearly 30 % of industrial equipment does not benefit from predictive maintenance technologies. The annual calibration of equipment mandated by quality assurance procedures and/or regulatory regulations is a typical example of these time-based methods.

Time-based failure models provide no precision prediction regarding when end-of-life occurs. The length of an equipment's stable period is never accurately known and varies for different types of equipment and different conditions in which that equipment is used. For an industrial component (i.e., a process sensor, a shaft in a motor, or tubes in a heat exchanger) maintenance and replacement schedules are not easy to establish. Following the bath tub curve, some plants replace equipment periodically (e.g., every 5-10 years) to avoid reaching the end-of-life. However, when a piece of equipment is replaced prematurely, the failure rate can actually increase because the new equipment may experience infant mortality (when equipment is new). Because of the unreliability of time-based maintenance methods, industrial processes should be online monitored throughout the whoe life of equipment to identify the onset of degradation and failure of equipment.

As some quipment begins to fail, it may poses signs that can be detected if proper sensors are placed to identify the onset of equipment degradations and failures. Integrating these sensors with the predictive maintenance techniques can avoid unnecessary equipment replacement, save costs, and can consequently improve process safety, availability, and efficiency.

It is easy to understand that the more sophisticated the maintenance strategy is the higher demands are given to IT systems as a lot of the improvements are based on information. At the lowest strategy level companies might have some basic Computerised Maintenance Management System (CMMS) that can handle issues like component, machine and workforce registry together with the capability of work order management. The next step is the use of history data which can enable some preventive actions. The basic CMMS usually do not have any means for condition monitoring which is needed for predictive maintenance. The optimal use of proactive maintenance gives especially demands for the integration of various IT systems such as CAD, ERP, CMMS and condition monitoring. In addition to integration demands high demands are given to the methodology that is used prognosing the maintenance needs. A term that is used for defining this integration of data is e-Maintenance [9]. By definition e-Maintenance is understood as the technology that provides the maintenance organisation to have the necessary information whereever it is needed. Typically this means that maintenance personnel are supported with mobile technology such as Personal Digital Assistant (PDA) for handling work orders measurements etc. E-Maintenance is by definition often considered as the IT step towards proactive maintenance.

## II. THE MANTIS PROJECT

The MANTIS project (http://www.mantis-project.eu/) received funding from the ECSEL Joint Undertaking. The project's overall concept is to provide a proactive maintenance service platform architecture based on Cyber Physical Systems that estimates future performance, predicts and prevents imminent failures and schedules proactive maintenance. Nowadays, maintenance is not just a costly necessity, but an important function that creates added value in the business processes as well as it creates new business models with a stronger service orientation.

Physical systems (like industrial machines, vehicles, renewable energy assets, health equipment) and the environment they are working in, are continuously monitored by a versatile range of intelligent sensors. This results in large amounts of data that characterise the usage history, operational condition, location, movement and other physical properties of the systems. Such systems form part of a larger network of heterogeneous and collaborative systems (like production assets or vehicle fleets) connected via robust communication mechanisms that are able to operate in challenging environments.

Sophisticated distributed sensing and decision-making functions are performed at different levels in a collaborative way. Functions range from *local nodes* that pre-process raw sensor data and extract relevant information before transmitting it, thereby reducing bandwidth requirements of communication, to *cloud-based platforms* that integrate information from ERP, CRM and CMMS systems and execute distributed processing and analytics algorithms for global decision-making.

The MANTIS research results will contribute to companies assets availability, competitiveness, growth and sustainability. The resulting platform will be obtained by partners from 12 countries while working on 11 use cases dealing with maintenance of production assets, vehicle fleets, energy production and health equipment.

### *A. Approach*

For an optimum maintenance of assets, different systems and stakeholders have to share information, resources and responsibilities, i.e., collaboration is required. Such a Collaborative Maintenance Ecosystem is able to:

- Reduce the adverse impact of maintenance on productivity and costs.
- Increase the availability of assets.
- Reduce time required for maintenance tasks.
- Improve the quality of the maintenance service and products.
- Improve labor working conditions and maintenance performance.
- Increase sustainability by preventing material loss (due to out-of-tolerance production).

Focus is on a *proactive maintenance* service platform architecture enabling service-based business models and improved asset availability at lower costs through continuous process and equipment monitoring and data analysis. The MANTIS also aims to identify and integrate critical information from other sources such as production, maintenance, equipment manufacturers and service providers. This service platform architecture will take into account needs of industries in the forefront of service-based business and operations as well as less mature ones so improvements in maintenance can be achieved gradually and consistently.

### *B. Objectives*

The proactive maintenance service platform will consist of distributed processing chains. These chains will efficiently transform raw data into knowledge while also minimising the need for transfer bandwidth. To achieve this overall objective a smart integrated domain knowledge system is needed with advanced data monitoring, communication and analytics with self-learning capabilities, and security. Thus, this chain includes key technologies (see Figure 1) such as:

- Smart sensors, actuators and cyber physical systems capable of local pre-processing.
- Robust communication systems for harsh environments.
- Distributed machine learning for data validation and decision-making.
- Cloud-based processing, analytics and data availability.
- HMI to provide the right information to the right people at the right time in the right format.

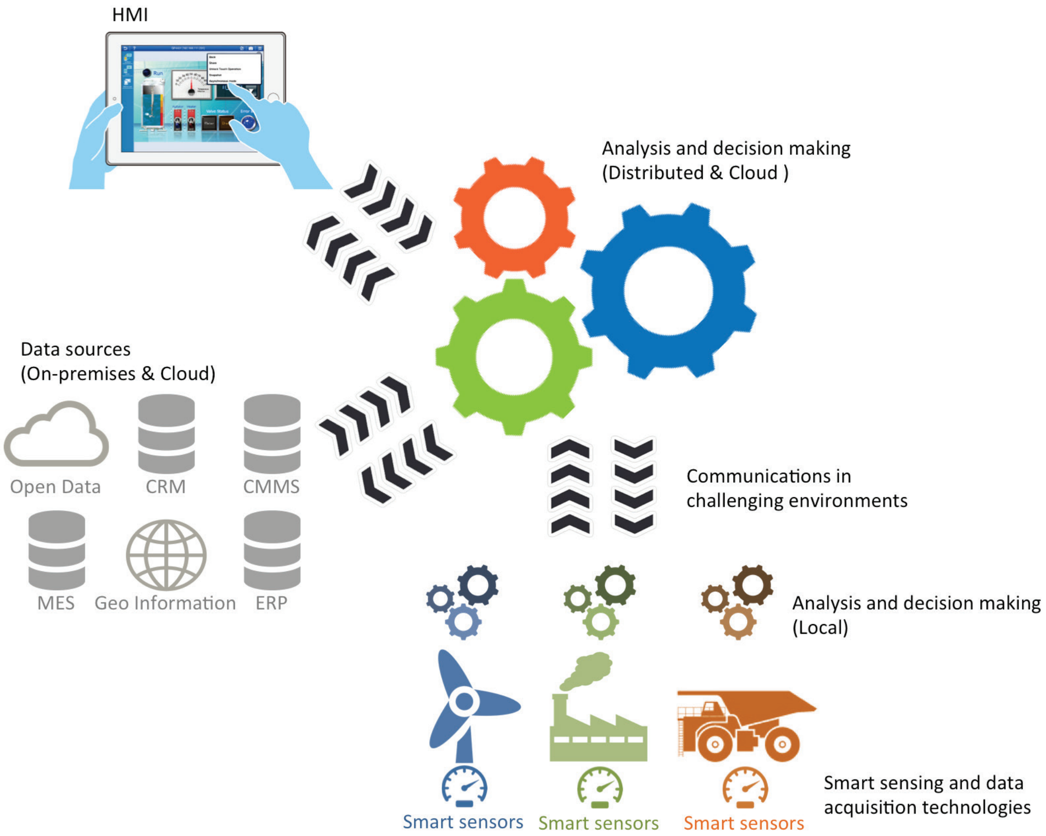

Fig. 1. Overall concept of the MANTIS. **Smart sensors** for data acquisition; **local and distributed** data processing; usage of **different data sources**; dealing with **communication in challenging environments**; **presenting the right information** to the right people at the right time and format.

## III. CONCEPTS

As the main objective of the MANTIS project is to *develop a Cyber Physical System based Proactive Maintenance Service Platform Architecture enabling Collaborative Maintenance Ecosystems*, some relevant concepts are considered.

A **collaborative** process is a process in which involved entities share information, resources and responsibilities, risks and rewards to jointly plan, implement, and evaluate a program of activities to achieve a common goal [10]. Collaboration involves mutual engagement of all participants to solve a given problem together. Coordination, as one of the main components of collaboration, is the way of harmoniously leading and working together.

In MANTIS, the common goal is the maintenance optimisation of assets, where different systems and stakeholders that take part in a maintenance have to share information, resources and responsibilities. From the process automation point of view, a key aspect of collaborative automation includes a single, unified environment to present any information to the operator. From the general point of view the importance is in the ability to present the right information to the right people at the right time. This implies that the Proactive Maintenance Service Platform Architecture of the MANTIS requires collecting data from all equipment regardless of type or age, storing and organising collected data over time, advanced analytics and decision support systems. Thus, the MANTIS pursues a collaborative maintenance ecosystem.

Predictive maintenance systems are characterised by monitoring for the purpose of detecting wear and malfunction before failure downtime and their costly repairs. This means, to identify without manual inspection when parts need to be replaced and may involve adapting usage to ensure operation until next service opportunity. This includes making sure that the needed spare parts are manufactured and delivered to be available at the intended maintenance occasions, preferably just in-time. One of the major challenges is related to the huge amount of data that to large extent contains imprecise information.

**Proactive Maintenance** commissions corrective actions aimed at sources of failure [11]. Its main purpose is in extending the life of mechanical machinery, as opposed to i) making repairs when there are no broken parts, ii) characterising failures as routine and normal, and iii) pre-empting crisis failure maintenance - these are all characteristics of the predictive/preventive disciplines.

Connecting and combining intelligent machines, advanced analytics and people at work offers new opportunities. In traditional statistical approaches historical data gathering techniques use more separation between data, analysis, and decision making. While nowadays system monitoring has advanced and information technology costs have fallen, the ability to work with massive volumes of real-time data has expanded. Therefore, high frequency real-time data brings totally new insight onto system operation and maintenance. Machine-based analytics offers better insight into the analytic process. The combination of physics-based approaches, deep sector-specific domain expertise, higher automation of information flows, and predictive capabilities can merge with the existing suite of big-data tools. As a result, Proactive Maintenance is able to encompass traditional approaches with newer hybrid approaches to leverage the power of both historic and real-time data with industry specific advanced analytics [12].

Thus, maintenance management can nowadays take advantage of many information sources for faster and more accurate prognosis as shown in Figure 1. Data can be extracted and stored from machines and components. Machine based data analysis may be used locally to optimise the machine's maintenance. Anyhow, better results may be expected if these particular data is combined with other data sources such as that from the MES, ERP, cloud based open data or workers. Big data analytics may be required if the amount of data is big enough. Finally, the information extracted from all this data must reach the right people and machines at the right time and format. This concept may be applied to different domains like manufacturing, vehicle, energy production, or health maintenance.

## IV. EXAMPLES OF MAINTAINED SYSTEMS

### A. Manufacturing assets

Machine tools, as a part of the manufacturing process, are composed of many subsystems (e.g., structures, electrical drive systems, controllers and actuators), which are involved during execution of the desired machining operations. The mechanical structure of the machine tool is usually designed to be extremely rigid to cope with the forces created during the machining operation. Multitask machine tools are designed to perform several machining operations (e.g., turning, milling, drilling) within the same setup. This brings more degrees of freedom than dedicated machine tools. However, the additional degrees of freedom comes with a price - i.e., regidity decrease. Multitask machine tools are therefore not used for their rigidity. Their main purpose is ability of handling large and geometrically advanced components, as well as flexibility of manufacturing in a single setup (without the need of refixturing the component).

Proactive monitoring of critical machine tool components and machining processes presents a key factor for increasing the availability of the machine tool and achieving a more robust machining process. Failures during the machining process and on the machine tool components can surely have negative effects on the final produced part. Instabilities in machining processes also shortens the life-time of the cutting edges and machine tool. The proactive monitoring system may utilise information from several sources to facilitate the detection of such instabilities in the machining process. Additional complexity to the machining system can be avoided by the use of internal sensors [13].

### B. Vehicles

Modern trucks, buses and other heavy vehicles, such as wheel loaders and dumpers, are monitored with respect to many different parameters (e.g., oil pressure, different temperatures, turbo or compressor status, and more). Results from the on-board diagnostic software are often presented in the cluster as a fault code. At the workshop the fault codes can then be further decoded to more precise information of the fault. There are different types of diagnostic algorithms and one thing in common is that there must be some kind of reference model, to compare with the real behaviour. Traditionally the reference model is derived before the start of production; if there is any kind of change or update of the vehicle then the diagnostic functions must be updated to the new configuration and characteristics.

### C. Energy production

Offshore maintenance of wind turbines differs from land-based maintenance due to accessibility and environmental conditions. As in the extreme case of exposure to corrosion and sea-water flow, it has been demonstrated that fatigue life may be reduced by more than 70 % [14]. Accessibility to perform maintenance is also reduced due to weather conditions, and it has been demonstrated [15] that an offshore maintenance example project had about four times longer expected mean duration compared to the same maintenance performed in perfect weather conditions. The accessibility and environmental conditions create an even higher demand for efficient maintenance strategies and technology to reduce costs compared to onshore maintenance. Up to now maintenance of e.g. electrical components, gearboxes and blades are typically performed mainly by a corrective maintenance strategy combined with condition-based maintenance for some components where condition information can be obtained.

The majority of (non-residential) photovoltaic (PV) plants are monitored. Electrical parameters, such as PV array currents and voltages, are measured by the inverter at least every 15 minutes. At many plants also environmental parameters, such as irradiation and temperatures, are recorded. In contrast to measurements obtained during momentary on-site investigations, these data contain longer term information on the evolution since installation and the dependency on constantly changing environmental conditions.

### D. Health equipment

Healthcare equipment is typically maintained using reactive and periodic planned maintenance. Most of the analytics and diagnosis of a problem is done locally. A large variety of product types and configurations in combination with low production numbers, different user types with different usage profiles makes it even harder to capture additional diagnostic information. Although it is possible to connect the systems to some remote service network, a lot of systems are not

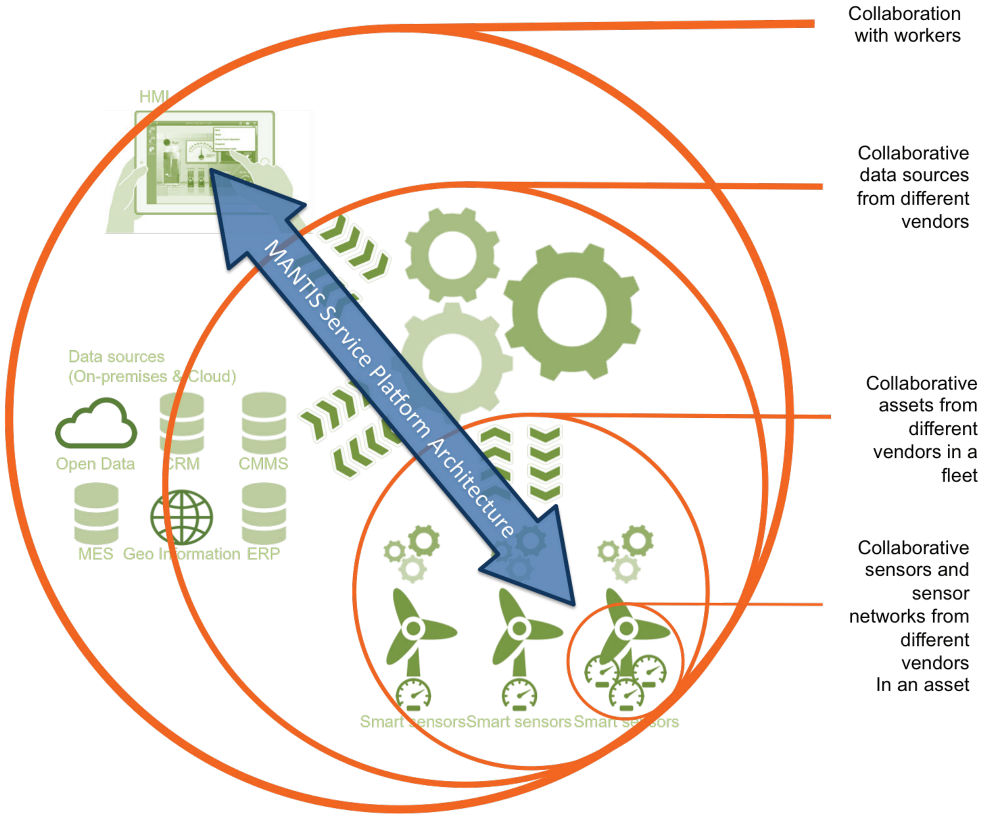

Fig. 2. MANTIS collaborative maintenance: on the levels of sensor data, different vendors and workers.

connected or are not allowed to send logging information on a regular basis due to confidential patient information, hospital IT regulations, country legislation, etc.

## V. MANTIS PLATFORM ARCHITECTURE

The Cyber Physical System based Proactive Maintenance Service Platform Architecture proposed in the MANTIS will provide a practical means for accomplishing Collaborative Maintenance including interoperability and integrability of services. Collaboration must take place at different levels as reflected in Figure 2.

Besides acceleration, temperature, humidity and distance, **sensors** can also measure pressure, sound, brightness and material properties in the surrounding atmosphere (e.g. air quality or radiation). This information can already be intelligently processed in sensors and shared with others in a sensor network. Smart sensors record many surrounding factors and help interpret events and contexts better. Due to the miniaturisation and flexibility of technology, sensors can be even designed for integration into almost all surfaces and objects, which however is not always a trivial task. Sensors must be robust and built in such way to withstand rigours of industrial environments. Information from sensors helps to predict asset failures and also to determine failures' root causes. Interdisciplinary skills are necessary to know which feature must be monitored, where and how in order to understand the physical phenomena behind the asset failure. On the other hand, sensors must be designed to interoperate in a wider and more complex information systems.

There is an increasing interest on wireless **communications** for industrial applications in the market. The main reason for this is that wireless communications between the devices would provide more flexibility concerning physical distribution and it would reduce costs derived from the establishment and maintenance of wiring. However, the large and numerous metallic machines and the electromagnetic fields inducted by high electrical currents, make industrial wireless channels specially hostile environments. For this reason robustness and reliability are two of the main requirements for industrial wireless communications.

**Data** often needs to be processed in (near) real-time, as results are needed as soon as the data arrives, or computations need to be performed on a continuous unbounded stream of data. Another challenge is the diversity of data, e.g. data originates from thousands of connected devices from different manufacturers, models and versions and through different protocols, can be discrete (e.g. log events) or continuous (e.g. sensor readings), is logged at different time intervals (e.g. every hour) with varying temporal granularity (e.g. production is reported over several-minute time intervals) and with different scales and formats (e.g. time zones), missing values occur for unknown reasons, etc. Data sources are very heterogeneous. An optimal way to analyse and derive predictions from such data is to use data fusion and advanced signal-processing methods instead of simple procedural algorithms. Data fusion and pattern analysis algorithms suitable for decision support systems need to be investigated and developed. Algorithms need to be tailored to provide specific solutions at different levels of data processing (see Figure 3):

- At low level: sensor data fusion (feature fusion, decision fusion), eliminating noise and erroneous data; includes stochastic methods, Kalman filter, fuzzy logic, logical links, rule-based methods. This will also reduce bandwidth requirements.
- At high level: data-mining (classification, cluster analysis, associations and regression analyses), intelligent assessment of data; includes recognition of outliers, k-means-algorithms, machine learning.

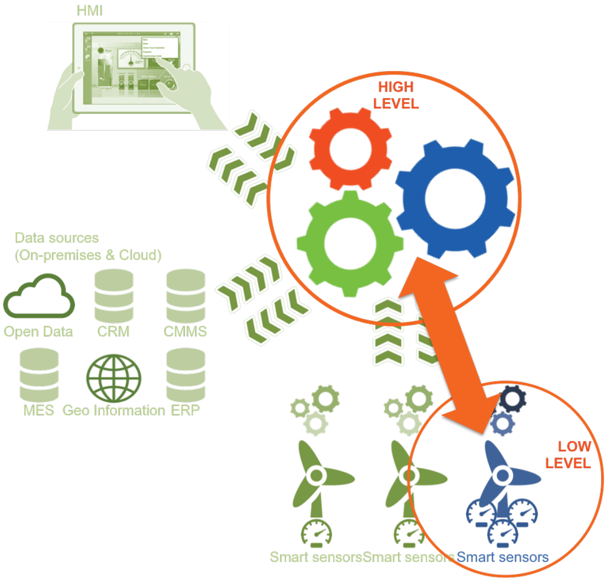

Fig. 3. Data processing levels in MANTIS: low level sensor data fusion, noise and erroneous data elimination; high level data-mining and intelligent data assesment.

A special characteristic in the use of data fusion in this project is the real-time implementation of a *local processing module* (local to a machine or a production line), to reduce the data load in further communication towards the cloud (from data based to feature based processing).

While **HMI** issues are being extensively studied and different approaches and solutions published in numerous papers and technical reports, usability aspects are becoming increasingly important. In this context, a common criterion associated with performance is the quality of service, which can be studied from the system point and from the user point of view. The evaluation approaches of these services are quite divergent, yet we have to follow the best practice in individual aspects such as input performance, interpretation performance, context appropriateness (at the system site) and perceptual effort, cognitive workload, and physical effort on user site.

## VI. CONCLUSION

The MANTIS project started in mid 2015 with duration of three years. After one year of execution, the MANTIS service platform architecture requirement definition, as well as a precise use case descriptions have been elaborated.

In the first year the first draft of the MANTIS Architecture Reference Model was generated, which is provided as a generalized architecture, which can be mapped to different domains, thus ensuring interoperability with legacy, current custom and commercial off-the-shelf, as well as future systems.

The nature of the MANTIS platform is a hyper-platform that allows connecting smaller ecosystems on different platforms into a larger one.

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