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Towards an Open Standards-based Architecture for Condition-based Predictive Maintenance and IIoT

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Abstract. In today's swiftly emerging Industry 4.0 environment, sensors/devices, machines and components have digital twins which are connected together enabling them to talk to each other. Factory operators can thus continuously capture machine states/condition and combine it with information from other systems, analyze it and predict the optimal point in time at which to initiate maintenance. This approach for maintenance generally called Condition-based Predictive Maintenance (CBPdM) can pinpoint imminent outages well before they occur, significantly enriching business performance by avoiding lengthy production outages.

CBPdM is among the major focus points of the Industry 4.0 and IIoT. Interoperability of the asset management systems is crucial in achieving accurate diagnosis and prognosis as it can highly augment the data received from assets. The foundation of an interoperability architecture are standards. Unfortunately, even after wider adoption of CBPdM in industry, to the best of our knowledge there does not exist any reference architecture for it. This paper contributes by introducing Open Industrial Interoperability Ecosystem (OIIE) architecture which is an outgrowth of several related industry standardization activities for achieving standards-based interoperability. We illustrate how the architecture addresses the requirements of Industry 4.0 and CBPdM with the help of a detailed use case.

Keywords: Condition-based predictive maintenance, CBPdM, Maintenance 4.0, Industrie 4.0, IIoT, OIIE, OSA-CBM, OSA-EAI

1. Introduction

Industry 4.0 introduces the concept of "smart industry" in which cyber-physical systems observe the physical processes of the industrial plant and make decentralized decisions. There is an increasing demand from industry to maintain high levels of efficiency in production while continuously giving feedback on equipment performance. The IIoT connects machines and sensors and these linked resources send rich data which can be used to improve collaboration between performance, operations, and asset maintenance [1]. Built on this connectivity, large amounts of data emanating from connected sensors are aggregated and analyzed to provide actionable insights and ability to generate automated decisions [2]. The real-time data access and derived intelligence is driven by the ongoing, recurring flow of information and actions between the physical and digital worlds also known as the "physical-to-digital-to-physical loop" [3]. Data from physical assets is digitalized and analyzed to generate insights which result in real-world physical actions. This loop allows harnessing of data and a proactive approach to determine future maintenance needs and their urgency.

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Maintenance is one of the most prominent operations with major impact on business performance [4]. IIoT uses sensors and connected devices across the industry to make smart maintenance decisions based on real-time accurate data which detects even slight deviations from the benchmark key performance indicators (KPIs) [5]. A large number of companies are combining the capabilities of IIoT and Big Data to predict equipment malfunctions [6, 7]. The accuracy of forecast is further getting more precise with improved Artificial Intelligence (AI) techniques and machine learning tools.

To achieve these smarter maintenance systems, the data received from IIoT devices cannot be simply stored in a data lake and analyzed independently of other information that may impact the results. Rather, the data must be linked to and processed within its wider context. Configuration of the entire system, particularly the management of change, becomes critical for ensuring data is being processed in the correct context [8].

For example, the measurement values from a sensor may be subject to drift over time, so it becomes important for analytics systems to know when the device was last calibrated to allow them to compensate, such as to identify and adjust for a false alarm state. This is not the only relevant contextual information, other information includes (but is not limited to): which device made the measurement, what version of the software/firmware was installed, where the measurement was taken (both physical and logical location), how the measurement was processed (e.g., for virtual sensors), when the device was last calibrated, and what are the (expected) properties of the sensor/device/asset. No single system of an enterprise typically tracks all of this information, instead it is scattered between different systems of record. To utilize this data effectively it needs to be shared between systems, systems of systems, and enterprises, which can only be done by achieving interoperability across systems at different levels.

The ideal way to achieve this kind of interoperability is through the use of (open) standards. This is made difficult, however, due to the number of standards for (or applicable to) industrial interoperability in existence (each with a different focus), the adoption of different standards in areas of industry, the evolution of standards to fulfill the requirements of their userbases, the inconsistencies of overlaps and gaps left when combining standards, and a lack of agreement between users of different standards.

In this paper we introduce the OIIE (Open Industrial Interoperability Ecosystem) Architecture that ties these different standards together in a coherent fashion to support interoperability between systems, systems of systems, and enterprises. Different standards are incorporated and applied where and when they are appropriate based on requirements and adoption by industry (or industry segment). We show how the architecture fulfills the requirements and principles of Industry 4.0 (as described by [9]). We then illustrate how this architecture can be used to support CBPdM through an OIIE use-case that will be validated in the upcoming OGI Pilot (Oil & Gas Interoperability Pilot), which has gone through several iterations developing and validating use-cases to address key industry requirements. The CBM (applicable generally, not just CBPdM) use case describes data exchanges[1] across the CBM process: from acquiring sensor data, to identifying alarm states and events, performing health assessments, diagnostics/prognostics, generating advisories for maintenance actions, and the performance of said maintenance while maintaining consistency of the contextual information in which the sensor data is created (i.e., configuration updates).

2. Asset Maintenance Strategies

Multiple maintenance strategies are currently in place to keep the equipment running at peak efficiency, ranging from reactive to pro-active strategies. The simplest one is failure-driven maintenance which is a reactive and unplanned maintenance approach and is carried out only after the occurrence of a malfunction, or breakdown of equipment [10]. Run-to-failure maintenance is suitable if the total cost of repairing equipment after breakdown is less than the cost of performing other types of maintenance on the equipment beforehand, but is unsuitable where equipment failure results in significant production loss. Time-based maintenance (a.k.a. periodic preventive maintenance) is a planned maintenance that is regularly performed while the equipment is still working to lessen the likelihood

[1]The OIIE focuses on getting data to where it needs to be, not the processing that takes place within the interconnected systems. This allows vendors to implement their own functionality while allowing them to participate in the ecosystem and allows end-users to choose their desired components from different vendors (and possibly internal implementations) while ensuring interoperability between their choices.

of it failing or breaking down unexpectedly [11]. It is based on either mean time between functional failures (MTBF) or machine usage because in most cases similar machines exhibit predictable failure rates when averaged over a long time.

Instead of running a part until failure (failure-driven maintenance), or replacing a good part which may have life left (time-based maintenance), *Condition-based Predictive Maintenance* (CBPdM) performs repairs only when needed or just before. Benefits associated with CBPdM are: less equipment downtime, fewer urgent work-order requests, lower maintenance costs, enhanced asset performance, considerably improved asset reliability, overall enrichment of the business performance and better budget planning. A detailed comparison of CBPdM with time-based maintenance and its benefits over the latter based on practical factors is provided in [12]. Limitations of time-based maintenance methods of equipment and the advantages of predictive maintenance techniques in anticipating the onset of equipment failure is discussed in [13]. An overview of the preventive and condition-based maintenance techniques with emphasis on how these techniques achieve maintenance decision making is provided in [14]. The authors concluded that CBPdM is more realistic based on the fact that 99% of equipment failures are preceded by indications about occurrence of failure.

The most advanced form of maintenance is prescriptive maintenance which builds on CBPdM as it provides further guidance on how to carry out the maintenance task in addition to telling what to do [15]. Prescriptive maintenance strategies extensively use advanced data processing and visualization techniques such as graph analysis, simulations, neural networks, complex event processing, heuristics and machine learning [16]. These tools provide the capability to calculate the timing and effect of failure, thus, determining the priority and urgency of the maintenance activity. In addition, these techniques are supplemented by prescription of guidance for the repair activity. For example, providing a pre-defined Solution Package[2], or a pre-planned work order along with the request for work to be sent to the Maintenance Management System (MMS). Both CBPdM and prescriptive maintenance are based on the use of IIoT concepts. Prescriptive maintenance is relatively new and less adopted by the industry due to its inherent complexity [17]. Prescriptive maintenance is the future of maintenance strategies, but currently CBPdM is gaining wider acceptance in the industry. In this paper, we are focusing on the CBPdM, although achieving prescriptive maintenance using OIIE architecture is our long term goal.

According to The U.S. Department of Energy, implementing predictive maintenance results in the reducing the maintenance costs by 30%, the elimination of breakdowns by 70% and the reduction in downtime by 40% for Oil & Gas companies [18]. Oil & Gas companies particularly benefit from applying predictive maintenance solutions. Physical inspection of oil & gas production equipment requires personnel to go into hazardous environment to examine the equipment, which in some cases is not feasible. CBPdM allows oil & gas companies to identify potential failures and increase the production of highly critical assets [19]. It drastically improves technical support by catching errors that no humans can see and increases the safety of workers.

Recently, organizations have adopted CBPdM where maintenance is carried out according to the need indicated by the equipment condition, enabling maintenance managers to better predict a possible breakdown event based on current and historical data [20]. This proactive approach is more data-driven and analytical in nature as compared to the previous approaches. CBPdM is among the major focus points of the Industry 4.0 and IIoT initiatives [21] and is also popularly known as Maintenance 4.0 mainly because of its applicability to Industry 4.0 [22]. Maintenance 4.0 forms a subset of smart manufacturing systems which are autonomous in their operation, capable of predicting failures and triggering maintenance activities. These systems are comprised of smart equipment in form of embedded or cyber-physical systems forming the digital twin of physical assets.

Leveraging condition monitoring to achieve near zero defects, near zero down-time, and automated decision making requires the implementation of capability to generate world class diagnostics, prognostics, and advisories [23]. While diagnostics help identify the cause of failures or deviations from acceptable performance parameters, prognostics aim to predict potential issues and their cause before they occur to allow them to be resolved *before* they adversely affect the operations of the enterprise. Such analyses can be based on a combination of condition and operations data—e.g., using sensors measuring the condition of a piece of equipment as well as sensors moni-

[2]http://www.mimosa.org/oiie-use-case-7

toring the primary products. Specific parameters such as valve stiction and pump vibrations are monitored using sensors, whose data is collected over time to establish a trend [24]. CBPdM has the ability to generate maintenance work advisories/recommendations based on the analysis of measurements, events, and alarms from control systems and condition monitoring systems. To gain greater understanding about equipment failure, it is vital for near real-time decision support systems (such as Operational Risk Management systems) to properly interact with the transaction processing oriented business systems (such as EAM) based on data/information feeds from true real-time systems involved in monitoring and control to eventually generate maintenance work advisories for the Maintenance Management Systems [25]. This interaction must be facilitated by providing sustainable interoperability among these systems of systems.

Interoperability of the asset management systems is crucial in achieving accurate diagnosis and prognosis as it can highly augment the data received from assets [26]. There does not exist any coherent standards-based architecture for achieving interoperability among various components of an enterprise business system, supporting both intra- and inter-enterprise interoperability, required to achieve CBPdM. The OIIE-based architecture is at its core an interoperability solution that enables devices and systems to communicate effectively in both inter- and intra- enterprise contexts using a variety of standards, data models, and exchange protocols.

The industry is moving forward at a fast pace to reap the benefits of the Industry 4.0 revolution, but unfortunately standards bodies have not been able to keep up with this pace [27]. Standards form the basis for introducing new technologies and innovations, ensuring that the products, components and services supplied by different companies are mutually compatible. Open standards are publicly available standards which are easy to adopt and improve upon. Even after the wider adoption of CBPdM in industry, to the best of our knowledge there does not exist any standard framework for it. MIMOSA has a history of developing and publishing open systems architecture for condition-based maintenance (CBM) and enterprise application integration (EAI). The OIIE architecture for CBPdM is built upon these well-adopted open-standards and extends them to utilize the potential offered by IIoT and Industry 4.0.

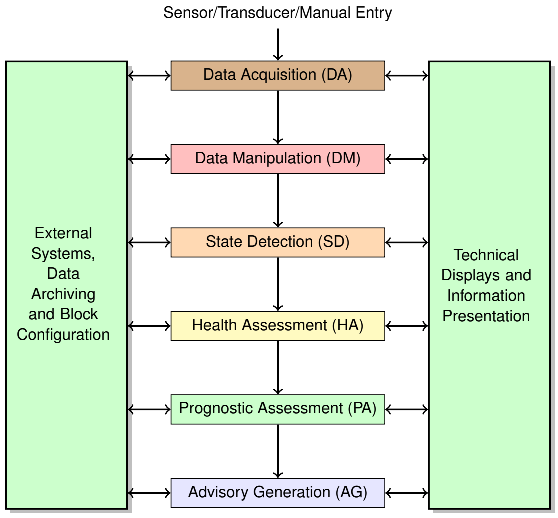

Fig. 1. Data processing block diagram [from ISO-13374-1]

3. International Standards for CBM

In this section, we discuss various standards related to CBM and how MIMOSA is coalescing with them. Table 1 lists various standards related to the CBM approach. Due to space constraints, we will only discuss the OSA-CBM and OSA-EAI standards and how they have either implemented open standards such as ISO-13374 or can complement open standards like IEEE-1451. The Open System Architecture for Condition-Based Maintenance (OSA-CBM) specification is an open standards based architecture which acts as a reference point for implementing condition-based maintenance systems. It was developed in 2001 by an industry led team partially funded by the US Navy through the DUST program [28]. The participants ranged from industrial, commercial, to military applications of CBM technology: Boeing, Caterpillar, Rockwell Automation, Rockwell Science Center, Newport News Shipbuilding, and Oceana Sensor Technologies. Applied Research Laboratory of Penn State University and MIMOSA were the other prominent contributors. It is now managed by the MIMOSA[3] standards body and its version 3.1 was publicly released on August 1, 2006.

OSA-CBM is a robust non-proprietary standard which added details of data structures and interface methods for implementing the six blocks of functionality in a condition monitoring system defined by the ISO-13374 standard (Condition Monitory and Diag-

[3]http://www.mimosa.org/

Table 1

International standards related to CBM

Standards	Description
IEEE 1451	Smart transducer interface for sensors and actuators
IEEE 1232	Artificial Intelligence Exchange and Service Tie to All Test Environment
ISO 13372	Condition monitoring and diagnostics of machines - Vocabulary
ISO 13373-1	Condition monitoring and diagnostics of machines - Vibration condition monitoring - Part 1. General procedures
ISO 13373-2	Condition monitoring and diagnostics of machines - Vibration condition monitoring - Part 2. Processing, analysis and presentation of vibration data
ISO 13374	MIMOSA OSA-CBM formats and methods for communicating, presenting and displaying relevant information and data
ISO 13380	Condition monitoring and diagnostics of machines - General guidelines on using performance parameters
ISO 13381-1	Condition monitoring and diagnostics of machines - Prognostics, general guidelines
ISO 14224	Petroleum, petrochemical and natural gas industries - collection and exchange of reliability and maintenance data for equipment
ISO 17359	Condition monitoring and diagnostics of machines - General guidelines
ISO 18435	MIMOSA OSA-EAI diagnostic and maintenance applications integration
ISO 55000	Asset management

nostics of Machines) as shown in Figure 1. OSA-CBM has become the de-facto standard for CBM, encompassing the complete range of functions from data collection through to the recommendation of specific maintenance actions. U.S. Army and Navy have evaluated the OSA-CBM architecture as a part of their global maintenance infrastructure [29, 30]. According to [31], MIMOSA OSA-CBM is the most evolved CBM related standard.

OSA-CBM can be complemented when used in conjunction with the IEEE 1451 smart transducer interface standard which is an open standard for distributed measurement and control. IEEE 1451 handles the integration of network sensors, while OSA-CBM handles the integration of software components responsible for condition monitoring [32]. Researchers have implemented a distributed embedded condition monitoring systems based on OSA-CBM standard, which offers reusable software for a class of condition monitoring applications [33]. Their open software framework was developed using Java and RMI middle-ware, whose application is validated on a distributed gearbox condition monitoring system.

The Open Systems Architecture for Enterprise Application Integration (OSA-EAI)[4] is another standard developed and managed by MIMOSA which defines data structures for storing and progressing information about all characteristics of equipment into enterprise applications. It focuses on information integration of asset life-cycle management (ALM) applications using a common standardized maintenance database, which is one level above the condition monitoring (CM) systems. OSA-CBM data can be directly mapped into any OSA-EAI-compliant relational database maintenance systems with ease, allowing better integration of CM and ALM systems. Examples of OSA-EAI compliant commercial off-the-shelf (COTS) software are Emerson Process Management RBMWare, Rockwell Emonitor Odyssey and IBM Maximo Oil and Gas.

OpenO&M[5] is another MIMOSA led initiative for collaborating multiple industry standards organization to harmonise the standards used for application integration in operations and maintenance. Multiple industry-focused JWGs exists under this initiative. Until now, the OpenO&M technical committee has produced two specifications for connecting information systems in the manufacturing domain, the OpenO&M Information Service Bus Model (ISBM) and Common Interoperability Registry (CIR) which are explained in Section 5.

The work in [34] describes design and implementation of a system which integrates enterprise asset management systems (using MIMOSA OSA-EAI and OpenO&M CIR specifications) and condition monitoring systems (using OPC UA). OPC UA data sources interfaced with OSA-EAI web services, while the CIR server facilitated the integration by mapping OPC UA object types to keys that referred the OSA-EAI. Another group of researchers have implemented a remote monitoring solution named Wapice Remote Management (WRM) platform utilizing OPC UA, MIMOSA OSA-CBM, and OSA-EAI [35].

An extensible condition monitoring software called BUDS was implemented using OSA-CBM with focus on vibration condition monitoring in [36]. The authors further investigated the use of the MIMOSA OSA-EAI database for implementing condition monitoring systems, and also discussed the issues and challenges faced during the development process. They concluded that OSA-EAI is suitable for use as a condition moni-

[4]http://www.mimosa.org/mimosa-osa-eai

[5]http://www.mimosa.org/openom-initiative

toring database because it covers the major aspects of condition monitoring, including asset and sensor registry management, measurement event management, and storing raw and processed signals. In [37], authors report their experience of implementing the OMAHA project using OSA-CBM and OSA-EAI. OMAHA project builds a demonstrator of physical health management for a fleet of passenger aircraft and implements a simple builder API for binary OSA-CBM messages.

A software framework for prognostic health monitoring of ocean-based power generation using MIMOSA CBM and EAI web services on vibration data is implemented in [38]. In [39], authors have provided an adaption of OSA-CBM architecture for providing Human-Computer Interaction through mixed interfaces. They have also proposed a methodology for management and visualization of information using mixed reality for interaction with OSA-CBM modules. In addition to the above, many researchers have adopted or extended OSA-CBM and OSA-EAI in their implementations which demonstrates the wider adoption of these open standards [40–47].

While standards for CBM are very important for supporting CBPdM, they are not the whole story. To achieve Maintenance 4.0 and improve decision making (for both maintenance tasks and operational decisions), CBM related information must be linked to its wider context in other systems. For this, interoperability across a wide variety of systems is necessary for which there exists a multitude of standards across various domains, which will be discussed in the next section.

4. Standardization in the Oil & Gas Domain

To achieve interoperability, a combination of published standards and external reference data libraries must be leveraged for format, protocol, content, and services across numerous functional domains. No single standards organization could realistically develop, publish and manage all of the standards that are needed for achieving standards-based interoperability in such a scenario as each typically operate within their own functional domain, whereas the overall interoperability scenario is cross-domain. MIMOSA has been leading efforts to establish pragmatic standards, specifications, and methods so that complex platforms, plants and facilities can be better modeled, monitored and managed across their life-cycle based on published, open, supplier-neutral standards. This led to a collaborative effort to define the OpenO&M Web Service Information Service Bus Model (ws-ISBM) and the Open Industrial Interoperability Ecosystem (OIIE) specifications, with its associated OGI Pilot.

The OpenO&M Initiative was formed by a Memorandum of Understanding between ISA, MIMOSA, OAGi,OPC Foundation, WBF/B2MML (now under MESA), in order to help solve key problems related to industrial interoperability surrounding operations & maintenance. Individually, these industry standards associations developed standards supporting the entire life-cycle of asset intensive plants, platforms and facilities, including modeling and managing the processes themselves, the physical assets required to execute the processes and the IT/OT activities and infrastructure. Multiple industry-focused JWGs exists under the OpenO&M initiative. Until now, the OpenO&M technical committee has produced two specifications for connecting information systems in the manufacturing domain, the OpenO&M Information Service Bus Model (ISBM) and Common Interoperability Registry (CIR) which are explained in Section 5. The OpenO&M ws-ISBM and ws-CIR specifications can be used to provide supplier neutral connectivity between the various systems focused on the information exchanges and events being propagated through Layer 3 of the Purdue Reference Model [48]. For example, OpenO&M ws-ISBM can be used in any industry, as it allows the transmission of any information model, including MIMOSA CCOM, ISO 15926, MESA B2MML and OAGIS.

The foundation of an interoperability architecture is standards, and the OIIE uses a portfolio approach in leveraging both international and industry standards. The selection of standards is based on their capability to meet the industry-specified requirements, as well as levels of industry adoption and community engagement. The OIIE architecture also leverages a group of other Internet oriented standards and recommendations developed by the World Wide Web Consortium (W3C), including basic requirements for web services and modeling. All standards and specifications included in the OIIE are licensed by the respective organizations. Additionally, ISO Technical Committee 184 has formed Working Group 6 in order to develop the official ISO Technical Specification (TS) for Oil and Gas Interoperability (OGI). The TS documents how to use a portfolio of existing standards and documenting capabilities which are shown in the OGI Pilot.

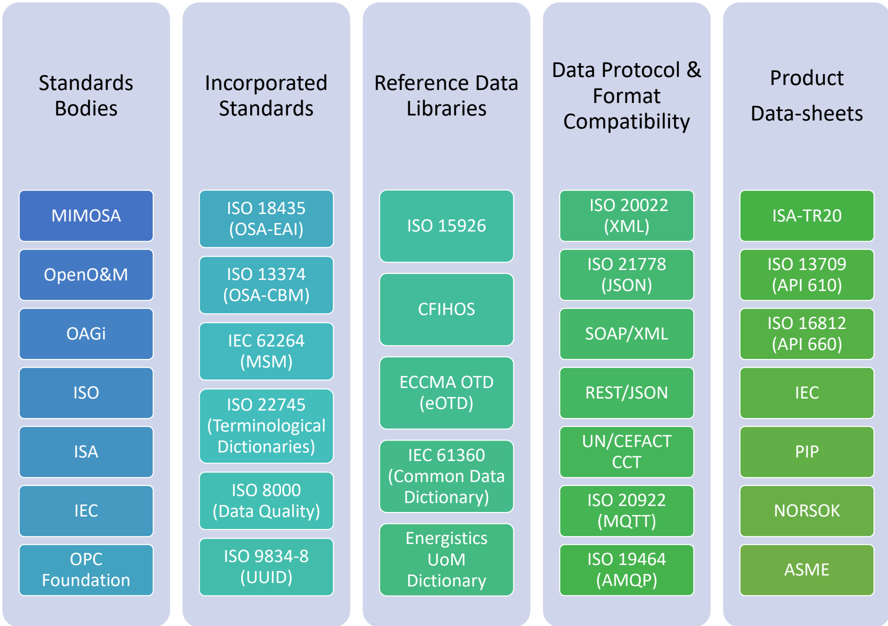

Fig. 2. OIIE alignment with other standards and standard bodies

The OIIE is the primary informative reference for ISO 18101.

Figure 2 gives an overview of how OIIE is aliasing with other standard bodies by either providing reference implementation for them or providing compliance to them. OIIE also makes extensive use of external reference data libraries and provides compatibility to multiple data protocols and formats. OIIE is working in close relationship with other relevant standard bodies such as OAGi, ISA, IEC and OPC Foundation. Open Applications Group Inc. (OAGi)[6] is an open standards organization which publish standards that help business applications talk to each other, typically focusing on Business-to-Business transactions, through standardized messages for any business process. OIIE uses Open Application Group Integration Specification (OAGIS) Business Object Document (BOD) architecture for message exchanges across the enterprise service bus. OAGIS is a widely accepted standard in supply chain domain which specifies a standard way of passing data in and out of applications using an XML format.

MIMOSA is adopting standards published by established standard bodies such as ISO, IEC and ISA. The International Organization for Standardization (ISO)[7] develops and publishes worldwide proprietary, industrial and commercial standards, while the International Electro-technical Commission (IEC)[8] prepares and publish International Standards for all electrical, electronic and related technologies. The International Society of Automation (ISA)[9] on the other hand provides process manufacturing conceptual standards to enable operations and maintenance process interoperability. There are multiple ISO standards that MIMOSA aligns with as listed in the Figure 2. With regard to IEC standards, MIMOSA/OpenO&M has adopted IEC 62264-6 Messaging Service Model to implement their enterprise service bus (ISBM). Also, MIMOSA uses IEC 61360 as a reference data library and provide industry standard data-sheet definitions for IEC product data-sheets. Out of all the standards published by ISA, MIMOSA specifically adopts ISA 95 [10] which is used for developing an automated interface between enterprise and control systems; and ISA-TR20.00.01-2007 which provides specification Forms for process measurement and control instruments in the ISDD project[11].

[6]https://oagi.org/
[7]https://www.iso.org/home.html
[8]https://www.iec.ch/
[9]https://www.isa.org/
[10]https://www.isa.org/isa95/
[11]http://www.mimosa.org/industry-standard-datasheet-definition-isdd-project/

MIMOSA is also working with OPC Foundation in a JWG to develop an OPC UA Information Model for MIMOSA CCOM in which OPC UA brings information from the factory floor and MIMOSA play its role in Asset Management. The OPC Foundation[12] creates and maintains open standards for connectivity of industrial automation devices and systems. OPC Unified Architecture (OPC UA) is a machine-to-machine communication protocol for industrial automation developed by the OPC Foundation. It bridges the gap between the service-oriented enterprise IT systems and the automation and control systems, including intelligent devices. It is a key standard for Industry 4.0. The prominent feature of platform independence makes communication compatible for different types of hardware and software applications [49].

MIMOSA OSA-CBM is a reference implementation of the ISO 13374 standard, which provides additional details about data structures and the interface methods. Similarly, MIMOSA OSA-EAI is a reference implementation of ISO 18435 standard that defines data structures for storing and exchanging information about all characteristics of equipment into enterprise applications.

The OpenO&M ws-ISBM is a standard implementation model for the IEC 62264-6 Messaging Service Model. The MIMOSA SDAIR's implementation supports the assignment, registration and system-wide use of an ISO/IEC 9834-8 compliant Universally Unique Identifier (UUID) for all technical objects, which are used to identify an object throughout its life.

Reference Data Libraries (RDLs) provides interoperability among systems in an enterprise and also across enterprises. OIIE utilize mappings to multiple external RDLs in addition to MIMOSA CCOM RDL as the system of record for any managed reference data. As shown in Figure 2, OIIE make use of multiple RDLs published by various organizations such as ISO 15926, CFIHOS, ECCMA, IEC and Energistics. ISO 15926-4 RDL[13] provides a mechanism by which consistent representation of engineering information can be drawn from diverse international and national standards including reference data. While ISO 15926 defines a general data model supporting complete asset life-cycle information, its emphasis and adoption is centered around EPCs (Engineering, Procurement, and Construction). ISO 15926 can be used in conjunction with other standards for industrial data including ISO 8000 which is an data quality standard. ISO 8000 can also be used in conjunction with other reference data libraries, parts libraries and data dictionaries based on international/industry standards.

Capital Facilities Information Handover Specification (CFIHOS) RDL[14] is built on the engineering information specification developed primarily by the owner operator to provide a useful standard for data handover for process industry community. Electronic Commerce Code Management Association (ECCMA)[15] leads the development of ISO 8000, which is an international standard for data quality and the exchange of material and service master data. ECCMA also leads work on ISO 22745, which is a standard for defining terminological dictionaries through mappings to standardized terms, and exchanging terms and meanings, without specifying the content. For content, ECCMA have developed an Open Technical Dictionary (called eOTD) of cataloging concepts (sets of related terms) used to create unambiguous language independent encoded descriptions of individuals, organizations, locations, goods and services. It is based on the NATO Codification System (NCS). IEC Common Data Dictionary (IEC CDD)[16] is a common repository of concepts for all electro-technical domains based on the methodology and the information model of IEC 61360 series. Energistics is an upstream oil and gas open standards consortium which publishes the Unit of Measure (UOM) Standard[17] providing harmonization of several industry UOM standards, such as POSC Unit of Measure V2.2, RP66 V1 and V2, and OpenSpirit Unit Dictionary V3.0.

MIMOSA keeps itself up-to-date with the latest technological advancements on an as-needed basis by providing compatibility to latest data protocols and formats. Along these lines, MIMOSA is hosting an OpenO&M Joint Working Group to initiate the work to add RESTful Services to the existing MIMOSA and OpenO&M specifications which are based on SOAP and XML Schema. Similarly, MIMOSA is working towards providing compatibility to popular (I)IoT protocols – MQTT and AMQP. The base types for MIMOSA CCOM XML Schema elements are derived

[12] https://opcfoundation.org/
[13] http://15926.org/topics/reference-data/index.htm
[14] https://uspi.nl/index.php/projects/frameworks-methodologies/136-cfihos
[15] https://eccma.org/
[16] https://cdd.iec.ch/
[17] https://www.energistics.org/energistics-unit-of-measure-standard/

from core component types that are compatible with the UN/CEFACT core component types. UN/CEFACT core components were defined in a Core Components Technical Specification (CCTS) developed by the ebXML project now organized by UN/CEFACT and ISO TC 154. The core components use several international standards for the representation of semantic and standardized information such as ISO 3166 for country and region code, ISO 4217 for currency code, ISO 8601 for date and time representation and so on.

MIMOSA is actively involved in building and publishing Industry Standard Data Definitions (ISDD) project which aims to capture existing Industry Standard Datasheets (ISDs) as machine interpretable business objects that are then fully re-usable, mappable and extensible. ISDD project is capturing high-value properties from existing, high-value ISDs published by credible industry associations including API, ASME, IEC, ISA, ISO, NORSOK and PIP.

While individual standards usually enable interoperability and cost savings in discrete functional domains, much greater benefits are achieved as multiple standards groups collaborate in appropriate industry-focused and cross -industry efforts. There does not exist any coherent standards-based architecture for achieving interoperability among various components of an enterprise business system, required to achieve CBPdM. MIMOSA aims to achieve interoperability of asset lifecycle information (including design, construction, operations, maintenance, etc. information) through the adoption of open information standards across manufacturing, fleet, and facilities environments using OIIE as explained in next section.

Standards are not an end unto themselves. They should help enable better, faster, cheaper solutions to achieve and sustain operational excellence. There is a complex mosaic of relevant existing and emerging IT and IM standards, each of which evolve to meet specific requirements. The OIIE (explained in section 5 brings these individual efforts together, with the direct participation and support of multiple participating industry standards organizations.

5. Open Industrial Interoperability Ecosystem

The Open Industrial Interoperability Ecosystem (OIIE)[50] ties together the previously published MIMOSA standards and provides interfaces for the integration and use of relevant domain standards across the ecosystem. An OIIE *ecosystem* crosses system,

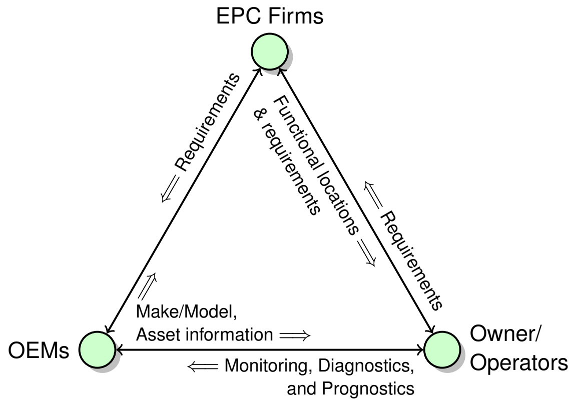

Fig. 3. Connections between organisations in the Oil & Gas Domain

software, and organisational boundaries to create a managed, distributed, federated System of Systems such as that required for the exchange of information between EPC (Engineering, Procurement, Construction), Owner/Operators, and OEM (Original Equipment Manufacturer) companies for the design, construction, operation, and maintenance of process plants in the Oil & Gas domain (refer Figure 3). The key components of the OIIE are briefly described in the following.

OpenO&M ws-ISBM (Web-Service Information Service Bus Model, which defines Web Services for an Enterprise Bus that supports both inter-/intra-enterprise communication through multiple modes, including request/response and publish/subscribe. The ISBM provides the backbone upon which the OIIE operates. The original standard[18] defines a set of SOAP/XML-based web services for configuring an ISBM instance and exchanging messages across it. The ISBM supports security at the transport layer via SSL/TLS and channel authorisation through token-based security.

MIMOSA CCOM (Common Conceptual Object Model), formerly part of the OSA-EAI [51], is the primary means of exchanging asset information in an OIIE. It provides a conceptual model and XML Schema for the exchange of asset life-cycle data, including: design (functional locations, requirements, etc.), serialised assets (built/installed assets, models, and their properties), CBM[19] (measurements, signals, alarms, etc.), and work management (work or-

[18] http://www.openoandm.org/ws-isbm

[19] The CBM related elements of CCOM are compatible with but not as detailed as OSA-CBM. In CCOM, the focus is on what information needs to be shared between systems to link it to it context.

ders, plans, etc.). It leverages other standards such as the UN/CEFACT Core Component Types and OAGIS Platform Specification. In particular, messag exchanges are performed primarily in the form of the OAGIS Business Object Document (BOD) format[20], which provides a standardised message format comprising message metadata, the verb or action to be performed, and a noun or object on which to perform the action. CCOM 4 defines BODs for general querying as well as BODs developed to address the use-cases defined for the OIIE.

Management and administration is an important aspect of an OIIE. As more and more systems/devices are connected, the complexity of the ecosystem grows and it has been recognised that the ability to configure, manage, and govern the ecosystem as a whole is required. Such management becomes the responsibility of the *Ecosystem Administrator* and helps to ensure data integrity and compliance. There are several components that assist the administration of the ecosystem:

1. The SDAIR (or Structured Digital Asset Interoperability Register) specification defines the functionality required for the management of Master Data available to applications in the OIIE for asset lifecycle and facilities management. Chiefly, it enables the registration of unique identifiers (UUID) for entities to be used consistently in CCOM exchanges across the OIIE; management of Systems of Record, which ensure data is modifiable only by the system that has the right to do so; supports Management of Change to ensure that a full audit log is available for asset configuration changes published by applications in the OIIE; and facilitates the mapping of property sets to an organisation's internal definitions. An SDAIR is typically provisioned with data during Engineering handover and Operations and Maintenance Provisioning.
2. The OpenO&M ws-CIR (Common Interoperability Register)[21] provides a SOAP/XML Web Service interface for the mapping and retrieval of identifiers used by different systems within an OIIE instance. Such an interface allows standardised and simple translation of identifiers, for example, between those of an internal application, standard data dictionary, or reference data library and the CCOM UUIDs used in exchanges across the OIIE.
3. The Service Directory specifies a Web Service interface that provides configuration and registration of services with the ISBM. Such centralised configuration allows the Ecosystem Administrator to specify the applications, which services they support, their scope, the exchange modality (i.e., request/response or publish/subscribe), and the associated ISBM endpoint, channel, topic configuration. Applications can then query the Service Directory to dynamically determine what channel/topic/request mechanism it should use to retrieve or publish necessary data.

Transformation is the final piece in the OIIE to support interoperability between a large number of disparate systems and devices. The transformation component can be configured as part of the OIIE just as any other system/application; however, its purpose is to transform the data it receives over the ISBM to the desired format (usually MIMOSA CCOM) and output the result to another channel/topic on the ISBM according to its configuration. Such an approach has been demonstrated to work in the 2012 OGI Pilot, in which the UniSA Transform Engine [52] was used to transform engineering design data from multiple vendor formats into CCOM during digital handover and provisioning of O&M systems.

Using these components, the OIIE aims to produce a truly plug-and-play environment, where vendors of COTS software can provide OIIE compliant adaptors rather than individual end-user organisations developing large numbers of point-to-point adapters.

MIMOSA has developed the OIIE around a use-case-based architecture through consultation with industry partners. The use-cases help drive the definition of scenarios and events (i.e. message exchanges) that the OIIE must be able to support (but are not necessarily required in every implementation/instance of the OIIE). This use-case-based approach allows the incremental development of standardised capability for the OIIE, demonstrated through the ongoing 'Oil & Gas Interoperability Pilot' (or OGI Pilot). Previous phases of the OGI Pilot have demonstrated the digital handover of design information from EPCs to Owner/Operator systems between differing standards[22]. An ISO Technical Specification is being

[20] https://oagi.org/
[21] http://www.openoandm.org/ws-cir
[22] http://www.mimosa.org/news/recording-live-oil-gas-interoperability-ogi-phase-1-pilot-demonstration

worked on by ISO TC184/WG6 to provide guidelines for sharing design information between standards.

Previously defined CBM use-cases and scenarios, where work orders are triggered automatically as a result of condition monitoring, are defined at a higher-level between the "Maintenance Management System" and the "Work Management System" (in whatever form they are realised). With the OIIE, MIMOSA aims to extend CBM use-cases and scenarios to ensure support for (I)IoT devices and Predictive Maintenance.

6. OIIE as an architecture for IIoT and CBPdM

One of the common assumptions for IIoT (Industry 4.0) environments is that standards and interoperability are a given (e.g. [53, 54]). As the OIIE is a platform for (open) standards-based interoperability, its application to an IIoT environment is a natural fit and is a natural evolution of the original architecture [55]. The prognosis and health management (PHM) system of the OIIE architecture is responsible for predicting the impending faults and to determine the remaining useful life of machinery. An efficient PHM can significantly speed up fault diagnosis by pin-pointing which parts of the machinery are most likely to fail and will need maintenance, thereby achieving CBPdM.

Figure 4 illustrates the OIIE architecture. The top of the diagram shows the different activities or systems involved in the lifecycle operations of a plant or facility. Each of these 'activities' may be a system or comprise Systems of Systems that can communicate directly with one another or through the ISBM. Moreover, the communication between systems may be intra- or inter- Enterprise. In the centre, the ISBM facilitates communication between the different components through web-services supporting both request/response and publish/subscribe modalities. While the initial specification defined SOAP/XML web-services, the ISBM specification is being revised to incorporate more lightweight RESTful/JSON web-services in an extensible fashion that will support the integration of other data formats and protocols in support of direct IIoT connections.

In the middle, the figure illustrates the myriad of connections that may occur between different components, IIoT devices, and the ecosystem as a whole (via the ISBM). It is common that the lower level automation and control networks (Layers 2 and below of the Purdue Reference Model [56]) are separated from the rest of the business network (Layers 3 and above of the Purdue Reference Model) by trusted systems. These trusted systems are often connected by local IIoT connections, field networks, or some other combination. The higher-level systems will then communicate with the rest of the OIIE via the ISBM. However, with the introduction of (I)IoT, the barriers are broken down slightly, with devices more typically preferring more direct connections to one another and higher-level systems. This is illustrated to the left of the diagram. This does not eliminate the need nor use of the OIIE, however, as it is still important to manage and govern the overall ecosystem. In that light, the OIIE can be used to manage *negotiated* access to the trusted systems for IIoT devices that exist outside of it.

The bottom of Figure 4 shows the connections to both industry-wide and enterprise specific reference data libraries (RDLs). Each of these components may comprise multiple RDLs of different origins and provide shared context for data exchanges in terms of common classes, terminology, and taxonomies. In particular, this includes metadata for IIoT devices. Another initiative of MIMOSA is the Industry Standard Data Definitions project (or ISDDs) which aims to provide a common basis for the digital capture and exchange of datasheet oriented properties typically published by standards organisations such as ISA, API, IEC, etc. The ISDD project covers the representation of property sets, their definitions, and exchange based on CCOM. This same architecture can be used to represent the IIoT device metadata in RDLs as well as the definition of the data transmitted by IIoT devices. Moreover, capable IIoT devices can use such standardised definitions to exchange data directly with the OIIE.

Its core set of features addresses all of the principles of Industry 4.0 identified by Hermann et al. [9]:

Interoperability is the primary goal of the OIIE, in particular, standards-based interoperability. In the context of IIoT, this interoperability will includes a combination of device-to-OIIE, device-to-system, and device-to-device connectivity.

Virtualization relates to the need to have a 'virtual copy' or *digital twin* of the system and processes. Creating and maintaining such a digital twin is one of the driving forces behind the OIIE as it provides the context required to support systems and services such as CBPdM.

Decentralization is provided as an OIIE instance comprises a System of Systems; there is no centralisation of decision making or data. The result

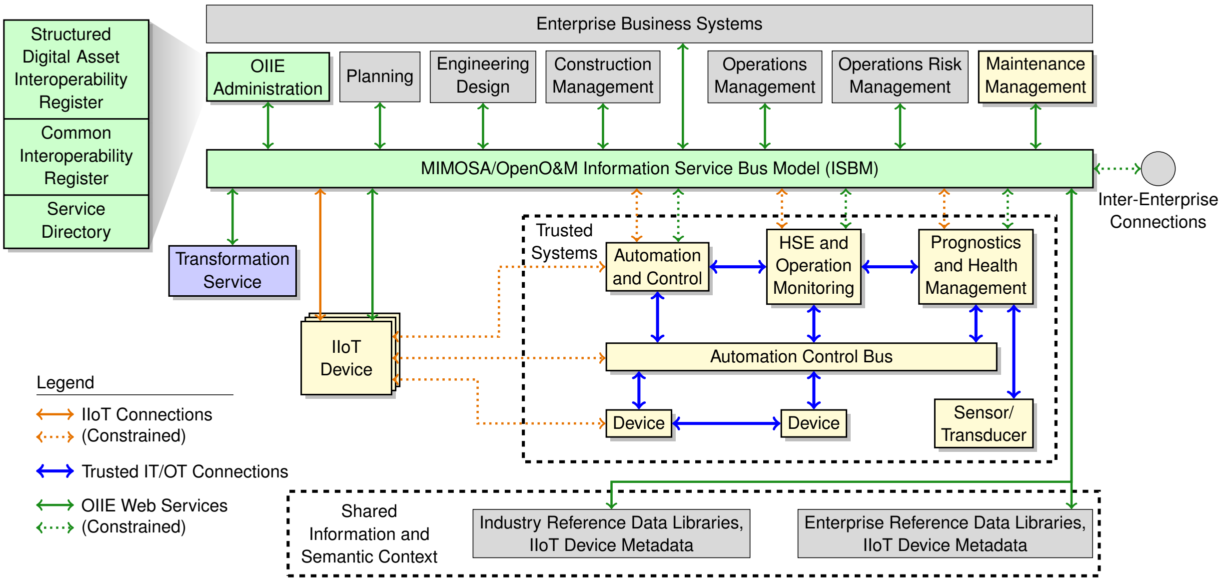

Fig. 4. OIIE Architecture for IIoT. Green components indicate MIMOSA standards and specifications; yellow components highlight IIoT and Maintenance related aspects of the architecture.

is a federated distributed system. However, management of the whole ecosystem is required for quality assurance and traceability. Such functionality is provided by the OIIE administration components.

Real-time Capability is required for data analysis and automated decision making to, for example, react to failures. This is supported in the OIIE by not requiring all communication to occur over an ISBM, which may not be real-time capable. This allows real-time systems to be directly connected to data sources for rapid decision making, while data and events are propagated more slowly across the OIIE to higher-level systems for other forms of analysis and decision making.

Service Orientation is present in the OIIE as the core standards upon which it is built have been designed using Service-Oriented Architecture principles. As such, the OIIE has been designed with service-orientation in mind. At the core sits the ISBM, which provides intra- and inter- Enterprise data exchanges through web services.

Modularity is natural to the OIIE as it is a federated distributed system that aims for plug-and-play capability of a variety of systems and software, including COTS. The core standards and specifications define interfaces and methods of data exchange, leaving the implementation details of individual components up to the organisations involved. This achieves maximum flexibility in the ecosystem by allowing an organisation to change components while maintaining interoperability across the ecosystem through the use of standardised interfaces, exchange mechanisms, and adaptors.

Security is provided by the OIIE in several ways. The core specifications define requirements that must be met in the OIIE such as the use of SSL/TLS for communication security; security tokens to manage the authorisation of systems to communicate across channels of the ISBM; role-based security for both people and systems in the OIIE; management provided by the OIIE Ecosystem Administrator.

Fulfilling these principles puts the OIIE architecture in an excellent position to support IIoT environments and Condition-based Predictive Maintenance. The sequel describes how the architecture can support this based on an OIIE use case that will be verified in the upcoming OGI pilot.

7. OIIE CB(Pd)M Use Cases

The definition of the OIIE includes standardized interoperability use-cases to describe the system, messaging, and data requirements necessary to achieve useful and demonstrable functionality for enterprises in the process industry. A key set of uses-cases to be validated by the upcoming OGI Pilot phases revolve around Condition-Based Maintenance. These use cases will cover a broad range of CBM activities starting with the acquisition of measurement data from a variety of sensor/device types, through alarm triggering, health assessments, diagnostics/prognostics, creation of advisories, and the resulting maintenance activity. A point to note is that, while the use-case focuses on *condition* data, most of what it covers is equally applicable to *operations* data.

For brevity we present the CBM use-case as a whole, rather than the individual use-cases that cover reusable portions of functionality. In the context of the OIIE architecture, breaking down the use-cases into logical chunks allows systems implementors to control how much they must implement by conforming to only those use-cases they deem necessary for the functionality they provide.

For primary activities of the use case we assume that the various systems are not integrated and perform most communication in using CCOM (in particular BODs) over an ISBM. Different groups of systems may be implemented by vendors with internal integration; however, such implementations should make their information available to other OIIE participants via the interoperability interfaces both individually and as a whole. This allows the OIIE architecture to provide modularity and choice of components by supporting interoperability between systems that are not internally integrated by a single vendor. Although we typically limit our discussion to CCOM-based message exchanges in the following, it does not mean to say that *all* inter-systems communication must be performed via the ISBM using CCOM.

7.1. CCOM BOD Messages and the ISBM

MIMOSA CCOM has adopted the OAGIS Business Object Document (BOD) Message Architecture [57] (part of the OAGIS open standard) for message exchanges in the OIIE[23]. The BOD message structure provides a *smart wrapper* that supports data and (extensible) meta-data to be exchanged in a protocol independent manner. This is useful when communicating via an enterprise bus, such as the ISBM, and supports consistency across different protocols, e.g., SOAP-based web services or REST/JSON API.

[23]Other styles of messaging are supported based on requirements such as efficiency, size of data etc.

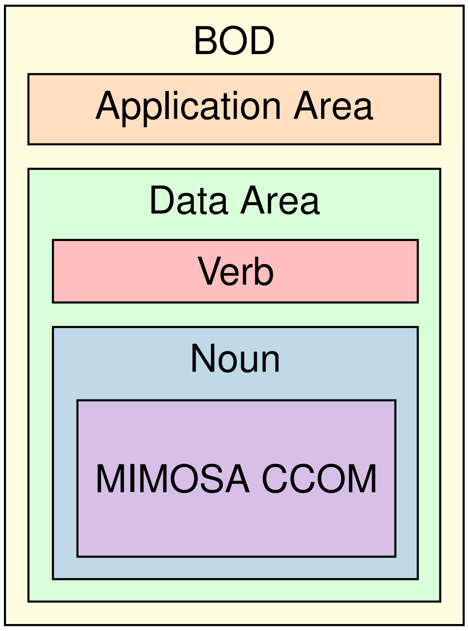

Fig. 5. BOD Message Structure (adapted from [57])

The basic structure of a BOD is illustrated in Figure 5, in which MIMOSA CCOM is shown to be used for the payload content of the message inside the *noun*. The different aspects of a BOD are:

BOD envelope for the entire message.

Application Area meta-data of the message, including common fields (e.g., unique message identifier) as well as application specific data.

Data Area the business data, including operation to be performed and the data on which to perform it.

- **Verb** the operation or action to be performed on the data.
- **Noun** the business data to be operated on or used to perform the operation, which consists of MIMOSA CCOM data structures.

There are many different *verbs* described in the OAGIS specification; however, CCOM BODs typically only involve a subset of the verbs, including: Get, Show, Sync, Process, Acknowledge, and Confirm. The different verbs map to the different message exchange modalities of the ISBM, i.e., request/response and publish/subscribe. The following is a brief description of the verbs and the exchange modality to which they are mapped:

Get/Show is a pair of verbs for query/response type messages, where the noun typically denotes the thing being queried. For example, GetMeasurements/ShowMeasurements BODs would query for (CCOM) measurement data and return the matching data. The Get/Show verbs are used over the request/response exchange mechanism of the ISBM.

Sync verb indicates the update of data between systems and should originate from the system that controls the data, i.e., the system of record. The Noun is the data to be updated, e.g., SyncMeasurements would be used to publish (CCOM) measurement data to interested systems. Sync is mapped to the publish/subscribe mechanism of the ISBM.

Process/Acknowledge that are a pair of verbs used when the receiving system must perform some processing on (or using information from) the provided noun. In CCOM, this is used for RFIs (request for information) and initiation of work orders, for example: ProcessRequestForWork/AcknowledgeRequestForWork, which initiates the creation of a work request (and subsequently a work order) where the acknowledgment provides the work request allowing the status to be tracked later. This pair of verbs is mapped to the request/response exchange mechanism of the ISBM.

Confirm is a special verb for responses to other BODs to indicate success or failure, independent of the expected type of BOD response. Part of the application data area of each BOD is an indicator for when a confirmation should be sent, with possible values being: *never*, *always*, or *on error*. Using *always* between systems in the OIIE can be useful as systems will often queue requests for alter processing, not necessarily respond immediately. For example, a system that receives a ProcessRequestForWork BOD may respond with an immediate Confirm, but cache the request for later, eventually responding with a AcknowledgeRequestForWork BOD once the request has been fulfilled.

CCOM defines BODs covering various aspects of the model and required interoperability scenarios. For example, BODs for querying configuration information (i.e., functional locations, serialized assets, etc.), processing requests for information or maintenance tasks, querying and publishing condition data (i.e., measurement data, alarms, advisories, etc.), and publishing events (i.e., asset installation events, etc.).

7.2. Mapping CCOM to the ISO 13374 CBM Stack

An important aspect of the architecture is that the standards incorporated into the OIIE typically define information models and data exchange between systems but not the processing that occurs within a system. Therefore, we do not describe how to perform CBPdM, rather we describe how to exchange data between all the interrelated systems to support the systems that perform CBPdM.

Table 2 shows the mappings to each functional block of the ISO 13374 CBM stack, including both contextual configuration information and data resulting from the processing of each block. The first block, *data acquisition*, has no mapping as sensors/devices these days handle their own analog to digital conversion. Moreover, CCOM handles the exchange of information at the higher-level, where the data of interest has already been associated with useful descriptors and context, such as virtual sensor measurements. This occurs at the *data manipulation* level. At this level there are configuration aspects to consider (such as signal processing setups for FFTs, and the flow of data through ports captured by the *algorithm* related classes of the model) as well as the generated measurement data associated with its context (such as the logical measurement location for a physical or virtual sensor). By associating measurement data with its context and overall configuration (i.e., which assets are installed on which functional locations at some time), systems are able to trace when/where a measurement was taken from a sub-component to a component, possibly aggregating all the way to an entire unit or area.

At the *state detection* block, CCOM represents the configuration of alarm settings, for example, as *regions*, while actual (triggered) alarms are represented using events and *triggered regions* that are associated with the measurements, and measurement location to which they relate. The outcomes of the *health assessments* block are represented as CCOM Health Assessments and Remaining Life Assessment. Such assessments are related to their context including the serialized asset or functional location to which they relate and the agent (person or intelligent system) that created the assessment.

Remaining life assessments may also be generated by the *prognostic assessment* block along with proposed events, i.e., possible events that may have or will occur that help explain other events, measurements, etc. Finally, the outputs of the last block, *advisory generation*, can be shared with other systems as CCOM

Table 2
ISO 13374 CBM Stack Basic Mapping to MIMOSA CCOM Classes

CBM Level	Related CCOM Configuration Classes	Related CCOM Data Classes
Data Acquisition	—	—
Data Manipulation	Signal Processing Setups, Algorithms	Measurements (e.g., SingleDataMeasurement, FFTMeasurement)
State Detection	State Regions (Alarm Settings)	Triggered Regions (Triggered Alarms) and Events
Health Assessment	—	Health Assessments, Remaining Life Assessments
Prognostic Assessment	—	Remaining Life Assessments, Proposed Events
Advisory Generation	—	Recommendations

recommendations. For example, if a prognostics and health management system were to receive a proposed event indicating that there will be a likely failure of an asset in the near future, then it may produce a recommendation that the asset be shutdown and replaced before that time.

7.3. Example CBPdM Overview

An overview of the activities involved in the CBM use case is illustrated in Figures 6 and 7. For simplicity the activities of different systems are shown as linear processes; however, each can be considered a subprocess that is executing in a loop in parallel with the others. Communication between systems in this architecture is primarily through BOD messages over an ISBM in various configurations. As such, data flows are not shown when messages are sent using the publish/subscribe method to emphasize the independence of the different systems. Data flows are illustrated, however, when the request/response method is used, even though communication is still via the ISBM.

As you move from left to right in Figure 6 and Figure 7, the systems progressively perform functions at higher-levels of the CBM stack (refer Figure 1): from data acquisition, through data manipulation, state detection, etc., to advisory generation. The right-most system is outside of the CBM stack and demonstrates the result of producing an advisory: that is, a maintenance work order is triggered to remove and replace an asset. This results in configuration change, which is important for CBPdM as it may affect the analytics. For example, replacing an installed asset that has sensors on board means the new asset includes a new set of sensors. The new sensors may have different firmware or be calibrated at different times using a different technique, etc., which may result in the measurements related to the asset/functional location being different from the previously installed asset. If none of this is known the predictive analytics may, at best, recommend maintenance be carried out on the asset or, at worst, recommend the replacement of the asset again because it "thinks" the asset is faulty.

7.3.1. Sensors and Devices

There are two types of sensors/devices considered as being part of an OIIE: (1) sensors that are considered to be *trusted*, such as those installed within a plant and connected directly the automation and control systems (possibly through) a bus; and (2) IIoT sensors that are outside of the trusted systems, which may include hand-held measurements devices, sensors that are external to the organization, etc. The latter may interact with the enterprise in different ways such as simply sending measurements to the "cloud" (where other systems can query the data[24]) or by negotiating access to the trusted systems and communicating via the automation bus or directly with other devices.

For most industrial applications, it is expected that the communication at the sensor/device level will leverage OPC UA. An OPC UA server will then publish measurements and triggered alarms, etc., to the ISBM through an adapter for consumption by other systems in the wider ecosystem. Conversely, a query for historical data may come from another system across the ISBM, which will be handled by the OPC UA server via the adapter. Other standard communications protocols may be used as well, such as MQTT (ISO 20922) for device-to-device communication; similarly, an adapter can listen to events of interest and publish them to the ISBM and vice versa.

Depending on the capabilities of a device, some local processing from functional blocks higher up the CBM stack may be possible. For example, a device may be able to directly identify an alarm condition and publish that itself, without relying on the OPC UA server or other control or condition monitoring system.

[24]Even in this case some for of trustworthiness is required for the data to be used effectively.

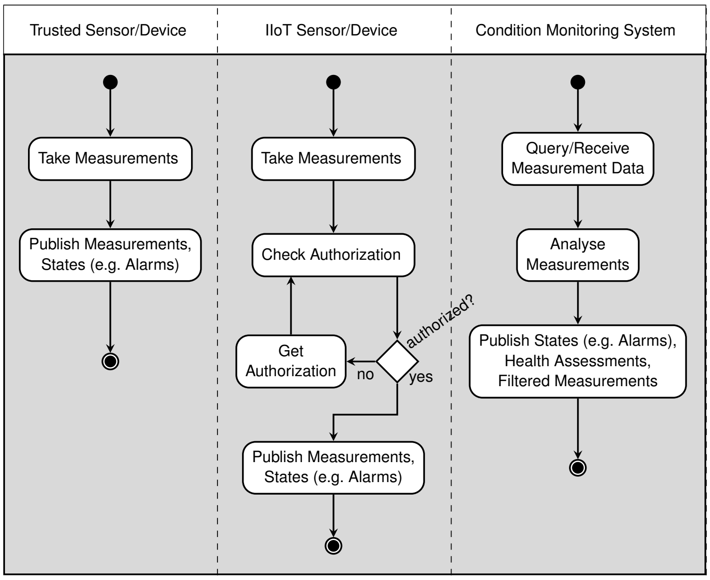

Fig. 6. Activities performed by systems in Condition-Based Maintenance

7.3.2. Condition Monitoring

A Condition Monitoring System (CMS) is a conceptual aggregation of systems that perform functions related to the state detection ad health assessment blocks of the CBM stack. In addition, it may support the automated sensing of asset removal and installation through monitoring of the connected devices.

In Figure 6, the main job of the CMS is to retrieve measurement data—either through querying measurement data from other systems/devices via the ISBM or by receiving published measurement data over the ISBM—and analyze it to detect alarm or error states based on its configuration details. In addition, the CMS may perform analysis of the health state of an asset. Finally, it publishes condition measurement[25], state, and event data to other systems—or allows those systems to query for it.

The CMS may also detect device removal and installation automatically when maintenance is performed (illustrated in Figure 8). These events can be published to the Maintenance Management System (MMS) for reconciliation against those recorded by the Maintenance Technician performing the work and/or published to the SDAIR to ensure up-to-date configuration information about the state of the assets in the enterprise.

[25]Not *all* measurement data would be published, but subsets of interest to other systems.

7.3.3. Operational Risk Management (Prognostics & Advisories)

The Operational Risk Management System (ORM) is a collection of systems that fulfill functions across the Health Assessment, Prognostic Assessment, and Advisory Generation blocks of the CBM stack. Collectively these systems query for, or receive published, measurements, alarms, and events to determine the health state of assets, including estimation of remaining life, perform diagnostics and prognostics to identify incipient or potential faults, and publish advisories regarding recommended maintenance activities to the Maintenance Management Systems. These activities are displayed in Figure 7.

The advisories can also be received by Control Systems to notify them that a asset should be/is being shut down and the ORM will notify them when the maintenance is complete and the asset can be brought back online.

7.3.4. Maintenance Management

The Maintenance Management Systems (MMS) assist in the scheduling, creation, and execution of work orders. They can interact with a variety of systems that may trigger various maintenance activities or for reconciling detected events against work orders. The interoperability of all these systems within a common context, provided by the managed configuration, i.e., digital twin, of the SDAIR and the wider ecosystem, is essential for CBPdM as it is not just about the measurement data received from sensors.

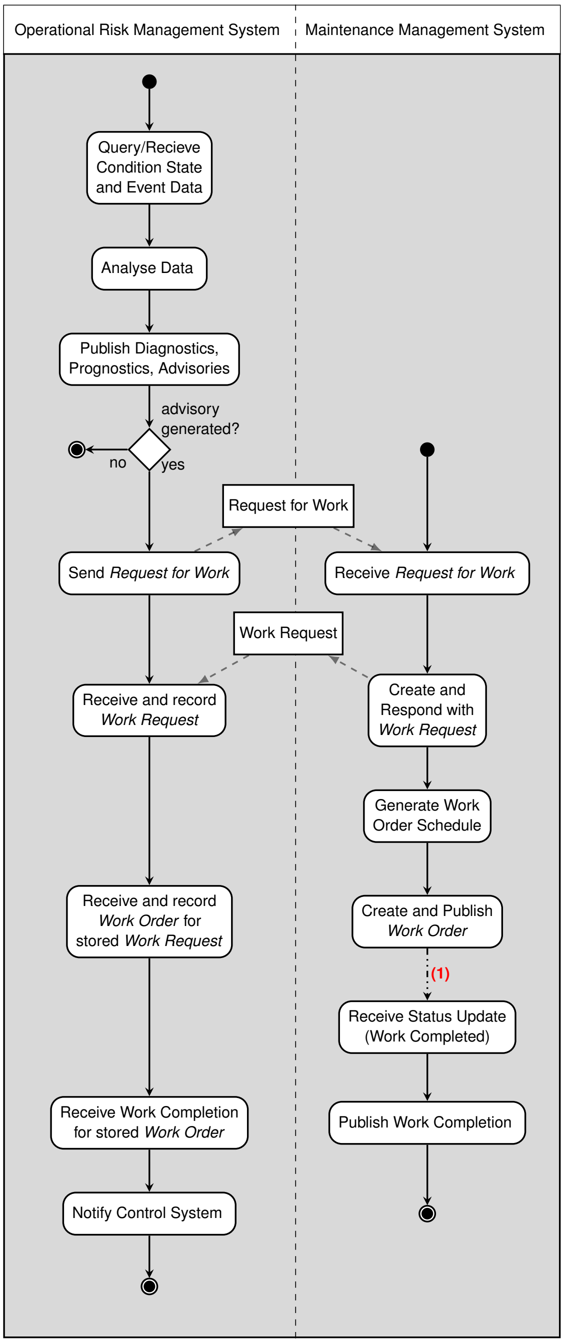

Fig. 7. Activities performed by systems in Condition-Based Maintenance. The annotation (1) refers to the separate Figure 8.

A simple work-flow for removing and replacing an individual asset is shown in Figure 8. This expands on what occurs between the MMS publishing a work order and receiving a notification that the work has been completed (bottom right of Figure 6). This process is important as it illustrates the event-driven update of the configuration managed by the OIIE instance through the publishing of remove and install events. The SDAIR can listen to these publications to ensure it maintains a consistent reference point of the digital twin that it not necessarily present in any specific participating system. Furthermore, it illustrates the "sensing" of the remove and install by a monitoring system. These events can be reconciled against those recorded by the MMS for auditing purposes or used to automatically publish work status updates.

7.4. Remote Monitoring

An important aspect of the overall OIIE architecture is the interoperability and decoupling that comes about due to the exchange of information over an ISBM that supports both intra- and inter-enterprise process flows. For example, the health and prognostics assessment systems do not have to be present within the boundaries of the Owner/Operator. Rather, it is possible for companies to provide remote monitoring and assessment services by exchanging information via the ISBM (possibly a pair of ISBMs bridged using a standard protocol like AMQP, ISO 19464) without needing to support all of the native formats and interfaces of the installed sensors/devices. The architecture supports arbitrary combinations as well. For example, a specialist company may install and configure its own sensors which it monitors remotely and sends prognostics and advisory information to the Owner/Operator, while the Owner/Operator monitors and manages other sets of sensors and generates prognostics and advisories internally. Moreover, the two companies may allow various degrees of information sharing (configuration information, property information about the assets and their models, etc.) enabled by the overall architecture based on contracts between the companies.

8. Conclusions and Future Scope

Implementation of Industry 4.0 is driven by the recent advances in cyber-physical systems, cloud computing, big data and industrial wireless networks. The IIoT is increasingly being adopted by industry to simulate production processes, remotely control machines and monitor the operations. Actionable insights obtained from industrial analytics are one of the pivotal means for achieving intelligent operations and maintenance. Intelligence here refers to making optimal deci-

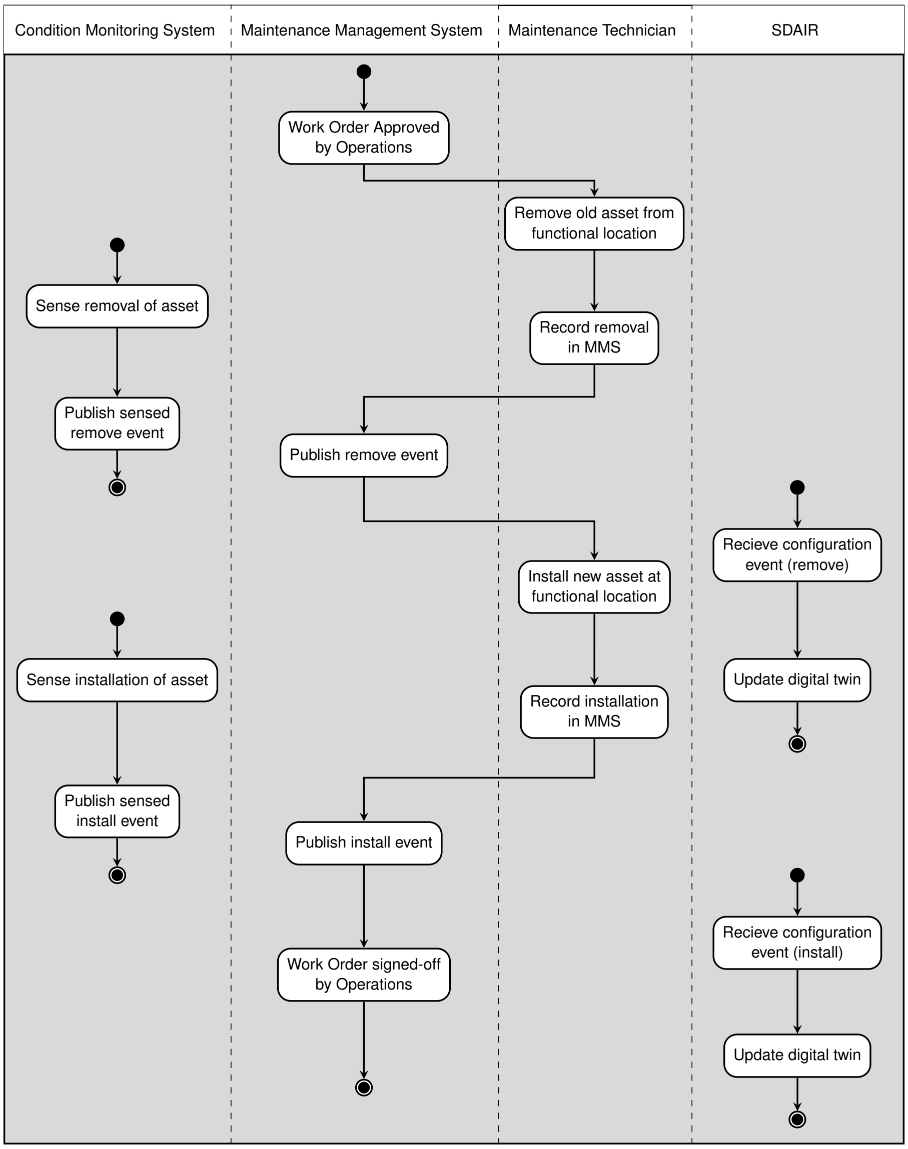

Fig. 8. Remove/Replace Activities, corresponds to the annotation (1) in Figure 7.

sions for both automated and human-in-the-loop decision making. Sensors track certain KPIs with the help of the IIoT and the digital twin of an asset is used for comparing the measured and trending values with ideal model values. Any deviation from the benchmark is easily detected and appropriate alerts or warnings are raised. Thus, the maintenance team is alerted for possible intervention before the equipment breaks down. This leads to optimum decision-making, improved intelligent industrial operations, and creation of new business values.

A single system cannot carry out the basic steps for achieving CBPdM which involves continuously monitoring the condition of a healthy system, issuing an alert if a variation is detected and generating maintenance work advisories based on the current and historical condition of the system. Systems like condition monitoring system, operational risk management system and maintenance management system must interact with each other and with the digital twin of the device/equipment/component for achieving reliable CBPdM. The digital twin provides the required context to the operational/condition history of the equipment usage and performed maintenance activities. This context helps in giving better accuracy for the prediction of maintenance work. It is pivotal to maintain operational context in dynamically changing environment. Furthermore, interoperability of the asset management systems is crucial in achieving accurate diagnosis and prognosis as it can highly augment the data received from assets. The prognosis and health management (PHM) system of the OIIE architecture is responsible for predicting the impending faults and to determine the remaining useful life of machinery. An efficient PHM can significantly speed up fault diagnosis by pin-pointing which parts of the machinery are most likely to fail and will need maintenance, thereby achieving CBPdM.

In this paper, we have discussed multiple standards each of which is trying to address different part of the industry's requirements. There is a significant need to fill gap in these existing standards by identifying relevant standards and using them together in a repeatable scalable manner. The foundation of an interoperability architecture is standards, and the OIIE uses a portfolio approach in leveraging both international and industry standards. The OIIE-based architecture is at its core an interoperability solution that enables devices and systems to communicate effectively in both inter- and intra- enterprise contexts using a variety of standards, data models, and exchange protocols. OIIE follows the levels traditionally identified in the Purdue Reference Architecture, ISO 18435-1 and IEC 62264, while also including the flexibility and adaptability needed for IIOT, cloud platforms, and digital ecosystems. MIMOSA collaboratively leads the OIIE effort in conjunction with other industry standards bodies, industry associations, software suppliers, system integrators, EPC contractors and academia.

Further, we explained the OIIE architecture which supports the IIoT requirements and reuses existing open standards of CBM, EAI and others to support CBPdM. We have outlined various standards related to the condition monitoring systems and showcased how OSA-CBM and OSA-EAI are used by research community to complement other standards. The OIIE is an outgrowth of several related industry standardization activities, each of which is addressing a part of the industries requirements for standards-based interoperability. We have showcased how OIIE is bringing these individual efforts together, with the direct participation and support of multiple participating industry standards organizations. A detailed use case of CBM was explained, detailing the various involved activities and discussed how OIIE achieves it. The future scope of our research will be to support prescriptive maintenance, where in addition to generating a condition based maintenance work request, a pre-defined work-order or solution package is also included in the generated work request providing details of how to carry out the maintenance work. This solution package will specify the exact required resources of materials, tools, documents and labor required to complete the maintenance job.

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