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Modeling a predictive maintenance management architecture to meet industry 4.0 requirements: A case study

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Abstract

Industry 4.0 is the latest paradigm of industrial production enabling a new level of organizing and controlling the entire value chain within a product life cycle by creating a dynamic and real-time understanding of cross-company behaviors. It is expected to have a considerable impact in the oil and gas (O&G) sector by revolutionizing current predictive maintenance and operation optimization. There are several challenges to be overcome before the Industry 4.0 vision is achieved: a standardized reference architecture, a business model, robust services, and products are all lacking. This paper develops a reference architecture for an intelligent maintenance management system that complies with Industry 4.0 visions and requirements. The industrial needs were derived from stakeholders and use case scenarios using a case study methodology. Systems engineering methods were applied to transfer the needs of the existing maintenance management system into a desired functional architecture. The new and upgraded requirements are predominantly related to advanced data analytics, resulting in new and modified functions within the traditional "Reporting" and "Analyses" modules. A more complex maintenance program is created through interfaces between various enabled data categories (historical records, real-time measurements of performance and health, expert-just-in-time). The study points to the changes required in the classical O&G maintenance management process to comply with Industry 4.0 vision and requirements.

KEYWORDS
architecture design, intelligent maintenance system, oil and gas industry

1 | INTRODUCTION

The core concept of Industry 4.0 is to create cyber-physical systems (CPSs) in a digital transformation process, connecting cyberspace to the physical space.[1] The main CPS enabling technologies are Internet-of-Things (IoT), big data, and cloud computing. Industry's use of digitalization has the potential to considerably reduce costs. For example, the initiative of British Petroleum (BP) to digitalize operation and maintenance (O&M)[2] could reduce the company's upstream operations' discovery and development costs by 5%, maintenance costs by 20%, overtime costs by 20%, downtime by 5% (mainly due to predictive maintenance [PdM]), and inventory levels for spare parts by 20%, while boosting production by a conservative 3% (conventional land operations). With the increasing use of digitalization, PdM and operation optimization are expected to be incorporated into industry, particularly in the oil and gas (O&G) sector.[2]

In the Norwegian context, the Norwegian Ministry of Industry[3,4] recommends industrial digitalization, and several large-scale O&G operating companies have taken commercial incentives in that directions. Design for intelligent operation is rapidly growing in Norwegian industry; the O&G sector is pioneering technological developments, eg, unmanned platforms, automated drilling rigs, remotely operated vehicles (ROVs), and automated substations. These advanced applications aim to increase the production rate and cut manpower cost, while avoiding unsafe conditions. They require reliable, monitor-able, and predictable physical assets; PdM and operation optimization are clearly necessary for these types of remote and unmanned (automated) applications.

PdM aims to detect failures before they happen and avoid downtime and high levels of repair (consequences), but its main concern is predicting the remaining useful lifetime (RUL) of an asset to effectively use opportunistic maintenance intervals and optimize maintenance services and operations. The RUL estimation can be used as a proactive policy to optimize controllable loading and operating conditions to extend the asset's lifetime. Bokrantz et al[5] presented 34 projections of industrial managers' expectations of the maintenance role in digitalized industry. In Norway, some of those projections are already in the research and development (R&D) phase.[6,7] However, these projections of intelligent maintenance must be considered and adopted by industrial work processes to gain the expected benefits of maintenance, notably through PdM.

Each company in the O&G sector has its own work processes to manage production operations and asset conditions. The work processes clearly define the functions to be performed and their sequence. The maintenance management loop developed by the Norwegian Petroleum Directorate (NPD)[8] is a generic and well-known work process used by the O&G companies operating at the Norwegian Continental Shelf (NCS). Intelligent maintenance management is required for Industry 4.0 applications to be adopted in the NPD maintenance management loop. Ramirez et al[9] did this in the context of the management of aging assets at Norwegian O&G facilities. It is also a common practice to upgrade or develop new maintenance management architectures (to facilitate desired work processes) whenever a new standard related to maintenance is released. For instance, Campos and Márquez[10] modeled a new maintenance management architecture to adopt the requirements of the PAS 55 standard (later replaced by ISO 55000). As these examples suggest, the NPD maintenance management architecture must be upgraded to meet Industry 4.0′s vision and requirements, and industrial companies must develop work processes for intelligent maintenance management. It is important to emphasize that this paper defines maintenance architecture as the structure and behavior of the entire maintenance system.

Industry 4.0 is often described in terms of the RAMI 4.0 architecture (an architecture with six layers).[11,12] The associations using the RAMI 4.0 model are working with the International Organization for Standardization (ISO) to create a standard for Industry 4.0. In maintenance, some architectures are already leading the development of intelligent maintenance in the Industry 4.0 context. For example, the 5C model (connection, conversion, cyber, cognition, and configuration)[1] has been adopted by Watchdog Agent.[13] However, a critical review of the existing maintenance management architectures, eg, IMS Watchdog Agent, SIMAP, PROTEUS, PROMISE, and TATEM, concluded no architecture for PdM currently integrates enterprise-level data with performance and health parameters.[14]

This paper integrates the Industry 4.0 vision and requirements into the NPD maintenance management loop to develop an intelligent maintenance management architecture. The developed architecture will enable advanced remote and automated applications within the O&G sector, satisfy stakeholders (ie, user-friendly, working-culture oriented, reliable business model), and support O&M use case scenarios. The paper applies a systems engineering methodology to manage the requirements of intelligent maintenance management and allocates them as functions in the proposed architecture. Systems engineering is a well-known methodology for developing complex systems; it can consider life cycle issues and handle detailed interfaces. The paper uses a case study method to determine the needs of industrial stakeholders and draws on both primary and secondary sources of information.

The rest of this paper is organized as follows. Section 2 presents the maintenance management requirements related to the standards and vision of Industry 4.0, as these appear in the literature. Section 3 explains the systems engineering methodology used to develop the novel architecture of intelligent maintenance management. This includes the process used to elicit stakeholders' needs, business, and technology requirements, and the development of the system context and use case scenarios. Section 4 presents the desired intelligent maintenance management architecture. Finally, Section 5 offers some conclusions and makes recommendations for future work.

2 | BACKGROUND

2.1 | Maintenance management at the leading edge of Industry 4.0

The NPD[15] is Norway's governmental directorate and administrative body responsible for developing frameworks and regulations for the O&G companies operating at the NCS. In most cases, these frameworks and regulations are developed through collaboration between the O&G industry and the NPD. In the late 1990s, the NPD[8] updated the traditional management loop (plan, organize, execute, control) into a more customized maintenance management loop transforming several maintenance programs into practice, as shown in Figure 1. The primary objective of this update was to support the O&G companies operating at the NCS to achieve a rigid maintenance management that reduced operational risk.

In fact, the maintenance management loop shown in Figure 1 includes two loops. First, a strategic management loop represents the full management loop from goals and requirements to improvement measures. Second, an operational management loop starts at planning, goes to analysis, and then returns to planning. This second loop is for rapid improvement measures. Clearly, given the Industry 4.0 technologies, the operational loop has the potential to be effective and efficient, as data are coming from multiple sources for different performance and health indicators at a more frequent rate and with higher resolution. Yet, it is vital to know how these data are actually used for decisions at the operational and strategic management levels.

Industry 4.0 is, as previously mentioned, often described in terms of the RAMI 4.0 architecture.[11,12] Some new maintenance architectures are already active and leading the standardization of a maintenance architecture suitable for an Industry 4.0 environment. For example,

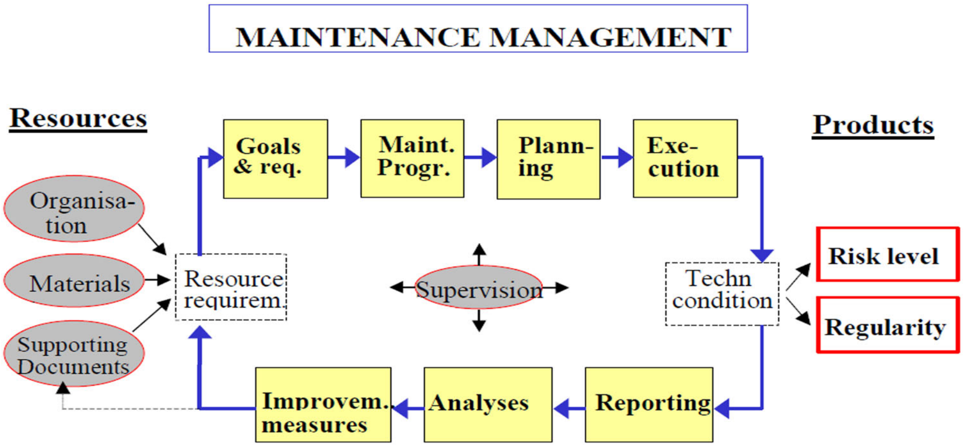

FIGURE 1 Maintenance management loop developed by the NPD (Norwegian Petroleum Directorate, 1998)

Watchdog Agent[13] proposed the 5C model[1] as an intelligent maintenance architecture. The 5C model excluded the business layer (the sixth layer in RAMI 4.0), however, so the 8C model was proposed as an update to cover customers, content, and coalitions.[16] Other examples are the well-known maintenance management architecture based on the requirements of the traditional PAS 55 standard,[10] the closed-loop feedback architecture for PdM in Industry 4.0,[17] and the architecture of deep digital maintenance.[7] In this context, perhaps, the most representative terminology for Maintenance 4.0 is e-Maintenance, as it covers the digital functions from data to decision.[18–27] However, disruptive technologies such as advanced robots, drones, and wearables of Industry 4.0 might enable maintenance to be even smarter by expanding the scope of maintenance intelligence to cover both physical and digital functions in the cyberspace covered by e-Maintenance. The Industry 4.0 context has a different architecture (functional layers) than Industry 3.0 because it includes IoT, big data, and cloud computing. To be more specific, these technologies have been present in the Industry 3.0 context for a long time, but their comprehensiveness and capabilities are greatly improved in the Industry 4.0 environment. For example, in Industry 3.0, IoT was applied at the enterprise level, but in Industry 4.0, it is applied at the asset level and between asset and enterprise levels.[14] Moreover, it presents novel ways of performing data analysis, ie, diagnosis and prognosis. Traditionally, such analyses were based on a single parameter originating from one sensor; in contrast, the Industry 4.0 environment requires combining several different sensor signals and parameters, ie, process and health, with enterprise level data.[28] Furthermore, the new techniques for data acquisition and analysis require new algorithms that analyze the big data from these multivariate sensor signals to perform accurate and reliable diagnosis and prognosis.[29] This calls for a PdM architecture that integrates enterprise-level data with monitoring data, ie, performance and health parameters.[14]

The main challenge is to upgrade the existing intelligent maintenance systems, eg, e-Maintenance, to use the three main technologies (IoT, big data, cloud computing) in a more comprehensive and beneficial manner. The scope must be extended to include the physical aspects of maintenance management, along with the cyber aspects covered in e-Maintenance. Kagermann, Wahlster, and Helbig say that general challenges implementing Industry 4.0 include the lack of a unified standard and reference architecture design, the lack of models for processes and work organization, the lack of new business models, and the lack of product availability.[30] Nordal and El-Thalji discuss this from an O&G maintenance perspective.[31]

3 | CASE STUDY

3.1 | Applying systems engineering to intelligent maintenance management

This paper applies a systems engineering methodology whereby needs and requirements are collected from different sources. These requirements are considered in terms of their defined function, input, mechanism, or trigger. The functions, inputs, mechanisms, and triggers are allocated to the functional and physical architecture to shape the final intelligent maintenance management architecture. A systems engineering methodology provides a traceable development path between needs (ie, stakeholders, system context, Industry 4.0 vision, and standards) and the final architecture. Thus, each element in the final architecture is justified by and can be traced to at least one extracted need.

In this case, the systems engineering process starts with the identification of the system's constraints: *business needs, Industry 4.0 requirements*, and *standards* deductively extracted from secondary data sources. The intelligent maintenance system, ie, the system of interest (SOI), is decomposed into four different aspects: (a) *system of interest including context diagram and use case scenarios*, (b) *business and stakeholders' needs*, (c) *standards*, and (d) *Industry 4.0*. All the associated requirements are inductively extracted from these aspects. The existing real-world needs are converted into desired requirements and functions that comprise the final architecture design. The process of this systematic systems engineering approach is illustrated in Figure 2.

The paper's methodology for the architecture development involves three steps. The first step comprises analysis of the existing system and identification of the needs for the desired future system. This includes

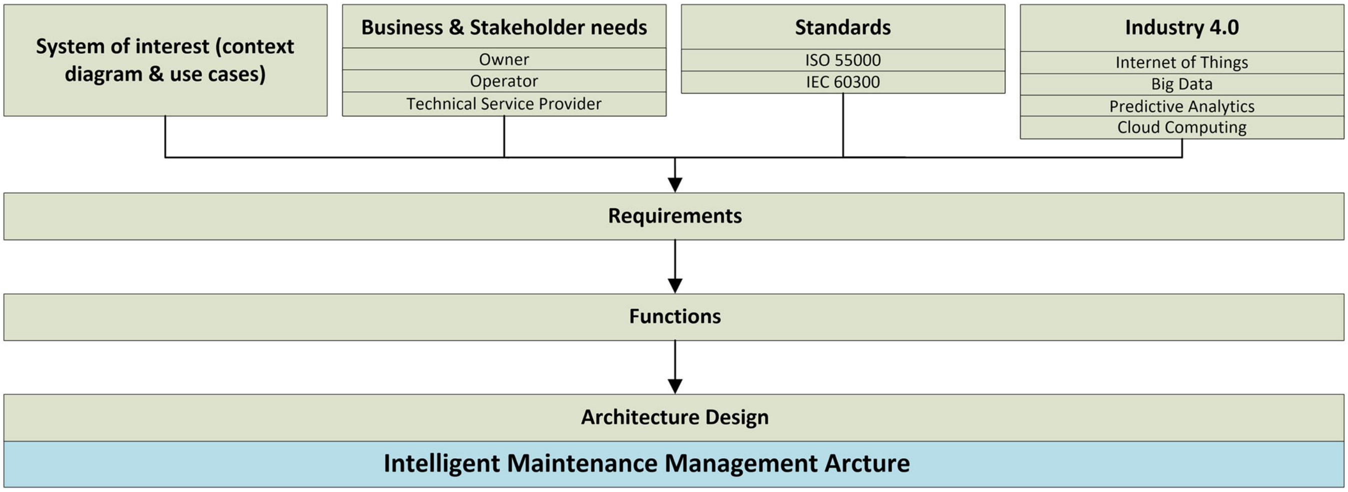

FIGURE 2 Requirement sources and applied system engineering approach

both the *system context* and *use case scenarios* to identify functional deficiencies, *O&M stakeholders* to identify operational deficiencies, and *Industry 4.0 architectures* to identify technology fusion and technology breakthroughs. The second step represents extraction of the requirements and associated functions for the desired future system, including stakeholders' needs (business needs), (inter)national standards, and Industry 4.0 requirements. The last step is modeling the future desired system.

3.2 | Case study analysis of existing system, identification of needs, and elicitation of requirements

3.2.1 | System of interest and system to support

The SoI in this case study is the maintenance management system to be modeled. To delimit the case study and provide a detailed model, a compression system is selected as the system to support (STS). More specifically, the main objective is to model a maintenance management architecture for a specific centrifugal compressor.

The industrial compression system compresses hydrocarbons to facilitate sales gas transportation from Nyhamna onshore process facility in Norway through the Langeled subsea pipeline and ensure correct pressure when it arrives at the receiving terminal in Easington, United Kingdom. The compression system can be divided into four identical compressor trains; each train includes the following equipment: *electric motor*, *gearbox*, *two identical centrifugal compressors operating in series*, *recycle line (surge avoidance)*, as well as *utility systems* (eg, lubrication and sealant systems) and an *inlet manifold*, *inlet separator*, and *outlet manifold*. In this research, the system boundary is one of the centrifugal gas export compressors.

The primary purpose of the centrifugal gas export compressor system is to enable the transportation of sales gas to consumers. The compressor train first receives rich gas from an offshore facility. The gas enters the separator and is separated into heavy hydrocarbons (eg, butane and propane) and lighter hydrocarbons, ie, sales gas (mostly methane), at Nyhamna. Then, the sales gas is fed into the centrifugal compressor and pressurised by dynamically increasing its velocity; this allows the sales gas to be transported through the Langeled subsea pipeline to its end users in the United Kingdom.

The maintenance architecture presently used by the case study company is quite fragmented and highly influenced by technological developments and product-supply changes over several decades. The architecture started with a single-system collecting process variable solely for control and supervision; it later included additional parameters, such as vibration analysis and different ways of scrutinizing monitored data to gain an operational advantage, ie, detection, diagnosis, and prognosis. Today, sensor technology and condition monitoring of the compressor train is also included, to some extent. The main objective of this monitoring system is to control the critical compression system; the compression system has a decisive influence on whether end users receive their booked gas or not. Because of the system's criticality with respect to operational availability, it is important to ensure its technical integrity throughout its life cycle.

The current maintenance architecture is examined in more detail in the following subsections. This includes identification and description of the system context, demonstration of two use case scenarios of maintenance management and monitoring, and extraction of the associated stakeholders' needs and requirements, as well as the requirements and functions of an Industry 4.0 architecture. The analysis takes an inductive approach, using interviews and discussions with relevant stakeholders.

3.2.2 | System context and extracted requirements and functions

The system context is the first source of needs for the enhanced maintenance management architecture. Therefore, the enhanced maintenance management system is considered the SoI and set in the center of the context diagram, as shown in Figure 3. The external

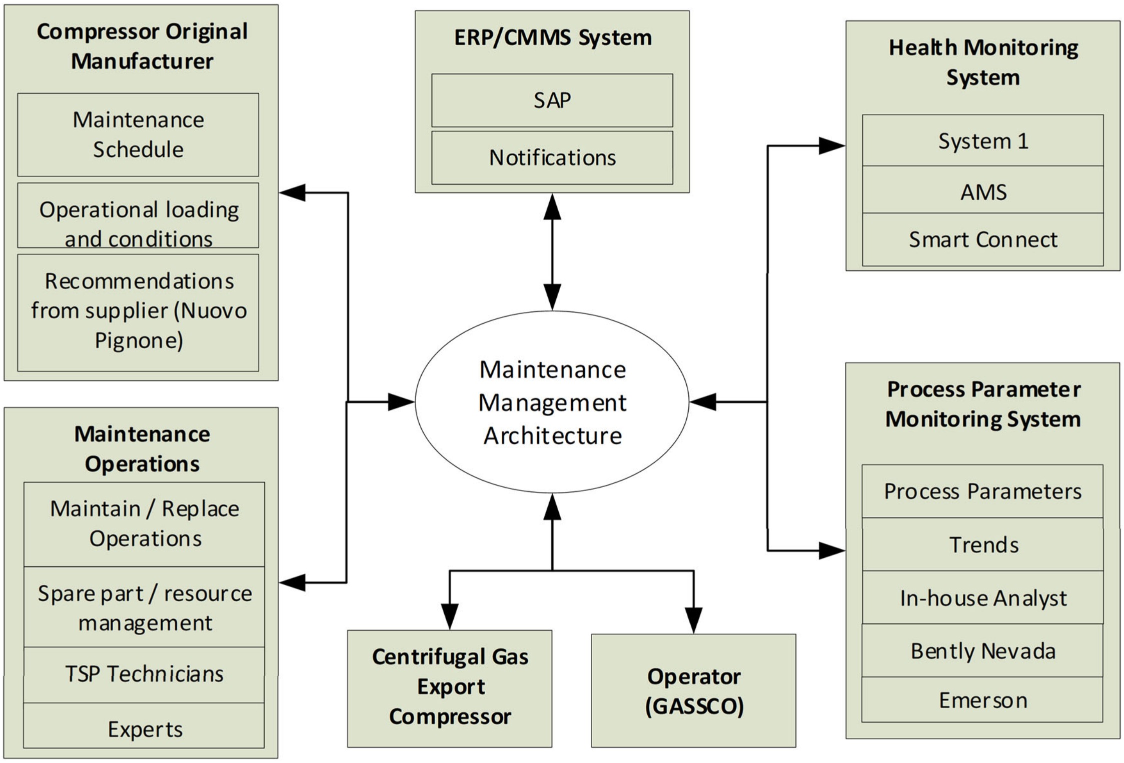

FIGURE 3 System context diagram of the maintenance management architecture

systems that influence and are influenced by the SoI are outside the center. To be more specific, the context diagram indicates that the enhanced maintenance management architecture should depend on inputs from the process parameter monitoring system (compressor control system) and the health monitoring system (condition monitoring system) and should enable communication between maintenance planners and asset owners, operators, original equipment manufacturers, spare part suppliers, maintenance service providers, rental equipment providers, and other stakeholders.

The enterprise resource planning (ERP) and computerized maintenance management system (CMMS) is currently considered the maintenance management system and not seen as an external system. However, in the interviews and discussions, the stakeholders said the link between the CMMS and diagnostic, prognostic, machine learning, and decision-making algorithms should be configured in the future. These algorithms communicate with the CMMS and send their results as input for the CMMS to plan and schedule the required actions, but they also need to communicate with the CMMS while processing the data to get maintenance management data as input. In this scenario, the maintenance management architecture should consider all these systems as external systems. Moreover, these external systems will probably be outsourced from external stakeholders and managed using an integrated business model.

In practice, the present maintenance management architecture includes the operator, technical service provider (TSP), and a third-party company, eg, experts from the equipment vendor (included in the maintenance management) and Bently Nevada (involved in the condition monitoring of the STS). As seen in Figure 3, the existing monitoring scenario comprises three different solutions: *Smart Connect*, *AMS Machinery Manager*, and *System 1*. Smart Connect is a software developed by Shell; it analyzes low-resolution vibration and bearing temperature data, along with process data, such as gas temperature and pressure, through trending. This yields both performance charts and bearing temperature and vibration propagation as a function of time, whereas the health of the equipment is visualized through traffic lights. AMS Machinery Manager offered by Emerson enables acquisition of offline vibration data that are analyzed once a month through trending in the time and frequency domains. This is done either by an in-house analyst at Shell or by Emerson employees on demand from the TSP. System 1, developed by Bently Nevada, facilitates online vibration analysis. This software allows offsite analysts from Bently Nevada to gain access to and analyze the vibration data that are locally stored at Nyhamna. In general, offsite analysts from Bently Nevada analyze the online vibration data acquired from the compression system for half an hour every morning. In addition, analysts from Shell located at Nyhamna access the software and analyze the vibration data once a month.

These needs, requirements, and functions are depicted in Table 1.

3.2.3 | Use case scenarios and extracted requirements and functions

Current maintenance management use case scenario

Figure 4 illustrates the maintenance management loop using integrated definition (IDEF) representation. The functional blocks

TABLE 1 Extracted needs, requirements, and functions based on the context diagram

Content elements	Observations	Requirements/criteria	Functions (capabilities and characteristics)
External systems	There are interactions between the compressor owner, compressor operator, and compressor condition monitoring (CM) providers.	A visualized/shared data of the compressor health should be provided.	Reporting function could be enabled with a visual aid via a cloud solution.
Interfaces	Interfaces between owner, operator, and CM provider depend on human interactions, possibly creating delays.	Human interfaces should be minimized or at least visualized to support human decision making.	Architecture interfaces
Passive stakeholders, eg, regulations, standards		NORSOK ISO55000 IEC60300 IEC60706-2	Life cycle management Risk-based inspections Maintenance managementDesign management

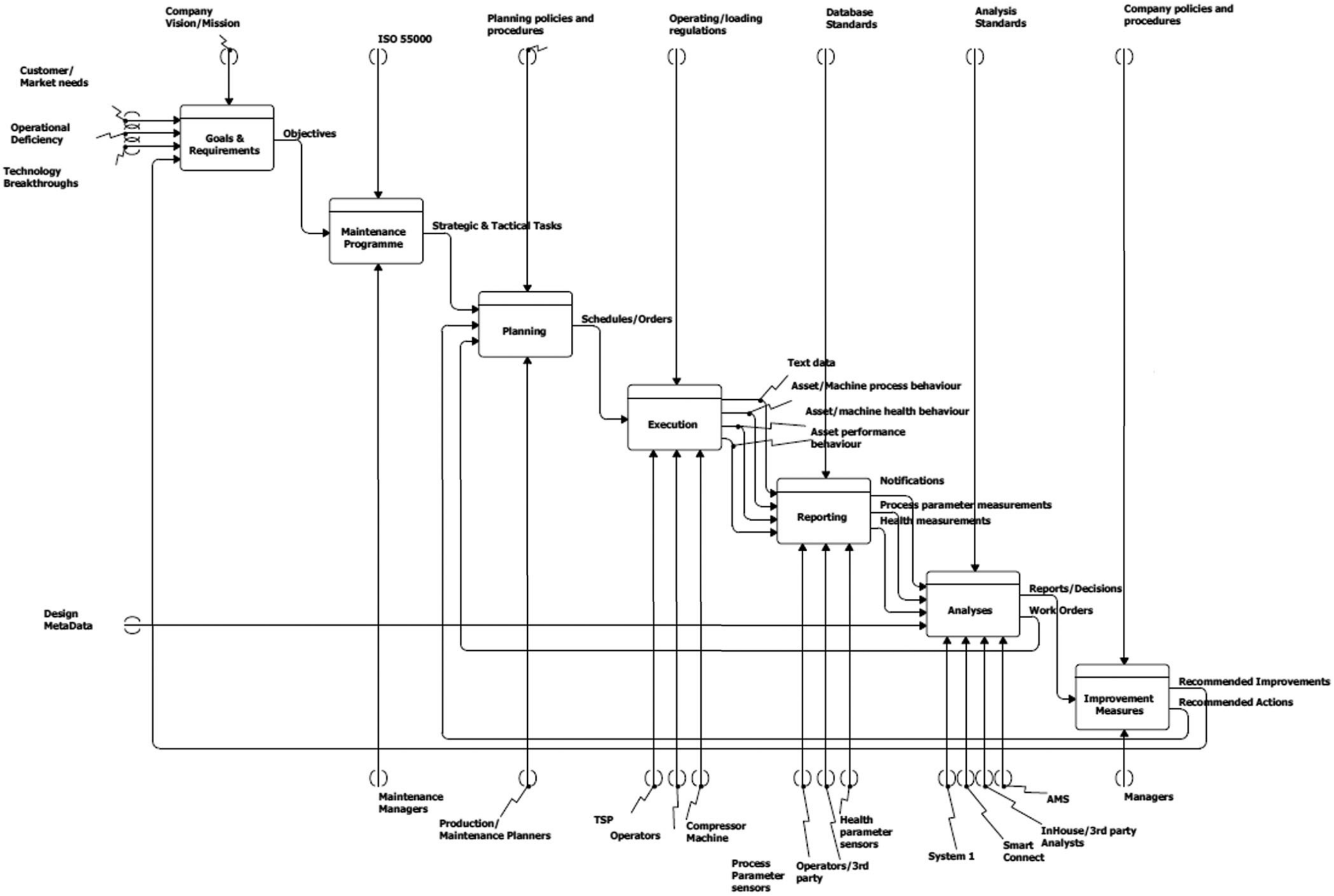

FIGURE 4 IDEF representation of existing maintenance management use case scenario

represent the same functional blocks and sequence as in the maintenance management loop (as shown in Figure 1). The maintenance management process starts at the strategic level and preferably as early as possible during the project phase of the asset or production facility design. The objectives, technical requirements, and specifications of the required maintenance management programs are established during the project phase. This is followed by several levels of planning: strategic planning for long-term projects and

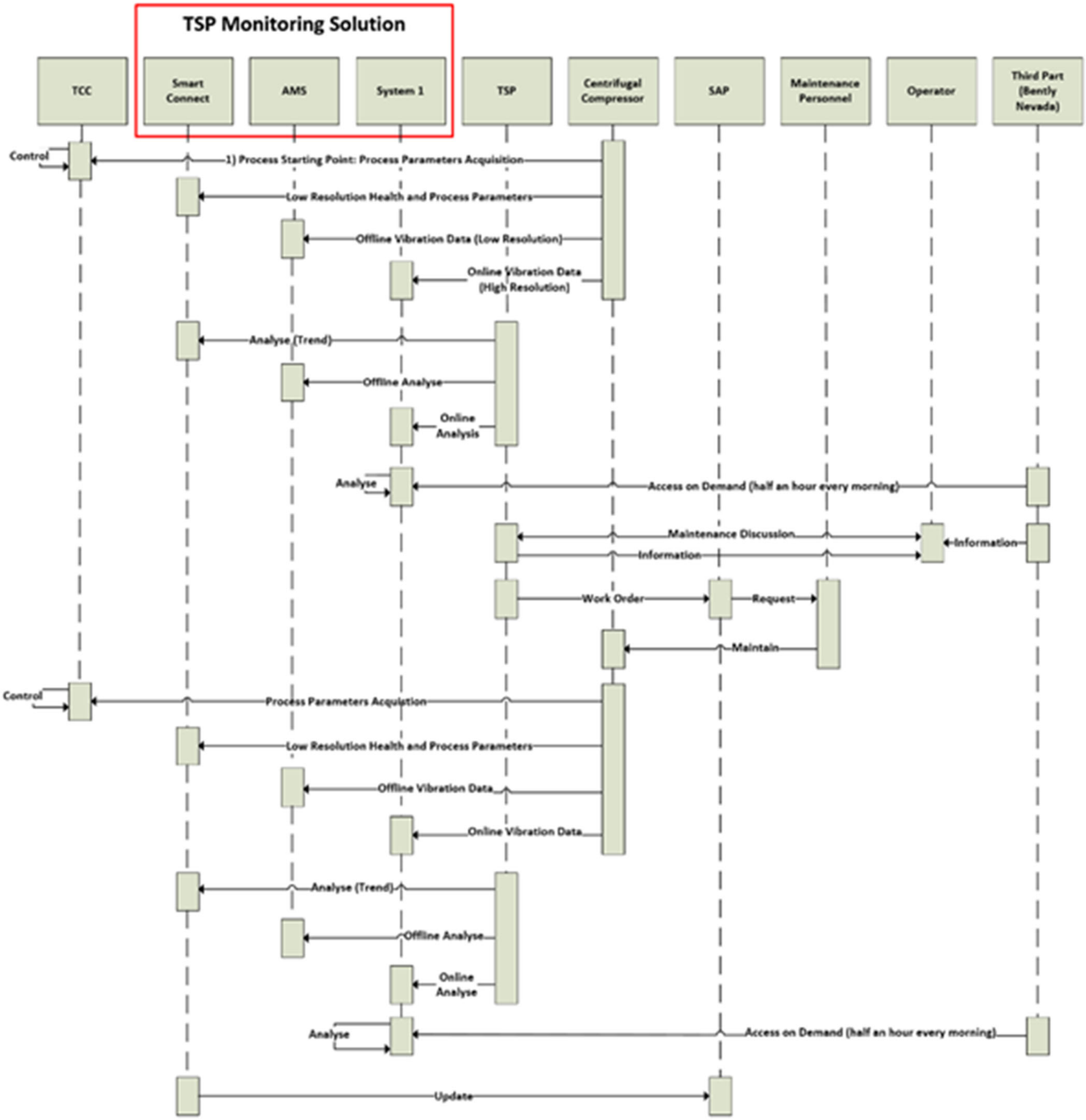

FIGURE 5 Current monitoring use case scenario based on inputs from discussions and interviews

tactical and operational planning for yearly, monthly, weekly, and daily operations. The results of execution, performance reporting, and analysis might lead to other actions that should be planned and executed as soon as possible, or recommendations should be made for strategic or improvement measures. The IDEF representation can identify the inputs (items on the left side), outputs (items on the right side), feedback mechanisms (physical allocations, eg, assets, software, and humans), and triggers (control elements and top items) of each function within the recommended maintenance management process. Thus, the IDEF representation is a more detailed representation than the loop in Figure 1.

Current monitoring use case scenario

The monitoring use case scenario illustrated in Figure 5 is based on inputs from discussions and interviews with relevant stakeholders. Briefly stated, the monitoring use case scenario starts with the TSP; the TSP acquires both process and health parameters from the STS. These parameters are mainly analyzed through trending. An operational anomaly is revealed when the trended measurements deviate from historical trends or exceed certain thresholds. In such cases, the TSP informs the operator who then informs the owner. The TSP and operator determine the best operational window to perform the required maintenance action based on the forecasted production plan and perceived severity and criticality of the abnormality supported by the trended measurements. After planning the specific future maintenance action, the TSP generates a work order in its own SAP system and starts procuring necessary resources. In addition, the TSP and the operator develop a risk analysis, eg, a safe job analysis (SJA), before the maintenance execution phase. In certain situations, there may be no time for analyzing or planning maintenance; the equipment is stopped immediately, and corrective actions are executed.

A sequence diagram is an effective way to review the sequence and the complex interactions between the main stakeholders in the monitoring use case scenario. It is vital to create a detailed representation of the monitoring use case scenario to suggest where the new technologies, eg, machine learning and PdM algorithms, fit within this sequence. The sequence diagram shown in Figure 5 reveals issues related to accessibility of data and the time consumption required to perform the maintenance tasks. Some interactions are still done in a manual or semimanual manner, eg, emails and phone calls, to handle data and information. The manual and semimanual communications usually occur because of a lack of available information (eg, no access or not existing). They increase the time and resources required to complete the monitoring process.

Business and stakeholder needs and extracted requirements and functions

The stakeholders in this case study are the equipment owner, operator, and TSP, including maintenance and monitoring engineers. Gassled is the owner of the transportation infrastructure and associated equipment, such as the centrifugal gas export compressor (STS), and is responsible for all the associated expenditures. Gassco functions as the operator, taking full operational responsibility for the asset on behalf of Gassled. The daily O&M activities are conducted by the TSP, in this case Shell. To summarize, Gassco's role is to maximize the shareholder value of Gassled by ensuring a safe and reliable operation safeguarded by seamless collaboration between the operator and the daily O&M activities conducted by the TSP. Given these varying roles and interests, the stakeholders have different needs and requirements that must be considered in the design phase of the architecture. The different qualitative needs and requirements are summarized in Table 2.

Table 2 demonstrates that all stakeholders have different needs and requirements. Clearly, they all agree about the main scenario of an intelligent maintenance system and the need to find a business model that satisfies these needs. One of the main conflicting needs relates to connectivity and data sharing; while the TSP needs data availability and flexibility, the operator is more conservative in terms of data security and information sharing. Overall, they all agree on the scenario and the need to find a business model, but these conflicting needs, ie, sharing and security of data, must be solved first.

The information from the interviews and discussions is supplemented by the findings of 34 maintenance projection studies[5] on expected changes caused by implementing Industry 4.0 in maintenance. These changes include maintenance management, big data, system interoperability, work processes, and new standards and legislations.

The perception of maintenance has been influenced by technological developments and has evolved from being a "technical matter," "cost-cutting contributor," or "profit contributor" to being a "cooperative partnership" that can potentially add value to the business.[32] As a result, maintenance strategies have developed from being reactive to being proactive and holistic.[33] Those strategic changes have led to the development of several maintenance programs, including reliability-centered maintenance (RCM), condition-based maintenance (CBM), and total productive maintenance (TPM).[32]

CIAM Knowledge HUB for O&M in Stavanger has written a white paper[34] on updating NPD's maintenance management loop by taking new technologies into consideration. An update is needed as maintenance is expected to play a key role in Industry 4.0, with a supportive function for both production and operation. Industry 4.0 will not be achievable without an intelligent maintenance system smart enough to perceive, learn, and care about its assets' performance and health.[2] To achieve this goal, the level of smartness of the maintenance management loop must be increased. The first update will be to enhance the maintenance supervision within the maintenance management loop by updating its link to the whole asset management loop and life cycle loop, eg, ISO 55001. The second will be to update the internal processes of each function within the management loop and to update the tools, technologies (eg, sensors and big data analytics), and advanced maintenance techniques (CBM, predictive health monitoring, updated versions of RCM, risk-based inspection [RBI], etc.). The requirements of intelligent maintenance management in terms of layers and functions are summarized in Table 3.

Technology-driven needs and extracted requirements and functions

The Industry 4.0 architecture[35,36] will revolutionize how maintenance management is performed,[5,27] as described in the following scenario and illustrated in Table 3. Starting with the physical space, the asset layer (eg, physical machines and human workers) will generate data related to maintenance (health and performance measurements, descriptive notifications, and reports) that will be acquired (perception layer, eg, sensors and controller) and transmitted (connection layer) into cyberspace. Several analytic functions will be performed in cyberspace: conversion (eg, data preprocessing and big data analytics), computations (state detection analytics and performance analytics), cognition (eg, health diagnosis and prognosis assessment analytics, maintenance optimization and decision support analytics, and maintenance management analytics), and configuration (eg, user interfaces, automatic actions, and actuators). The configuration layer will transmit (via the transmission layer) the required maintenance actions back from cyberspace to the physical space. The whole process is a closed loop from physical to cyber and back to the physical space again.

TABLE 2 Extracted needs, requirements, and functions

Source	Needs	Requirements/criteria	Functions (capabilities and characteristics)
Business			
International/national standards	- Architecture needs to comply with relevant (inter)national standards.	- Transparency. - Compliance.	Relevant standards should be considered as triggers for the functions of the new architecture; some should lead to new functions.
Oil & Gas Operating Culture	- System must replace the functions of current fragmented solutions and be easy to access, along with improving and enhancing the capabilities of diagnosis, prognosis, and maintenance optimization.	- Cover all current functions provided by the different solutions and improve the capabilities in terms of maintenance optimization. - Data should be located in the cloud and thus provide flexible access for any relevant stakeholder, as well as improved HSE and more cost-efficient operation.	Maintenance optimization should be actively supported by real-time diagnosis and prognosis.
Owner	- Intelligent maintenance system that makes it feasible to perform continuous diagnosis and prognosis of the equipment. - System that facilitates optimizing existing maintenance schedule and thus improves operational availability and HSE. - Access to the system/cloud solution is not needed.	- System should function as intended and give accurate and reliable diagnosis and prognosis results. - Reliability.	Ability to provide diagnosis and prognosis.
Operator	- Notification process that generates an alarm when the intelligent maintenance system identifies operational abnormalities. - Traffic light visualization. Notification is generated when the visualization changes from green to either yellow or red. - Access to the cloud solution. - System needs to include a production forecast. This will play a decisive role in maintenance optimization.	- Access to the cloud solution. - System works as intended. - Alarms generated by the system, and results of the diagnosis and prognosis must be reliable (no false alarms). - System develops accurate and optimized work orders.	New functions are required: 1. Connection to a cloud solution. 2. Generation of reliable and earlier alarms. 3. Support of the planning/scheduling process.
Technical Service Provider (Analysts and Maintenance Engineers)	- Access to the intelligent maintenance system for continuous control and supervision of the data. - Possibility to perform manual diagnosis (detecting symptoms of failures, fault type, fault severity) and prognosis (estimating fault propagation through RUL) if necessary. - Current SAP system should become an integrated part of future cloud solution to enable a solution generating accurate and reliable work orders into SAP.	- User-friendly system that visualizes the results from diagnosis and prognosis in an understandable manner (ease of diagnosing and predicting). - Generate accurate and understandable work orders automatically (useful for decision-making).	Allocation of a function to generate simplified diagnostic results.

TABLE 3 Brief description of a cyber-physical maintenance system given the requirements of Industry 4.0

Space	Layers	Main functions
Physical space	Business	Production, operations, maintenance, supply chain, and marketing.
	Asset and maintenance operations/executions	Platform, compressor, operators, and maintenance staff.
	Info/data perception	Data acquisition, eg, vibration sensor, reports, and notifications.
Transmission	Data between physical/cyber spaces	Communications and networks.
Cyber space with interface to physical space	Cyber space	Cloud solution
	Conversion (data)	Data manipulation
	Computation (information)	State detection and descriptive analytics
	Cognition (knowledge)	Diagnostic, predictive and prescriptive analytics, health, and prognostic assessment
	Maintenance management	Maintenance program planning, capacity planning, spare part planning, and scheduling
	Support decision making (optimized solutions)	Maintenance optimization
	Configuration	User interfaces and automatic actions

The paradigm of Industry 4.0 also comprises three integration levels:[37,38] integration across the entire value creation network, integration across the entire product life cycle, ie, end-to-end engineering, and integration across the manufacturing/O&M systems network.

A number of different terms are used to describe the new generation of maintenance management models (using IoT and CPS) even though the processes are more or less the same: e-Maintenance, intelligent maintenance, smart maintenance, digital maintenance, deep learning maintenance, and Maintenance 4.0. In fact, there is no standardized definition of intelligent or smart maintenance. Operation and Maintenance 4.0 (O&M 4.0) might be the best term to represent the development of O&M systems toward the Industry 4.0 vision. Moreover, standards related to Industry 4.0 and IoT will appear soon, and updated O&M standards (eg, dependability) will follow. Therefore, this paper adopts the term O&M 4.0.

The needs, requirements, and functions for intelligent maintenance management in an Industry 4.0 environment are depicted in Table 4.

4 | RESULTS

4.1 | Modeling the desired architecture

The enhanced maintenance management architecture is shown in Figure 6. The needs of Industry 4.0 and its associated RAMI 4.0 architecture, stakeholders, architecture context, and relevant standards are divided into three sections: *maintenance program*, *reporting*, and *analyses*.

First, the maintenance program function is profoundly impacted by the recommendation that Industry 4.0 architecture should be adapted at the early design phase. For example, smart equipment should have a high level of perception to enable PdM cognition and a high level of automated actuation to enable autonomous actions and prescriptive decisions. The maintenance program function should also comply with standards, such as ISO 55000, IEC 60300 (in particular, see section 3, part 15, on engineering of system dependability), and future standards of Industry 4.0.

Moreover, the maintenance program function, as shown in Figure 7, should integrate several maintenance programs: time-based, event-based, risk-based, condition-based, experience and expert-based, reliability-centered, predictive-oriented, opportunity-oriented, and prescriptive-oriented. The case study stakeholders thought that smart and cost-effective digital tools would enable them to collect the relevant data for each maintenance program so that all programs could be used. However, it is challenging to integrate these programs to provide a unified schedule and to optimize maintenance operations. Thus, the enhanced maintenance management architecture should be able to acquire, store, analyze, and visualize the data, information, and knowledge related to all these maintenance management programs, instead of selecting one or handling several in a fragmented way.

Second, the reporting function within the maintenance management architecture is highly influenced by IoT and data acquisition technologies. These technologies enhance the ability, quality, and speed of reporting the different types of data from various and multiple sources. The report function is decomposed into more detailed subfunctions to satisfy different maintenance programs, as shown in Figure 8. For example, data are reported in terms of notifications, orders, reports, records, and measurement datasets.

Third, the analyses function is definitely influenced by maintenance programs and reporting techniques. As shown in Figure 9, each type of data has its own analysis techniques, ie, algorithms and (un)supervised learning processes, to reach optimal utilization over time. Moreover,

TABLE 4 Extracted needs, requirements, and functions for intelligent maintenance management based on Industry 4.0 architecture

Source		Requirements/criteria	Functions (capabilities and characteristics)
Business			
Industry 4.0 context	Asset and maintenance operations/executions	- System should enable diagnosis and prognosis. - System should replace current fragmented functions provided by the different solutions. - System should provide access to relevant stakeholders. - System should facilitate transparency and traceability throughout the whole maintenance management loop. - System should facilitate optimizing existing maintenance schedules and thus enhance right maintenance at the right time.	- Diagnosis and prognosis. - Unified/integrated solutions. - Easy to access. - Filtered/secure access.
	Info/data perception	- Associated failure modes and root causes need to be detectable. - Seamless connection between different symptoms of failure and its associated failure mode is required. - Sensor technology must enable scrutinizing specific symptoms of failure through different sensor variables (health and process parameters).	- Systemic detection (multiple detection techniques). - Smart sensors must be allocated.
	Data between physical/cyber spaces	- Converge physical space with cyberspace. Big data to be monitored should sent to the cloud solution to be analyzed. - Manage big data transmission to the cloud solution.	Special functions to transmit a high volume of variable data at high-frequency rates from several sources with a certain veracity.
	Cyber space	- O&G operating culture needs a cloud solution (cyber space) that facilitates a seamless connection between cyber space and physical space in terms of application. This includes data storage and remote accessibility, along with diagnosis and prognosis capabilities. - Must have the capacity to store big data in terms of performance, health, diagnosis, and prognosis, along with enterprise-level data, and make them accessible.	Special functions to store, manipulate, and evaluate big data.
	Conversion (data)	- Signal analysis must be able to turn monitored signals into useful information. This comprises techniques like data filtering and coping with missing data. - Should be able to convert big data into useful information for subsequent feature extraction.	Functions for data preparation and cleaning.
	Computation (information)	- Must perform automatic diagnosis and prognosis based on monitored health and performance parameters thus yielding health assessment of the specific component and its remaining useful life (RUL) prediction, respectively. - Validity, reliability, and accuracy of the results from diagnosis and prognosis are decisive in the context of optimizing existing maintenance schedule.	- Time domain analyses. - Frequency domain analyses.
	Cognition (knowledge)	- Visualization of the knowledge and results from the diagnosis and prognosis to provide a clear understanding. - Visualization tool must present the results in a reliable way that is easy to perceive.	- Systemic diagnosis and prognosis (multiple/integrated techniques). - Data-driven diagnosis. - Model-based diagnosis. - Mixed diagnosis. - Data-driven prognosis. - Model-based prognosis. - Mixed prognosis. - Reliability-based prediction, eg, Weibull prediction.

(Continues)

TABLE 4 (Continued)

Source		Requirements/criteria	Functions (capabilities and characteristics)
Business			
	Maintenance management	- Enterprise level data that facilitate the next stage of maintenance optimization and maintenance program planning. - Comprise relevant enterprise-level data, such as forecasted production plans, spare part indicators and logistics, available resources, and detailed descriptions of the relevant equipment, along with its components.	- Maintenance planning/scheduling.
	Support decision making (optimized solutions)	- Access to all parameters included in maintenance optimization. This requires the diagnosis and prognosis results, along with enterprise-level data, such as production forecasts, storage-level indicators, equipment information (eg, P&ID), etc. - Transparency of data and results from calculations.	- Maintenance optimization. - Maintenance decision making.
	Configuration	Needs to communicate the required maintenance action to the execution agent. Hence, converge the information from the cyberspace in terms of maintenance optimization solution and perform it in the physical space—thus, the right maintenance is executed at the right time.	- User interface of CMMS. - Mobile interfaces. - Utilization of artificial reality/virtual reality aids.

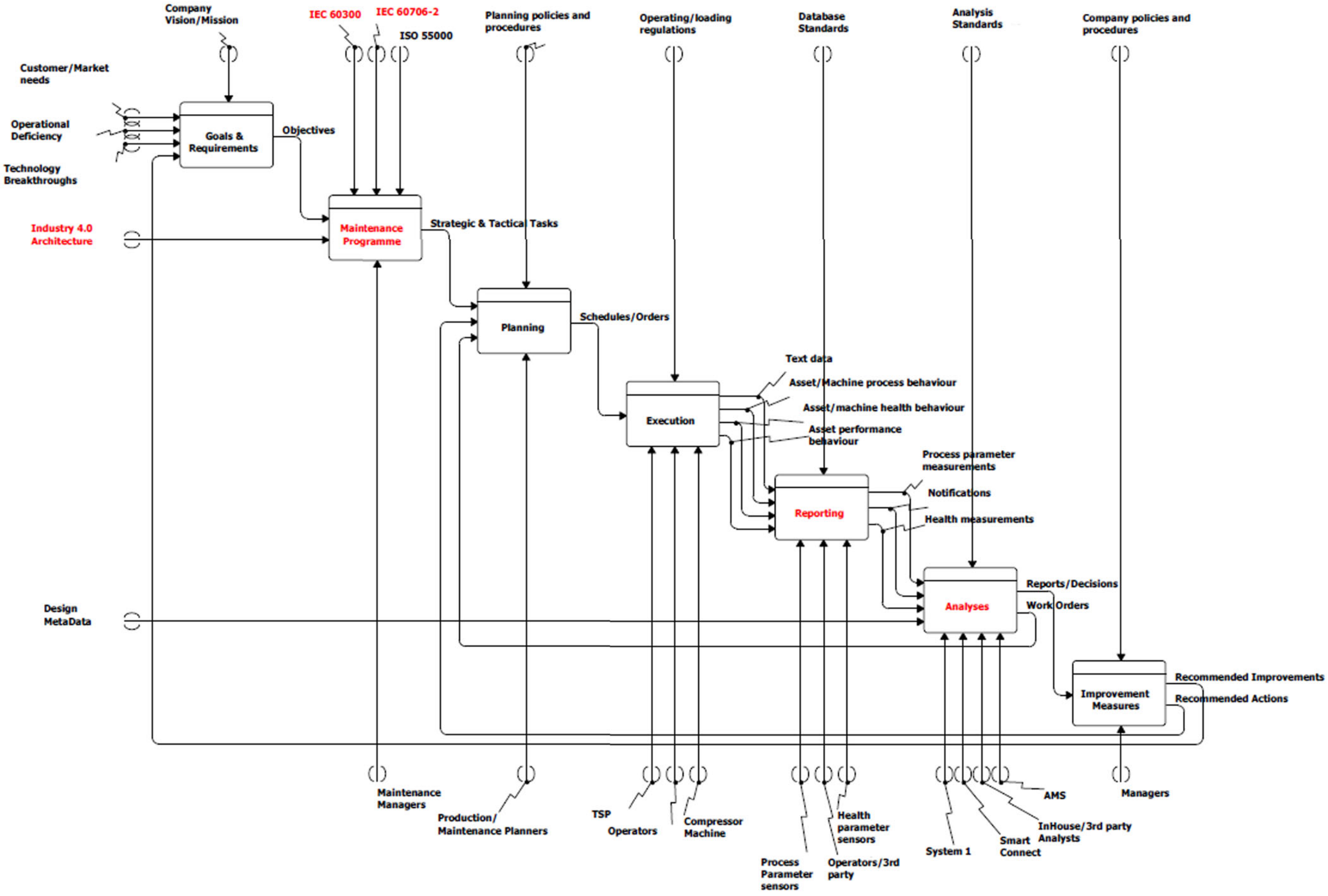

FIGURE 6 IDEF representation of the enhanced maintenance management architecture

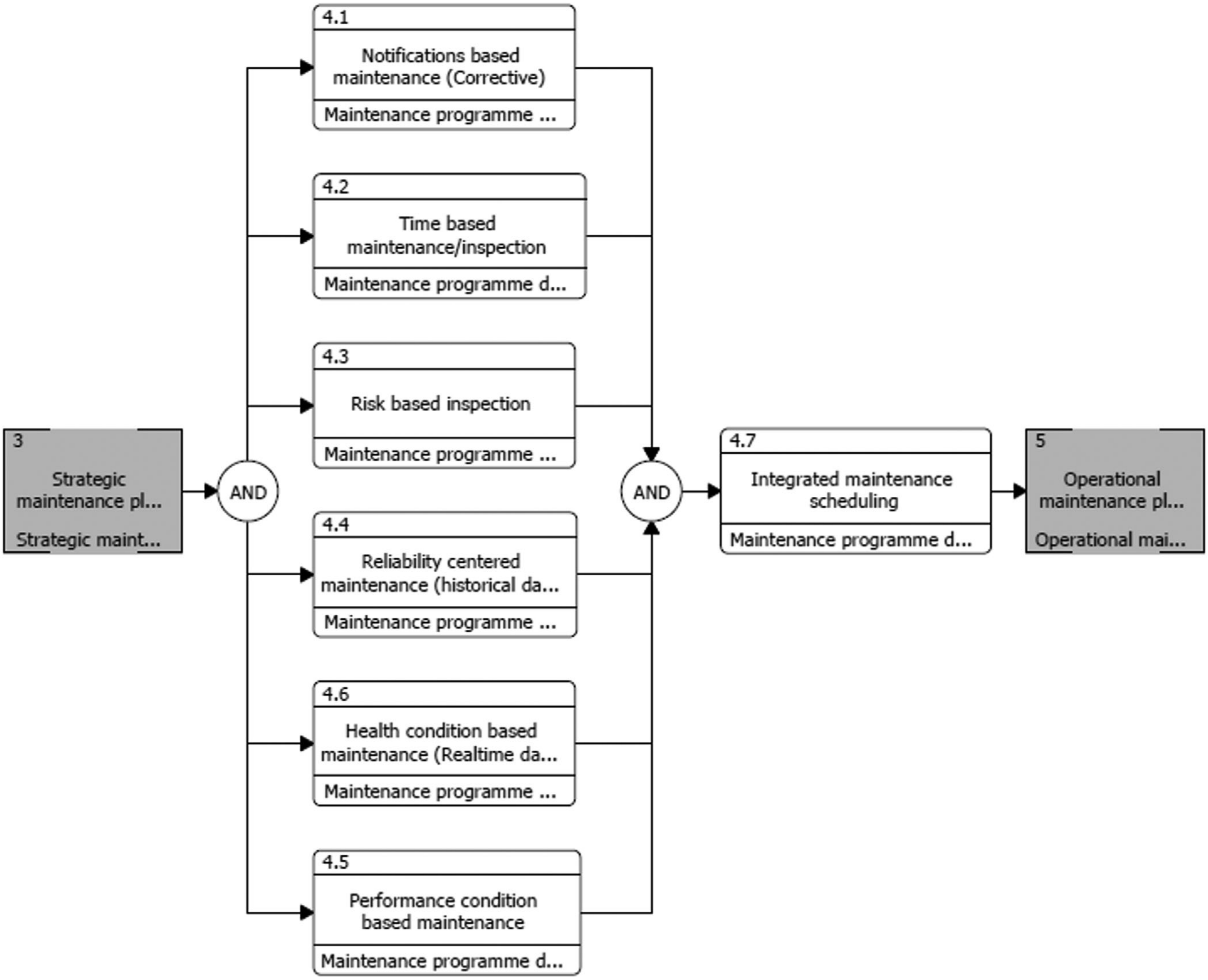

FIGURE 7 Logical decomposition of the function of “Maintenance program”

the analyses in an Industry 4.0 era are expected to reach the system level and reveal critical systemic dependencies. For example, performing PdM for specific assets might influence their operational reliability and risk assessment measures, ie, frequency and consequences. The case study stakeholders' expected system-level analyses would help to optimize the operations of different maintenance programs, minimize associated production losses of the unintended maintenance events, and lead to reduced costs, high levels of services, and asset life extension.

To summarize, the new monitoring use case scenario based on this new Industry 4.0 architecture starts with an intelligent maintenance system that acquires process and health parameters, ie, big data, from the equipment. The data are (pre)processed and analyzed, ie, diagnosis and prognosis, through the application of cloud computing. Based on the results from the diagnosis and prognosis, combined with the enterprise-level data, such as production forecasts, available resources, and spare part management, etc., the intelligent maintenance system develops reports and work orders for associated spare parts, tools, and resources that are integrated into the SAP system. In the case study company, SAP should be integrated into the intelligent maintenance system as the reporting system for two reasons: first, the personnel already have experience with this specific solution; second, SAP recently initiated a collaboration with MIMOSA[39] to create an open system architecture for condition-based maintenance (OSA-CBM)[40] as an implementation of the ISO 13374.[41]

The TSP can continuously control and supervise the work of the intelligent maintenance system. In contrast, the operator only receives a notification whenever the system identifies an operational anomaly, and the visualization indicator changes (eg, traffic light changes from green to yellow or red). After the work order, the TSP and the operator must collaborate to develop a risk analysis (eg, SJA), before the TSP technicians and experts (if necessary) execute the specific maintenance action at the given time by the specific procedure, as indicated in the cloud solution. When the equipment is back in operation, the intelligent maintenance system automatically updates the diagnosis and prognosis and thus the associated visualization indicator. Hence,

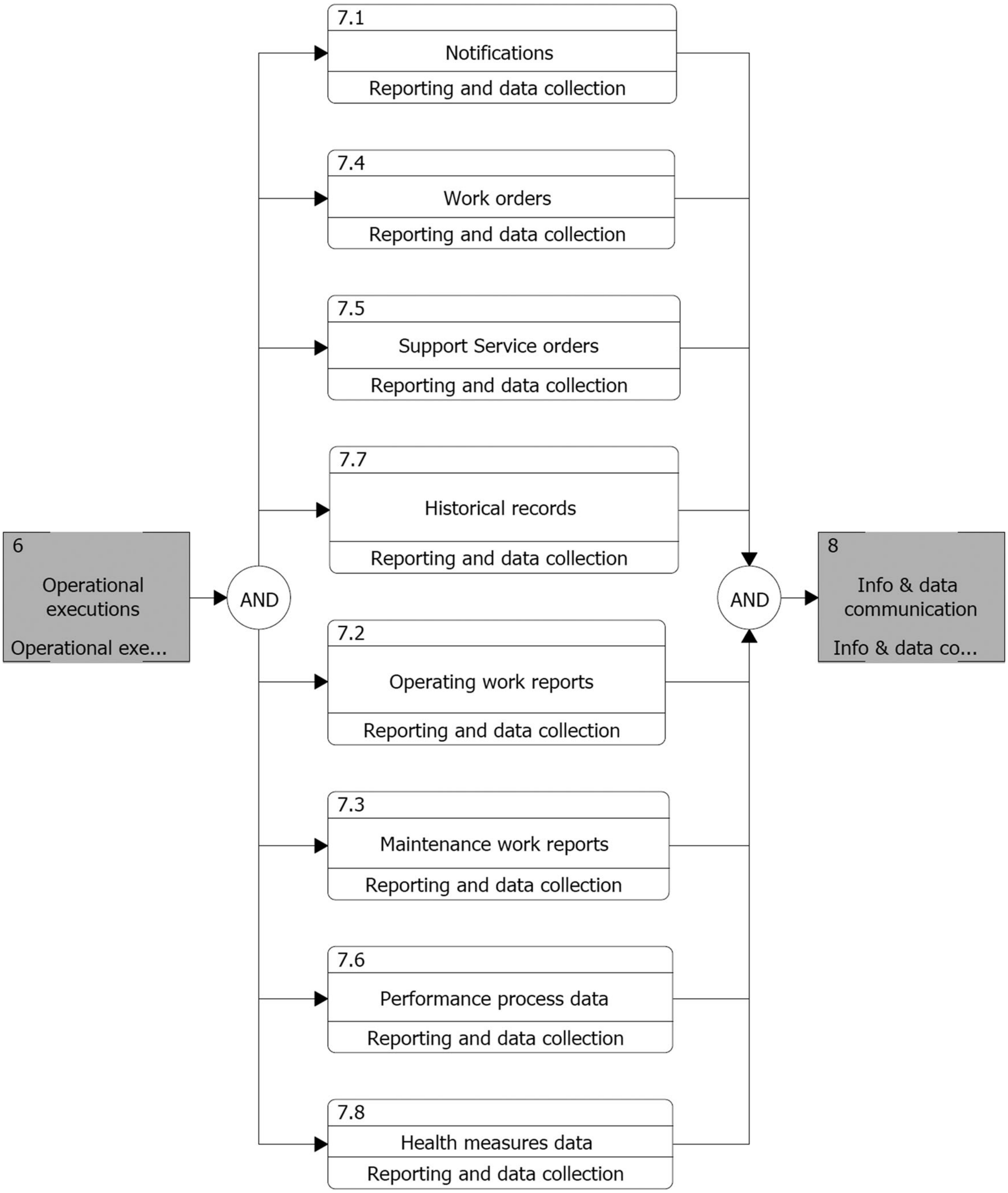

FIGURE 8 Logical decomposition of the function of “Reporting”

the TSP and the operator receive a notification that verifies and validates the success and effectiveness of the specific maintenance action.

Compared to the traditional monitoring scenario depicted in Figure 4, the future monitoring scenario will facilitate a seamless connection between the equipment and component at the floor level, in the cloud solution, and at the enterprise level of the TSP and the operator. It will ensure reliable analyses and decisions with improved flexibilities and capabilities in both short- and long-term scenarios. In addition, it will replace the need to rely on several different solutions that are not well integrated and thus provide limited capabilities.

Finally, predicting the behavior of equipment health will leverage the O&M of this specific case-study asset, as well as other parts of the O&G value chain, both upstream and downstream.[2,42–44] In general, the predictions generated by health behaviors will facilitate opportunistic maintenance that supports balancing the O&M of the entire value chain. It will also improve the transparency of the gas transportation from production to consumption, whereby the upstream knows the exact amount of gas the downstream demands, and the downstream knows the exact amount of gas that is ready to be supplied to the market. Benefits include the prevention of equipment failures

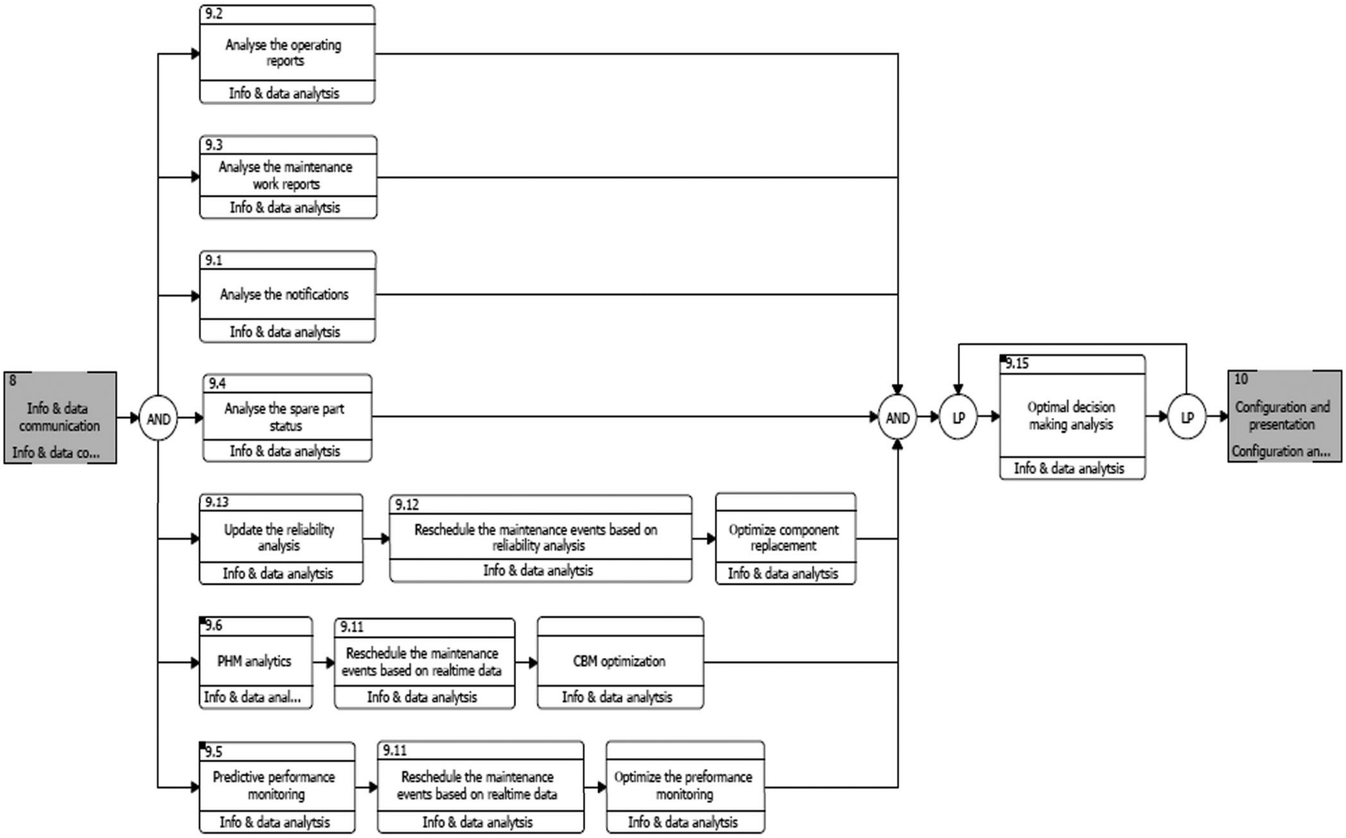

FIGURE 9 Logical decomposition of the function of "Analyses"

and the extension of the equipment life, resulting in reduced unscheduled downtime and increased asset utilization rate.

5 | CONCLUSION

The paper has developed a reference architecture design for intelligent maintenance system deployment in the era of Industry 4.0. The first conclusion is that the existing maintenance management architecture used by the case study O&G company does not satisfy the requirements of Industry 4.0. The comparison of the extracted functions based on an Industry 4.0 architecture and the existing functions based on the system context and the use case scenarios clearly indicate that some new functions are required and others must be upgraded. The new functions are mainly related to the perception coverage (sensors that perceive symptoms of critical failure modes), computation capabilities (algorithms that detect symptoms of fault evolution over time), and cognition capability (process abnormality detection, health diagnosis, process performance, and health prediction). The functions to be upgraded are related to data infrastructure and configuration (storage, connection, transmission, accessibility). The business model and human interfaces still dominate the performance of the existing architecture. This can delay access to data, analyses, and relevant maintenance decisions.

The second conclusion relates to the difference between the architecture based on PAS 55 and that based on Industry 4.0. The new and upgraded functions also represent the difference between the Industry 4.0 architecture and its requirements (and this paper's study of maintenance management) and the PAS 55 standard and its maintenance management architecture (described by Campos and Márquez[10]). Several functions at different communication levels must be clarified to enable a maintenance management architecture to comply with an Industry 4.0 architecture; these include asset-to-asset, asset-to-enterprise, and enterprise-to-enterprise communication. Moreover, a maintenance management architecture requires an advanced level of computation and cognition analysis (machine learning analytics, predictive health analytics, reliability analytics, and maintenance optimization). It is worth noting that several communication and analytic techniques have already been developed; they are not in use, however, because of difficulties in data collection.[45] This data collection challenge might potentially be solved by acquiring big data according to the characteristics relevant to the Industry 4.0 architecture (volume, velocity, veracity, variety, variability).

The third conclusion stems from the stakeholders' concern that implementing a new maintenance management architecture and ensuring its acceptance depends on how the maintenance operations are managed in that specific organization/sector and the CMMS in use (and its use case scenarios). In the O&G sector, the maintenance management loop and its functions[8] are well established; the terminology is standardized and has been used since the 1980s. There is no point changing current use of "analyses" and replacing it with "conversion, computation, cognition, and configuration," especially when the word "analyses" already covers these other terms. Nevertheless, the "analyses" function must be upgraded to enable the advanced computation and cognition analyses required in the Industry 4.0 context. Therefore, the architecture developed here builds on the maintenance management loop[8] and upgrades it based on the RAMI 4.0 model,[35] not the opposite.

We hope that our proposed industry-oriented approach to modeling new architecture will increase the probability of acceptance. In the new model, the ERP and CMMS will be the main configurations to communicate with real-time monitoring services (in-house and third part). Those systems will be enabled to receive analyzed data to optimize a decision and provide historical or metadata to the other services of analytics. This means the CMMS will provide new capabilities to store, access, manipulate, analyze, and evaluate a high volume of data arriving with high frequency from different resources and do so at a high level of veracity and variability. Moreover, the exploration of the benefits of IoT, cloud computing, and big data might influence stakeholders to expand their sensor coverage and algorithms; this means the CMMS would be flexible for reconfigurations and user-friendly enough to be done by users themselves.[46]

Because no standardized maintenance architecture currently complies with Industry 4.0, we expect that the NPD will update its traditional architecture and create state-of-the-art maintenance management guidelines. Before doing so, the NPD must first highlight issues related to cyber security and work processes. Other O&G companies are beginning to work on similar challenges.[5]

The fourth conclusion concerns the novel maintenance management architecture developed. Unlike the traditional maintenance management loop, the proposed complex maintenance program is based on interfaces between different types of data (eg, historical records, real-time measurements of performance and health, expert-just-in-time). The most extensive upgrades needed for the traditional management loop to comply with the requirements of Industry 4.0 relate to the functions of "maintenance program," "reporting," and "analyses." These upgrades will depend on the application of sensor technology to monitor performance and health parameters and the development of algorithms for cloud computing, ie, diagnosis and prognosis. The results will be combined with the enterprise-level data to identify the best and most opportunistic maintenance window.

This study stayed mainly at the architecture level; consequently, the missing and upgrading functions require more detailed investigation. This includes analyzing the failure modes at the component and system/process level to determine the required specifications of those functions. Therefore, the next step will be to analyze the whole compression system and its behavior to explore the component and process symptoms of faulty behavior. Another consideration is that the number and types of stakeholders were limited in this case study; the next step will be to involve other stakeholders, eg, technology experts and developers, to extract more detailed functions and features.

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