MODULAR MAINTENANCE DECISION ARCHITECTURE

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ABSTRACT

The operation of large production assets requires many decisions from the acquisition and design of new assets to the choice of lubricant for a specific piece of equipment. The decisions made in maintenance have a direct effect on the management of the production process, making it important to ensure correct maintenance decision making. However, studies on maintenance decision making tend to focus on smaller areas of decisions being made in a process, but rarely the entire process. To introduce more studies that consider the entire maintenance process, this paper proposes using a modular Maintenance Decision Architecture. The paper introduces a framework for structuring information sources into standardized information modules and mapping them to maintenance decisions made across the entire organization. The application of approaches from product, system, and service engineering are used to support the management of the complexities of maintenance of large production facilities.

Keywords: Decision making, Product architecture, Big data

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1 INTRODUCTION

The operation of large production facilities requires informed decision making, ranging from decisions on the purchasing and design of new assets down to which lubricant to purchase for repairing a component. In the operational stage of an asset, the decisions made about maintenance have a direct effect on the management of the entire production process (Ruschel et al., 2017). Decision are made based on available information and experience of the decision maker. However, the quality of decisions can generally be hindered by not considering enough alternatives, evaluating alternatives in a disorganized manner, or not spending enough time per decision. Introducing data sets such as big data can help mitigate these drivers of faulty decisions, but factors such as stress perception during decision making and a lack of analytical skills can also hinder the decision quality when using big data (Ghasemaghaei & Turel, 2022). The study by Ghasemaghaei & Turel (2022) indicates that decision making quality when using big data can be improved through a series of interventions, one of which is the use of data analytics tools. However, harnessing operational data for the use in maintenance decision making is a generally underutilized approach (Chilamkurti et al., 2014; Hodkiewicz & Ho, 2016). Though literature on data-driven decision making in maintenance exists, it tends to use simulated or otherwise perfect data that is typically not available in companies (Chilamkurti et al., 2014; Hodkiewicz & Ho, 2016). The processing and transformation of the data often requires collaboration across an organization and especially including the decision makers in the process (Janssen et al., 2017) and making sure the transformations of the data are clear to them (Coussement & Benoit, 2021), makes decision makers more likely to trust and utilize the data (Coussement & Benoit, 2021; Janssen et al., 2017). As achieving this is in part an issue of the complexity of the data, this paper proposes the application of an architecture framework based on architectures from product, service, and maintenance architecting. Architecture studies have shown that the application of architecture and modularization approaches can improve a company's ability to manage large, complex product portfolios while still being able to deliver wide ranges of variety to customers (Mortensen et al., 2016; Simpson et al., 2014; Ulrich, 1995). The approaches have more recently been applied in fields such as services and maintenance as well, showing promising results in these more intangible and multidimensional domains as well (Julie Krogh Agergaard et al., 2022; de Mattos et al., 2021; Eissens-van der Laan et al., 2016; Kristoffer Vandrup Sigsgaard et al., 2022). The study in this paper applies an architecture approach from engineering design in order to map decisions to standardized information modules. This is to help communicate the handling, quality, and availability of the information sources used in decision making. Therefore this paper seeks to answer the following research question: *How can an architecture approach help improve information source utilization in maintenance decision making?* By architecture is understood a scheme by which functions are mapped to components (Ulrich, 1995). In this paper, a decision is understood as the function of maintenance management and information sources are the components of the architecture. This paper studies the improvement of information source utilization as a qualitative increase in the use of information sources in decision making within the organization. The research question led to a proposed architecture framework that was then applied in a case company. Multiple types of decisions made using the Maintenance Decision Architecture are highlighted and the benefits of applying the framework compared to the current company approach are discussed.

This paper is structured as follows: the second section is an introduction to the research methodology applied in the study presented in this paper; the third section introduces literature on the subjects of data-driven decision making and architecting; the fourth section introduces the proposed architecture framework; the fifth section introduces the application of the framework in a case company; the sixth section concludes on the study and discusses the case study findings compared to the literature and the uncertainties of the study.

2 RESEARCH METHODOLGY

The study presented in this paper followed a process close to the Design Research Methodology (Blessing & Chakrabarti, 2009). The study began with an observation in a case company of the lack of control and utilization of the information sources for decision making across the organization. This led to a lot of uncertainties in the decisions being made across the organization. The observation showed a need for a clarification of research on decision making and the standardization of information sources for decision making in research. As a need for more studies in this area was identified, the review turned to

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architecture approaches that are useful for the standardization and visualization of complex systems using architectures that span across an entire organization. Different stakeholders from the case company were then interviewed in semi-structured interviews to understand how the company utilized or did not utilize data in a multitude of different types of maintenance decision making. As it was observed in both the case company and literature that a format for structuring and aligning information sources across the organization was needed, the Maintenance Decision Architecture framework was developed. Multiple smaller case studies were performed at the case company to verify the usability of the decision interfaces that were designed based on the architecture.

The case company operates large offshore production facilities. Maintenance on the platforms is essential to ensuring availability of the equipment, and safety for the personnel and environment on and around the plants. The company has operated these same plants for many decades. With the introduction of a Computerized Maintenance Management Systems (CMMS), the company converted from paper-based to electronic maintenance management. All information created in the CMMS since its beginning in 2010 is stored, but is an underutilized resource of knowledge, as there has historically been a lack of the analytical skills required to harness the value. At the same time, the company works within silos, with no information management roles that go across the organization. As the facilities are aging, the daily decision making has become more and more focused on fixing critical errors, leaving little time for data exploration beyond the expertise of the employees. The information collected at the company comes from their CMMS and documentation of their physical plants in the form of 2D piping and instrumentation diagrams and design briefs. The knowledge collected about the maintenance process and the decisions made throughout was collected through semi-structured interviews and workshops with stakeholders throughout the organization: from the engineers doing detailed maintenance job planning to managers making more strategic decisions.

3 LITERATURE REVIEW

Maintenance is a necessary operational effort to keep equipment running as they were designed to. It is the responsibility of maintenance management to ensure availability of the equipment as well as safety of the people and the environment around the equipment. All of this while trying to minimize costs. An essential part of achieving this is maintenance management. Maintenance supportability is the ability of a maintenance organization to support the required maintenance. A core function of this support is decision making support (Dansk Standard, 2017). In order to make decisions, some type of knowledge or information foundation is typically required (Julie K. Agergaard et al., 2022a; Kristoffer V; Sigsgaard et al., 2020). Information exists in all kinds of forms. As an example, in a development processes, data is generated throughout the organization's systems in such as the Product Lifecycle Management (PLM) system in product development (Stark, 2016) or the development of maintenance operations in a Computerized Maintenance Management System (CMMS). But transforming such raw data into something useful for decision making is a big task (Bhat et al., 2013; Chilamkurti et al., 2014; Coussement & Benoit, 2021; Ghasemaghaei & Turel, 2022; Hodkiewicz & Ho, 2016; Janssen et al., 2017; Stark, 2016), making it a generally underutilized resource (Hodkiewicz & Ho, 2016).

Streams in data science tend to focus on pre-processing methods rather than how to bring the data to the decision makers (Coussement & Benoit, 2021). Decision makers might then be reluctant to use the data when they cannot see how the results were obtained (Coussement & Benoit, 2021), were not included in the process of developing the tools (Janssen et al., 2017), or generally lack the analytical skills to understand the big data sets (Ghasemaghaei & Turel, 2022). Still, a company's ability to transform raw big data into decision making tools in collaboration with decision makers have been shown to impact the performance from the use of the data (Janssen et al., 2017). In maintenance operations development, data is created throughout the process, but is a generally underutilized resource due to mistrust of the quality (Hodkiewicz & Ho, 2016) and the requirements for making the data available such as the wide amount of people required for the process (Hodkiewicz & Ho, 2016), the quality of the data (Chilamkurti et al., 2014; Hodkiewicz & Ho, 2016), frequent changes of the data (Chilamkurti et al., 2014), the levels of cleansing required (Hodkiewicz & Ho, 2016), and a general lack of approaches that work for real life data not just simulated data (Chilamkurti et al., 2014). Use of data is also minimized when it is generally unknown who is responsible for what (Chilamkurti et al., 2014; Hodkiewicz & Ho, 2016). The use of big data in decision making is a big topic in both research and industry, but the impact of the use of big data on the quality of decision making is reported with mixed, unclear results (Ghasemaghaei & Turel,

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2022; Janssen et al., 2017). Janssen et al. (2017) found that the quality of the decision is influenced by the quality of the source data, the processing of the data, and how the transfer of data is handled. They concluded that this shows a need for appropriate mechanics for handling the big data management process. Ghasemaghaei & Turel (2022) studied the effect of stress in the use of big data for quality decision making. They found, that allocating resources to big data processing will not necessarily increase the quality of decisions, as stress plays an important factor in decision quality. As such, the study found that the right level of autonomy in decision making can reduce stress and subsequently improve decision quality. Another lever in reducing the stress can be introducing data analytical tools, and improving the analytical skills of the decision makers. But this needs to be further studied in the context of big data. From the studies on decision making in maintenance it is seen that more information such as an operational data source can improve decision making, but that the data is often underutilized due to multiple barriers, many of which stem from the size and complexity of the data.

4 MAINTENANCE DECISION ARCHITECTURE

The use of data can enhance the quality of decisions made in an organization (Ghasemaghaei & Turel, 2022; Janssen et al., 2017), but data generated throughout an organization is typically an underutilized resource (Hodkiewicz & Ho, 2016), as reaching the stage at which data is useful to decision makers requires data processing (Chilamkurti et al., 2014; Hodkiewicz & Ho, 2016), multiple stakeholders (Hodkiewicz & Ho, 2016), data handling and analytical skills (Ghasemaghaei & Turel, 2022; Janssen et al., 2017), and more clear definitions of responsibilities (Chilamkurti et al., 2014; Hodkiewicz & Ho, 2016). At the same time there is a general lack of methods that can be applied to real-life, imperfect data (Chilamkurti et al., 2014), such as operational data generated throughout a development process. As these factors stem in part from the complexity of the systems surrounding the maintenance, this paper proposes the use of approaches from architectures to standardize the process and gain an overview that is not currently available. Architectures and platforming approaches are used for standardizing and managing large, complex systems (Otto et al., 2016; Simpson et al., 2014). The field has been developed over many decades within product portfolios (Meyer & Utterback, 1992; Mortensen et al., 2019) and engineering systems (Selva et al., 2016), and has more recently been implemented in fields such as services (de Mattos et al., 2021; Tuunanen et al., 2022), product-service systems (Cenamor et al., 2017; Johnson et al., 2021), and maintenance operations (Julie K. Agergaard et al., 2022b; Julie Krogh Agergaard et al., 2022; Kristoffer Vandrup Sigsgaard et al., 2022). This paper takes basis in the definition of a product architecture as the scheme by which functions are mapped to physical components (Ulrich, 1995). By defining modules from this scheme and standardizing the interfaces between them, companies are able to mix and match modules to create variety demanded by customers (Mortensen et al., 2016; Ulrich & Robertson, 1998). A major development in systems architecting was the introduction of frameworks. The frameworks help system architects achieve a common language that can facilitate communication across teams (Selva et al., 2016). As maintenance architectures are still at the beginning stages, the research is currently moving towards developing and verifying frameworks that can achieve similar benefits in maintenance management (Kristoffer Vandrup Sigsgaard et al., 2022). This section introduces such a framework.

While the development and execution of maintenance operations is quite dissimilar from product design, it is more similar to services as they are also intangible and multidimensional, indicating that the benefits reported so far from services (de Mattos et al., 2021) might also be seen in maintenance management (Julie K. Agergaard et al., 2022b; Julie Krogh Agergaard et al., 2022; Kristoffer Vandrup Sigsgaard et al., 2022). The study by (Kristoffer Vandrup Sigsgaard et al., 2022) proposes understanding the architecture in the dimensions physical, action, and process. Combining the views in a high level architecture gave an overview that allowed segmentation and regrouping of maintenance activities that was not previously available (Kristoffer Vandrup Sigsgaard et al., 2022). The same three dimensions were utilized by (Julie K. Agergaard et al., 2022b) to modularize maintenance jobs with the goal of clarifying and then improving the impact of maintenance on the amount produced.

The proposed framework for the Maintenance Decision Architecture is shown with a bike example in Figure 1. The framework maps information modules to decisions made throughout an organization. The decisions included in the architecture are ordered from strategic to more detailed decisions. An 'X' between a decision and an information module indicates that the information in tha t module is required to make the decision.

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		Decisions to be made				
		Strategic				Detailed
Information Modules	Interface	Replace Bike	Replace Part	Repair whole bike	Repair part	Take the bike or the bus
Part Specifications	Part Name	X	X	X	X	
Part status	Part Name		X	X	X	
Failure Notifications	Part Name		X	X	X	
Weather reports	Weather Type					X
Bike Conditions	Part Name + Weather Type	X		X		X

Figure 1: TOP: The maintenance decision architecture framework. The organization's decisions are mapped to standardized information modules. BOTTOM: Example of decisions made around the ownership of a bike.

The format of the proposed Maintenance Decision Architecture framework maps standardized information modules to different decisions made throughout the organization. This gives an overview of what information was used for each decision, and allows the configuration of decision making tools. Forming all of the decision making tools used in an organization from the architecture ensures that the information used for the decisions are the same. This can help align the language used and ensures that results from decisions in different parts of the organization will not be based on contradictory data. Likewise, changes in the data sources can be rolled out across the organization from a central point. The mapping also allows traceability of the information used for different decisions in an organization, meaning it is always possible to go back and see the content of information modules used in a decision making tool.

This section uses a bike example to further describe the Maintenance Decision Architecture framework. A simple architecture for bike maintenance decisions is shown in Figure 1. The example concerns decisions made around the maintenance of a bike. The contents of the bike example Maintenance Decision Architecture were developed in an iterative process, connecting decisions surrounding the operation of the bike and the available information modules. The following sections describe each of the elements of the framework using the bike example.

4.1 Information modules

An information module is a collection of interconnected information. The content of the information modules is any formalized data source that can be commonly accessed across the organization. Delimiting the information sources into information modules is based on how the data is structured in the company and how it is generally used. This paper proposes delimitation of thee information source in a way that changes them the least from their raw data format. This will help avoid complications in the transformation of the information sources for use in decision tools and help increase traceability of the information sources at later stages. Each information module connects to other types of information through a standardized, well defined interface. The modules define the dimensions physical, action, and process proposed by (Julie K. Agergaard et al., 2022b) for the maintenance jobs. Instead of interfacing through the dimensions as proposed for maintenance job modules by (Julie K. Agergaard et al., 2022b), the information modules interface other information modules through information types. Deciding on the interfaces will depend on the chosen delimitation of the information sources and which information types are available across the majority of the information modules. It is also necessary to ensure that the selected interfaces makes the information modules link to all the modules, otherwise some modules will not be combinable.

For the bike example the interfaces in play are part names and weather type, as these are the commonalities across the tables. The information modules available for the bike example are part specifications, part status, failure notifications, weather reports, and bike conditions. The majority of modules interface to other modules using part names, while weather reports match with weather type. Bike conditions is the information module that ties together all of the modules by interfacing with both part names and weather types, making the interfaces selected for the other modules feasible. Weather Reports is a detailing of real-time weather data. The Bike Conditions module describes the general information about the bike including a list of all parts and their compatibility with weather types. The Part Specifications module includes detailing information about all of the parts of the bike. The part Status module describes the current status and age of the parts of the bike. Part statuses range from good-as-new to not-functioning. The Failure Notifications module is a collection of reports of the parts not functioning as needed. This module also describes the historical failures on a part.

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4.2 Decisions to be made

One of the types of elements in the framework is the decisions to be made. These are decisions made within the organization. To distinguish between different types of decisions, the framework ranks the decisions from strategic to detailed. For the bike example, the decisions rank from a complete replacement of the bike, through part replacement, full bike repair, part repair, down to the most detailed decision of deciding whether to take the bike or the bus. All of these decisions require some type of knowledge to do. In order to replace a part the person maintaining the bike needs to know the specifications of that part. Or if the whole bike needs repairing, the person maintaining the bike needs to know which parts have failed to bring the right tools. Mapping the decisions to the standardized information modules is where the value of the Maintenance Decision Architecture is created. When it is understood which information is used for what decisions, it is possible to trace back decisions when confirming validity and the information that lies at the base of the decisions is the same, aligning the decisions across the organization no matter the organizational structure. If the information modules are formalized in a central data source used by all the developed decision tools, it will also be possible to roll out data changes and do version control across the entire organization. The standardized format of the interfaces also allows the addition of new decisions or data modules when the company changes the information sources. If the interfaces stay the same, decision makers can continue to use the information modules without large rework requirements of the decision making tools.

Decisions included in the Maintenance Decision Architecture framework should be as many as possible. However, only decisions that can be based on the available data from the information modules can be included. It is important to define which decisions were not included in the architecture. These may be available through more data collection or with the implementation of other technologies.

For the bike example, a decision that cannot be based on the currently available information modules is how much effort to put into biking to the destination. This decision requires knowledge about the energy level of the bike rider, distance to the destination, and the required remaining energy level at the destination. While the architecture is currently not able to handle this, it is possible in the future to expand the available modules to include this type of information. The added information modules just need to be able to interface with the remaining data modules.

The framework also needs to be continuously updated to ensure that the benefits are always available. If the version control and updates are not rolled out it will no longer be possible to trace back the information modules used for a decision. If decisions are made that are not included in the Maintenance Decision Architecture, benefits of cohesive information foundation and the ability to roll out changes to the entire organization fall away.

5 CASE STUDIES

This section introduces the application of the proposed Maintenance Decision Architecture Framework in a case company. The current approach is compared to the approach with the use of the Maintenance Decision Architecture and the differences are highlighted.

The case company operates large offshore platforms. The platforms are made up of more than 300.000 pieces of interconnected equipment that operates as close to continuously as possible. Decisions within the company are typically based on the experience of the employees, as the data that is created throughout the operational process are spread out in multiple sources and are barely standardized. In the As-Is state of the company, a vendor software was in use for the Computerized Maintenance Management System (CMMS) and for the plant documentation in the shape of Production Flow Diagrams and Piping and Instrumentation Diagrams. The CMMS was used to manage the workflow and the data created throughout the maintenance process, but did not have decision support abilities beyond showing manually filtered information in a tabular format. The plant documentation software was able to show the as-built documentation of the plants, but had no live link into the maintenance process, meaning the users had to manually identify activities within the plant documentation. Identifying activities was how the majority of time was spent in decision making. Figure 2 shows an excerpt of the Maintenance Decision Architecture for the case company.

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		Decisions to be made					
		Strategic					Detailed
Information Modules	Interface	Future Facilities	Configuration formulation	Large shutdown Clustering	Equipment Restarts	Isolation Area Definition	Failure History
Production Flow Documentation	Location Tag			X	X		
Piping & Instrumentation Diagrams	Location Tag			X	X	X	
Maintenance Orders	Location Tag + Order Number	x	x	X	X	X	x
Maintenance Production Impact	Order Number	x		X		X	x
Maintenance Operations	Order Number	x	x			X	x
Material Availability	Order Number			X		X	
Equipment Characteristics	Location Tag	x	x		X		x
Failure Notifications	Location Tag	x			X		x

Figure 2: Maintenance decision architecture for the case company.

The first step in creating the architecture was identifying decisions that were being taken within the organization that could benefit from the addition of structured, formal information. This was done through semi-structured interviews with experts from different parts of the organization. The decisions studied using the Maintenance Decision Architecture framework proposed in this paper are shown in Figure 2: Future facilities - designing future facilities based on maintenance impact; configuration formulation - basing the contents of an operational configurator on historical data combined with expert knowledge; large shutdown clustering - finding opportunities for clustering that can help improve production availability; equipment restarts - identifying impacted sensors that need testing before the restart of equipment that has been out of service; isolation area definition - trade-off decisions on expanding an area of the facilities that has been affected by maintenance; failure history - designing new maintenance jobs based on past best practice. The delimitation and formulation of information modules was then made based on the information required to take these decisions as well as the structure of the raw information currently available at the company. As the company uses a central Computerized Maintenance Management Software (CMMS), the tables available in this system were the foundation for the modules. The modules included that were not available in the CMMS were formulated as modules based on the detail level of the information as well as the internal department responsible for the information, e.g. Production Flow Diagrams and Piping & Instrumentation Diagrams separately even though they are managed by the same department. This means that for a given required level of detail only module is needed and that when actions are taken regarding the specific contents of a module, only one department needs to be involved. The information modules included in the Maintenance Decision Architecture (Figure 2) are: Production Flow Documentation - Interface: Location Tag - Description of the overall production flow from extraction to export. Connects larger equipment to each other. The production flow can be visualized; Piping & Instrumentation Diagrams - Interface: Location Tag - Detailed description of all pieces of equipment and how they are connected. The detailed diagrams can be visualized; Maintenance Orders - Interface: Location Tag + Order Number - General maintenance job information. Main function is to link orders to the location where they were performed; Maintenance Production Impact - Interface: Order Number - Describes the impact of the maintenance on the production flow, both the affected area and the extent of the impact; Maintenance Operations - Interface: Order Number - Detailed description of the actions that need to be taken within a single maintenance job. Also describes requirements such as skills, materials, and planned time; Material Availability - Interface: Order Number - Shows expected delivery dates of the material required for the maintenance jobs.; Equipment Characteristics - Interface: Location Tag - Describes the type of equipment, components, and specification of the piece of equipment present at a location tag; Failure Notifications - Interface: Location Tag - Reports of equipment failing to perform within function. Includes how the failure was discovered, the perceived cause of the failure, and the part of the equipment's function that is outside of specification. These modules were selected based on availability, quality of data or the processing options available to improve the quality, and relevance to the identified decisions. All information modules were standardized into a data format and made into singular tables that could be used in a data model in a business intelligence tool. To illustrate the use of the information modules for different decisions the following subsections introduces two of the individual case studies from within the case company.

5.1 Future facilities

Decision details: A not uncommon decision in large organizations is the acquisition and/or design of new facilities. The decision in this case study focused on the strategic design decisions in the design of new oil and gas facilities based on the maintenance impact during the operational phase.

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Current approach: The case company set out to perform this decision based on engineering experience as the only source of historical information.

With the information modules: Using the information modules, a decision tool that maps cost of maintenance to the design of an asset was created. Specifically, historical data from the information modules Maintenance Orders, Maintenance Production Impact, Maintenance Operations, Equipment Characteristics, and Failure Notifications were used to achieve such an overview.

Difference: The decision tool allowed decision makers to add quantified expected costs of maintenance to different design configurations of the future facilities. No precise quantifications of the operational stage of the life cycle of an asset was available prior to this. The Maintenance Decision Architecture was used to document the information used to make these high impact decisions.

5.2 Large shutdown clustering

Decision details: Impact of maintenance on the continuous production flow is one of the biggest operational costs for the case company. A decision exercise that greatly can maximize availability is the opportunistic grouping of maintenance with production impact when a critical shutdown is already happening.

Current approach: In order to identify impacted equipment, decision makers are manually surveying drawings and looking up open maintenance within the tables of the CMMS. This is time consuming both due to the many manual steps involved, and because the information required exists in four different sources.

With the information modules: Combining the understanding of the production flow and connectivity of equipment with the maintenance activities and the material availability made it possible to decide which maintenance actions could be opportunistically handled within the planned shutdown.

Difference: The time it takes to find the opportunities for clustering was greatly minimized, making it possible to perform the decision on both long and short terms no matter the amount of other tasks. This gave more time for the decision makers to focus on choosing the right combination of orders within the shutdown instead of spending hours looking for and visualizing the information. See Agergaard et al. (2022b) for a more in depth description of this case.

5.3 The general impact of the maintenance decision architecture

As seen from the examples described in the previous sections, the introduction of the Maintenance Decision Architecture allowed the design of decision interfaces that were not available before. In the cases either information took a long time to acquire and structure or was not used at all. For configuration formulation, historical operational text was used to identify the options for the configurator. Without the historical data the discussion would have been about preferences of the experts rather than the quantified choice that was enabled by the architecture. The equipment restart and isolation area cases utilized a decision interface similar to the one described for the large shutdown clustering case described in section 5.2. This enabled the automatic identification of equipment affected in the area around either the restart of the equipment or the identification of other maintenance in and around a defined isolation area.

It was new for the case company to have based this many decision interfaces on the same, standardized information sources. Prior to the development of the architecture, the decision interfaces in use were local, making them difficult to update and trace. While other vendors were in use for various decisions made throughout the organization, not a single vendor had the ability to deliver a structured system that spanned the organization nor were the programs able to exchange data across. The proposed framework could instead connect all of these vendor programs together, ensuring an aligned data foundation. The information modules were based on the data from these vendor software, but the framework ensured the link across the data that was missing in the As-Is state of the company.

Decisions that were not included in the framework were also collected during the semi-structured interviews with company experts. One such decision is the scheduling of maintenance activities. Scheduling is the placement of the planned maintenance jobs in time, deciding specifically when to do a maintenance job. The automation of this process required many changes in the information modules, which made it difficult to include in the framework. At the early stages of the adoption of the framework at the company there was a general mistrust of the data included in the information modules. Through continued discussions on data processing, data quality and an increased usage as proposed by Coussement & Benoit (2021) and Janssen et al. (2017), both adoption of the data and quality of the data were developed concurrently. Included in the discussion were both data management stakeholders as well as users of the data.

6 CONCLUSION AND DISCUSSION

This paper presents a study on the application of a Maintenance Decision Architecture with the goal of increasing information utilization to improve maintenance decision making. Specifically the paper studied the research question: *How can an architecture approach help improve information source utilization in maintenance decision making?* The question was researched through a literature study and the development and application of a Maintenance Decision Architecture framework. The goal of the framework is to help organizations structure decisions and information sources in one place. The proposed framework maps decisions taken in the maintenance management process to information modules that contain the information required to take the decisions. The mapping enables a standardized format for using and tracing information source utilization for maintenance decisions across an entire organization. The Maintenance Decision Architecture Framework was applied to multiple different decisions in a case company. The implementation of the Maintenance Decision Architecture enabled design of decision interfaces that were not available before. Having the architecture at the centre of the design of the decisions interfaces aligned the information used across the organization, made it possible to roll out updates and changes, and ensured a traceability and overview of decisions not previously available.

The application of the framework in a case company across multiple decision case studies showed how the use of a shared Maintenance Decision Architecture can enable the use of standardized maintenance information modules across a variety of maintenance decisions. The architecture framework formalized the available information in a way that made it possible to communicate across departments and align the decision foundations that was not previously available. While the case studies presented in this paper indicate benefits, the findings are qualitative. Future studies should focus on quantifying the impact on decision quality and alignment across the organization to fully understand the true impact of the introduction of the Maintenance Decision Architecture. Likewise, the application of the framework was strongly dependent on the existing information structure at the company - especially in the formulation of the information module. At this stage it is unclear whether this process will function similarly in other contexts, both within the same industry, but also for other industries. More studies are therefore needed to truly define the approach for mapping and delimiting information sources into information modules. As such, the work from the study presented in this paper on implementing architecture approaches in maintenance is part of a newer series of studies on achieving benefits found in engineering design within maintenance as well. This study presents findings from a maintenance decision perspective, but more studies are needed to fully understand the impact of maintenance architecting. Future studies should focus on applying the framework and other architecture approaches in more case companies and industries. As this study focused on the framework itself, future studies are needed to formalize the process of identifying the decisions and information modules that go into the Maintenance Decision Architecture.

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