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# Modularizing Maintenance for Improved Production Impact Clarification

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**Abstract**

Maintenance is an essential aspect to keeping production facilities running and safe. However, without an overview of the maintenance impact on production, gaining clarification of the impact of maintenance is difficult. This paper introduces modularization of maintenance based on the dimensions of maintenance: physical, action, and process. The approach is applied in a case study where maintenance decisions are improved and faster than prior to the introduction of the modularized maintenance.

*Keywords: product architecture, modularisation, data-driven design*

## 1. Introduction

Maintenance of equipment is essential to keeping production running without safety issues. However, often maintenance has some type of effect on the production flow. To minimize negative impact on the production efficiency the right decisions about the maintenance must be made. These decisions can be what actions to take, when to take them, what materials are required and more. To make the decisions, trade-offs are made between costs, production loss, and safety (Ruschel *et al.*, 2017). Without an overview of the maintenance when making these decisions, it can be difficult to take a decision that is fully informed (Chilamkurti et al., 2014; Hodkiewicz and Ho, 2016). However, maintenance data might be buried in different tables, be too large to overview, or be using different language depending on the department that created it . Data like this typically requires a longer collection process (Hodkiewicz and Ho, 2016). This large amount of variation makes it difficult to gain an overview and forces decisions to be based more on the experience of the decision maker, rather than the actual maintenance information. Modularization has been shown to be a method useful for evaluation and standardization of variation in product (Harlou, 2006; Meyer and Lehnerd, 1997; Simpson et al., 2014) and service (Løkkegaard *et al.*, 2016; de Mattos *et al.*, 2021) contexts. More recent studies have also seen the introduction of product and service architecture and modularization approaches in maintenance (Sigsgaard, Soleymani, et al., 2021). Maintenance is similar to services in that they are intangible (Løkkegaard *et al.*, 2016) and multidimensional in nature (de Mattos et al., 2021; Sigsgaard, Soleymani, et al., 2021). Sigsgaard et al. (2021) proposes an architecture approach grounded in the dimensions physical, action, and process, covering the aspects that influence decisions and highlights dependencies and overlaps in the maintenance. This paper continues the studies into maintenance architectures and modularization by seeking to answer the following research question: *How can modularization approaches be applied in maintenance to improve production impact clarification?* Based on the previous study on the application of architecture approaches in maintenance architectures and the definition of modules from service literature (de Mattos *et al.*, 2021), this paper develops a decomposition and definition of the modules and interfaces of maintenance with the goal of achieving improved production impact clarification. The modularization approach is applied in a case company, where the impact of the use of the final modules is studied. This paper is structured in seven sections. The first section is the introduction, and the second section describes the methodology used to develop the proposed method. The third section introduces the literature review. Sections four and five introduces modularization in maintenance for production impact clarification and describes how it was applied in a case company. The final sections six and seven discuss and conclude on the study.

## 2. Methodology

The research presented in this paper followed the design research methodology (DRM) (Blessing and Chakrabarti, 2009). The research project was started as a need for a better way of standardizing maintenance was seen in a case company, and is a development of maintenance architecture and modularization approaches from a case based perspective. In the case company, the production support team were spending large amounts of time identifying opportunities for production impact minimization, as the information was spread out with large amounts of variation. The project began with identifying previous work on maintenance standardization and modularization. As there was little on the subject, the needs of the decision makers in the case company were mapped out and compared to literature, identifying the dimensions that define the function of the maintenance. This knowledge was then used to conceptualize and develop the definition and decomposition of maintenance modules for production impact clarification. Finally, the resulting concept was applied in the case company to verify the applicability and effectiveness of the definition. The proposed decomposition of the maintenance into modules was applied, and the resulting modules were used to identify and clarify opportunities for minimizing the production impact much faster and with more certainty than before. The results were evaluated through workshops and semi-structured interviews with key stakeholders in the company.

## 3. Literature review

This section highlights literature within maintenance and product and service architectures. The section on maintenance introduces literature in the three dimensions proposed by Sigsgaard et al. (2021) and the use of data in these dimensions. Next, terms and approaches from technology architectures are introduced. Applications of architectures in services are introduced as a foundation for the implementation of similar approaches in maintenance (Sigsgaard, Soleymani, et al., 2021).

### 3.1. Maintenance dimensions and data

Maintenance is the effort introduced to keep items performing at the functionality they were designed to do. This makes maintenance essential to keeping facilities productive and safe for both the environment and the people working there (Dansk Standard, 2017). Effectiveness of maintenance is directly linked to good planning, but achieving this requires insight into the multiple elements of the maintenance process (Ruschel *et al.*, 2017). Maintenance can either be corrective where an identified failure is mitigated, or preventive where a potential upcoming failure is identified or mitigated. Different approaches can be taken to decide what type of maintenance to do when, and depends on the objectives of the maintenance (Dansk Standard, 2017). Recent years have seen introduction of sensors on production equipment that are used to predict and evaluate the risk of failure. There are multiple variants such as predictive, risk based, or reliability centred maintenance (Azadivar and Shu, 1999; van Horenbeek and Pintelon, 2013; Zille *et al.*, 2011). Another way to optimize maintenance is to group the actions taken. The grouping of maintenance can minimize the resources required and the production impact by taking advantage of the dependencies there are across maintenance actions (Dekker *et al.*, 1997; Guo *et al.*, 2018; Nzukam *et al.*, 2017). This section introduces studies on maintenance data and maintenance in the dimensions proposed by Sigsgaard, Soleymani, et al. (2021): physical, action, and process, as well as the use of data to describe and document these dimensions.
Maintenance data is commonly stored in a computerized maintenance management system (CMMS). Typically this data will be documenting the operational data such as actions to take, resources required, and timing of the maintenance. The importance of maintenance to the safety and profitability



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of a facilities makes the maintenance data a valuable resource (Hodkiewicz and Ho, 2016). Such data can give insight into the state of the facilities and assist in decision making (Hussin *et al.*, 2010) for ensuring the most effective production possible. Despite the upsides of maintenance data, it is often seen underused (Hodkiewicz and Ho, 2016). Generally, the use of data is under researched compared to the processing of the data (Coussement and Benoit, 2021). Incorrect or lack of data is a prevalent issue in maintenance data (Chilamkurti et al., 2014).

### *3.1.1. The physical, action, and process dimensions*

The physical dimension of maintenance pertains to anything that physically exists. This can be the actual pieces of equipment being maintained (Sigsgaard, Agergaard, *et al.*, 2021), the sensors used to monitor the condition of the equipment (Dansk Standard, 2012), or the spare parts and support materials used to perform the maintenance (Dansk Standard, 2017). The physical characteristics of a piece of equipment determine the type of maintenance required (Sigsgaard, Agergaard, et al., 2021; Sigsgaard, Soleymani, et al., 2021). The study by Sigsgaard, Agergaard, et al. (2021) showed how equipment types can be used to benchmark maintenance strategy performance within an asset. The physical state of the equipment is also important to maintenance performance measurements such as breakdown severity, mean time to repair, system complexity (Azadivar and Shu, 1999), and equipment age (Raouf, 1993). The process structure and an understanding of the dependencies is also important when implementing more knowledge intensive approaches such as predictive maintenance (van Horenbeek and Pintelon, 2013) or maintenance clustering (Cui and Li, 2006; Dekker *et al.*, 1997; Do *et al.*, 2015; Guo *et al.*, 2018; Hu and Zhang, 2014; Nzukam *et al.*, 2017; Wildeman *et al.*, 1997). Equipment data can be stored in the CMMS, but can also be supported through documentation in the form of drawings or CAD models. The study by Sigsgaard et al. (2020) how the contextualization of data can help improve opportunities for analysis across a plant. The study introduces a hierarchical system data structure based on Theory of Technical Systems (Eder and Hubka, 1988). The study showed that closer the data can be linked to the physical structures and hierarchies, the wider the breadth of analyses available. The data was contextualized by creating a data structure that represents the physical structure in a data model.

The action dimension includes descriptions of the actions taken, the resource requirements of the actions, the impact on the location of the maintenance and more (Sigsgaard, Soleymani, et al., 2021). A maintenance action is performed with an objective, typically pertaining the maintaining the intended function of one or multiple pieces of equipment. It can be everything required of the functionality of the equipment from inspections of the state of the equipment to cleaning, repairing, or even full replacement of a part (Dansk Standard, 2017). Historically, the easiest way to deliver instructions on actions to the person performing the maintenance was paper based. However, recent years have seen an introduction of digitally based solutions such as tablets and smartphones or augmented reality (AR) based solutions (Fiorentino *et al.*, 2014; Toscano, 2000). The data describing maintenance actions can be many varied when multiple languages, variable industry terms, and a free text format are used. The free text format can be difficult to compare in large quantities, rendering the data difficult to use (Agergaard *et al.*, 2021).

The process dimension pertains to aspects such as maintenance management processes (Ben-Daya et al., 2009; Deighton, 2016; Sigsgaard et al., 2020), decision making (Ruschel *et al.*, 2017), information governance (Chilamkurti et al., 2014; Hodkiewicz and Ho, 2016), and human resources (Dansk Standard, 2008; Gulati, 2012). The maintenance management process consists of the steps taken to perform the maintenance (Deighton, 2016; Sigsgaard et al., 2020). The definition of this process varies, but the definition from a combination of multiple sources by (Sigsgaard et al., 2020) contains the steps identify, plan, schedule, execute, close-out. The identification step focuses on defining the need and urgency of the maintenance at a location; the planning step is when the actions, resources, and time requirements of the maintenance are set; scheduling is placing the defined actions in time; execution is the actual performance of the maintenance; close-out is the documentation, quality control, and financial settling of the job. These steps are being performed in parallel for all the maintenance jobs in the pipeline at any given time (Sigsgaard et al., 2020). Data documenting the process dimension can be qualitative, such as work flow maps or semi-structured interviews



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(Sigsgaard et al., 2020), or by following maintenance job statuses in the CMMS measuring aspects such as change over time, maintenance response time, or amount of job rework (Kumar and Parida, 2008).

### 3.2. Technology architectures

Architectures can be implemented to improve an overview of a product or activity being managed (Sigsgaard, Soleymani, et al., 2021). Traditionally, the architecture approach was derived from a need to manage complex product programs while still delivering large variety to the customer (Meyer and Utterback, 1992; Mortensen et al., 2019; Otto et al., 2016; Simpson et al., 2014). The complexity in product programs is introduced when the program is built product by product, introducing overlapping solutions that are not value adding but increase costs (Meyer and Lehnerd, 1997; Wilson and Perumal, 2009). A product architecture is a configuration of functional elements into building blocks which can be combined in predefined configurations (Meyer and Lehnerd, 1997; Ulrich, 1995). Benefits of product architectures have been shown to be lowered production costs, shorter time-to-market, easier introduction of new technologies, and improved product quality. These benefits are achievable when the building blocks called modules are well-defined, and the interfaces between the modules are kept static (Harlou, 2006; Meyer and Lehnerd, 1997). A central tool In the success of product architectures is the modularization of the product assortment. In order to modularize a product assortment the products in the assortment are separated into building blocks describing the functionalities of a product. Modularization is then the synthesis of these into modules with well-defined, locked interfaces (Harlou, 2006; Meyer and Lehnerd, 1997). More recent research in services and maintenance has also seen the introduction of architecture approaches. As service and maintenance architecture studies are still in the early stages of conceptualization and practical application, it is still highly influenced by studies from the product architecture domain (de Mattos et al., 2021; Sigsgaard, Soleymani, et al., 2021). An immediate challenge in service modularization is how to decompose services into modules when services compared to products are intangible (Løkkegaard *et al.*, 2016) and multidimensional by nature, involving service, process, physical, and human interaction dimensions (Eissens-van der Laan *et al.*, 2016). This is similarly reflected in the lack of a clear definition of surface modules and interfaces de Mattos et al. (2021) compared service modularization literature and synthesized the definition of a service module as a set of components that offers perceived value to a client and interfaces as connections across these service elements in the form of people, information, and rules of governing information flow. The study also shows that it can be beneficial to distinguish between service and process modules. A process module is here defined as an invisible and standardized process step that allows process reconfiguration as required for the service delivery (de Mattos *et al.*, 2021). Studies into maintenance architectures is a relatively uncharted field. Similar to services, maintenance is more intangible in nature than products. Compared to services, the value delivered by maintenance is to an optimal and safe production instead of a customer or client (Sigsgaard, Soleymani, et al., 2021). The framework for a maintenance architecture by Sigsgaard, Soleymani, et al. (2021) utilized the three dimensions physical, action, and process achieve an overview of the as-is preventive maintenance activities. The physical view presents an overview of the physical structures being maintained. The action view shows the actions taken during maintenance of those facilities. Finally the process view shows how maintenance goes from identification of a need for maintenance to a finished and documented maintenance job. The combination of the three views gives insight into the overall performance of the maintenance and allows strategic decision making on an improved knowledge foundation (Sigsgaard, Soleymani, et al., 2021).

## 4. Modularized maintenance

This section introduces the decomposition of modularized maintenance based on service and product literature and an understanding of the dimensions at play from maintenance literature. From the review of maintenance and maintenance architecture literature the three dimensions physical, action, and process were identified as the core dimensions of the maintenance. Each function offers a functionality to the total maintenance output while being dependent on each other: the physical dimension is where the need for maintenance occurs and where the maintenance is performed; the actions dimension is the



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maintenance action itself that is decided by the process and influences the physical dimension; the process dimension is where decisions on what issues in the physical dimension to solve and how, i.e. what action to take. The decomposition of modules for clarifying the maintenance production impact is achieved by mapping out the functions of the maintenance in each of the three dimensions (Figure 1). The physical dimension is decomposed by the hierarchical technical system, where the top level represents the full asset and each subsequent level the systems, equipment, or components that make up the asset (Eder and Hubka, 1988). Each node represents a functionality to the overall production system from highest level of complexity e.g. a plant or asset, to the lowest level, e.g. a component. The lowest level of complexity included will depend on the scope of the modularization task, and can be individual pieces of equipment or components. Each relationship in the technical systems describes the connections and dependencies to other system functionalities. A production impact on a node higher in the system will as such cause an impact on the children nodes. This way the hierarchical decomposition also reflects the dependencies in maintenance production impact. The action dimension is decomposed by the value delivered by the individual action blocks, i.e. the objective of a collection of maintenance actions. Each action block delivers some type of value to the physical dimension by ensuring the continuous system functionalities. The connections between these blocks can come from shared actions, resources or, as shown in Figure 1, the impact on the function of the physical dimension during the maintenance, i.e. production impact. The level of decomposition is dependent on the scope of the modularization task. The process dimension decomposes the process by the type of decisions made in the process steps. In the example in Figure 1, the decomposition was based on the process steps proposed by (Sigsgaard *et al.*, 2020). The process step at which the maintenance is at determines how defined the maintenance action is and whether it is currently having an impact on the function of the physical dimensions. As an example, at the scheduling stage everything but the exact timing of the maintenance has been determined but the maintenance is not yet having any effect on the physical dimension. When the maintenance reaches the execution stage all aspects are determined and the maintenance is actively having an effect on the physical dimension.

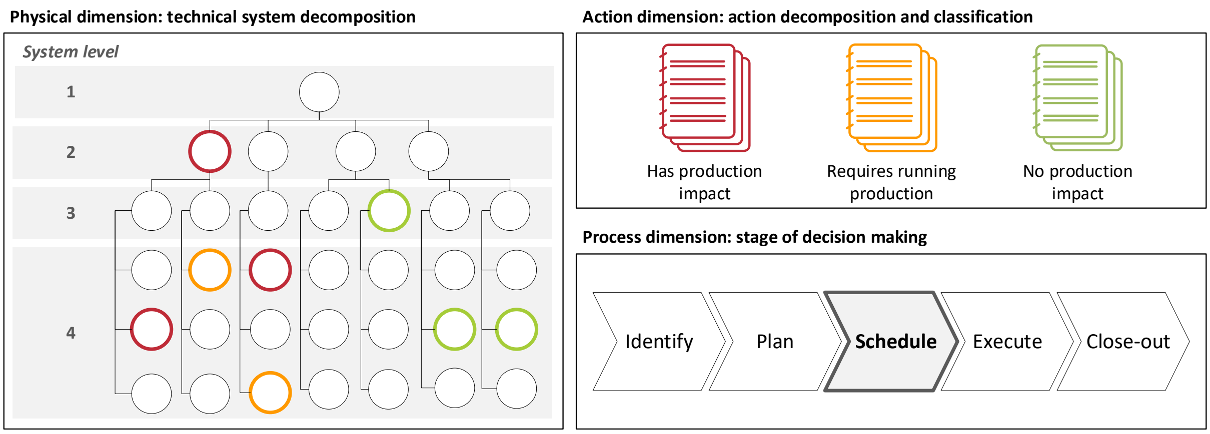


**Figure 1. The three dimensions of maintenance.**

The service module and interface definition is used to define how the functions and connections of the maintenance in the three dimensions can be used to achieve a maintenance modularization definition. In service or product modularization, a module is an offering of value or function to the client (de Mattos *et al.*, 2021; Meyer and Lehnerd, 1997; Ulrich, 1995). In the case of maintenance, the client is the asset or the asset owner that requires a safe and functioning production. The offering of value or the function of maintenance, i.e. the maintenance module is multidimensional, including maintenance actions directed at a given physical location on the asset at a given stage of the maintenance process. As interfaces are standardized connections across these elements (Harlou, 2006; de Mattos *et al.*, 2021; Meyer and Lehnerd, 1997), the interfaces between maintenance modules are multidimensional, defined by physical plant connections and dependencies, and overlaps in the maintenance actions and process stage. As an example, say the eight coloured nodes in the system decomposition in Figure 1



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are indications of locations with maintenance actions in the scheduling stage marked in the process dimension decomposition. Each maintenance action is defined by a need for maintenance at that location based on a failure e.g. valve leakage or pump vibrations. The maintenance actions then contain a set of instructions that in the execution stage will deliver value to that location in the technical system. To identify interfaces between these eight maintenance modules, they are categorized by their impact on the production. As the goal of the scheduling stage is to place these value offerings in time, the jobs that are connected in the technical system that have an impact on the production can be placed in time together, having only one production impact instead of multiple. Likewise, the jobs that also have interfaces to this part of the technical system that require the production equipment to be running are placed at a different stage in time, as the interfaces of the jobs in the action dimension do not match.

As such, the modularization of maintenance by the three dimensions physical, action, and process allows definition of modules and interfaces that standardizes the configurations available within maintenance. The following section introduces the modularization of maintenance in a production company to show the decomposition in practice and a use case of the resulting definitions of modules and interfaces.

## 5. Case study

Modularization of maintenance was introduced in a production company that owns 50 plants that have a continuous production flow. As the production is continuous, impact of maintenance is costly to the sales potential, but the production also runs at high pressures with flammable materials making maintenance an important safety factor. To minimize the impact of maintenance on the production, the production support team work to identify overlaps in impact requirements when planning larger production shutdowns. However, the amount of variation and lack of connection between different information and data sources makes it a time consuming process that is more likely to let opportunities go unnoticed. Most parts of the plants being operated are documented in design briefs, Production Flow Diagrams (PFDs) and Piping & Instrumentation Diagrams (P&IDs). The tags of the equipment are available in the company maintenance database, and most maintenance is planned down to the specific piece of equipment. The company performs around 1000 jobs every 14 days and has over 300 000 pieces of equipment running in production, supporting, and utility equipment. With this amount of maintenance, there is little time to investigate options for improvement across all the different data tables and departments. The modularization of the maintenance was applied to create an overview that can help the production team identify planned or upcoming maintenance that affects production. The modularization allowed faster identification of opportunities, allowing more time and an improved foundation for making decisions on production impact grouping.

The modularization of the maintenance was achieved by collecting and mapping information from the plant documentation and a data model that was developed prior to the start of the study presented in this paper (Sigsgaard, Agergaard, *et al.*, 2021; Sigsgaard *et al.*, 2020). The model includes information on maintenance jobs and their link the physical structures of the facilities. The amount of data available about a job and status' created by the CMMS indicate the stage of the maintenance action in the process. The maintenance job data includes multiple aspects of the maintenance performed at the case company. The physical structure data includes information from full facility level down to individual pieces of equipment. The data used for the study described in this paper is the maintenance objectives, impact on production, locations, dates, and statuses of the maintenance. An addition to the data model for this study was the linking of the physical structures of the facilities through the tags of each individual location onto the piping and instrumentation diagrams (P&IDs) created by the case company.

In the final, modularized maintenance overview, a maintenance module equalled a single maintenance job from the CMMS. The function of the job was defined by the objective of the maintenance actions in the job, i.e. repair valve leak, vessel visual inspection, etc., and the physical location of the equipment in the technical system, as well as the stage of the job within the maintenance process. The interfaces between the jobs were identified in the physical dimension from the technical system and the location on the P&IDs, in the action dimensions through various factors in the jobs that indicated



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production impact group-ability, and in the process dimension by whether the job was released from planning awaiting scheduling, making it possible to place the maintenance within a production impact window. The following explains in more detail the aspects included as functions and interfaces in the final application used to identify production impact.

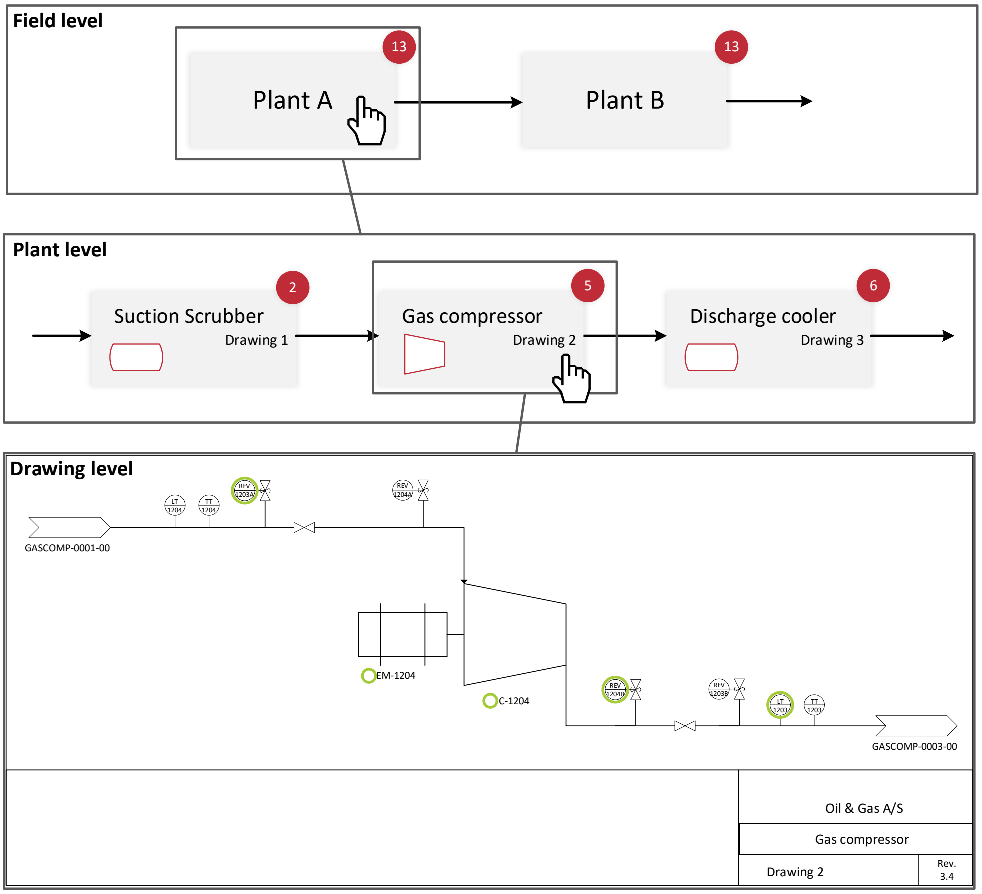


**Figure 2. An example of the overview created. The user can switch between a field view, a plant view, and a drawing view depending on the task requirements.**

An example of the application developed using the modularized maintenance is shown in Figure 2. The connection between plants of two fields operated by the case company are visible in views representing three different levels of the technical system: Field level, Plant level, and Drawing level, representing the hierarchical decomposition of the functions and connections of the physical dimension. The initial scope of modularization included a full field overview, the systems on two of the plants in that field and a component level for the P&IDs on those plants. The user is able to shuffle between the full field view, through to the plant view showing the connections between all major equipment and function views down to a component level where the maintenance was visualized directly on the P&IDs. This functionality of the application takes advantage of the interfaces between the maintenance modules in the physical dimension. In that sense, it gives the user an overview of how the maintenance modules can be configured for an upcoming production impact window.
On each level of the overview was shown the number of open maintenance jobs. The user has the option to make multiple selections in different filters to create the desired overviews of specific job types. Selections were available for shutdown requirements (or lack thereof) , the material delivery status, and the option of selecting the step of the maintenance job within the maintenance process. These options are the interfaces in the action and process dimension, defining connections across the maintenance modules along the visualization of the physical dimension. Included in the view were also functions of the maintenance including the maintenance objective, the planned hours required for the maintenance, and the priority of the maintenance. The decision makers from the production



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support team who were involved in the development of the overview found the results useful: *"This can help us achieve an overview of upcoming critical shutdowns that we did not have before." - production support team lead.*

Two smaller specific cases were performed to evaluate the impact of the use of the modularized maintenance. Upcoming, larger production impact windows were identified and any options for including other maintenance while the production was already being impacted was identified using the application developed from the modularized maintenance. The first case considered a complete shutdown of a functional subsystem of the maintenance plant. One of the pieces of equipment required an overhaul that would require a complete shutdown of the subsystem. A portion of the production medium can be rerouted, but due to capacity maximum in the rerouting system, the overhaul or any shutdown of the area causes a significant production loss. Looking into the affected area using the decomposition of the system as shown in Figure 2 opportunities for other jobs that were released from planning but not yet scheduled or executed were identified. Using only these interfaces in the physical and process dimensions, 45 potential opportunities for including other jobs in the planned production impact period. Including the interfaces shutdown requirement and material readiness from the action dimension, the amount of maintenance modules compatible with the interface was 20. These maintenance modules all were planned to have an impact on the production in the affected area, had the material delivered prior to the execution of the planned production impact, and had been released from planning but had not yet been executed. This suggestion of maintenance to include during the planned production impact were identified within 2 hours using the application developed from the modularized maintenance. Out of the 20 maintenance modules, 6 had been identified by the production support group within 7 work days. The second case considered a similar complete shutdown of a functional subsystem, but on a different part of the asset. This production impact was caused by an external factor in the form of the move of a rig after well servicing. Using the same approach as for the first case, maintenance was identified in the affected area that were released from planning but not yet scheduled or executed. In this case, 19 potential maintenance modules were identified. Out of these, 7 matched the interfaces in production impact and material delivery, meaning they could be included in the planned production impact. These were identified and presented within 90 minutes. 2 of the 7 opportunities had been identified by the production support team within 5 work days.

## 6. Discussion and conclusion

The study presented in this paper sought to modularize maintenance with the goal of clarifying the impact of maintenance on production. The modularization was achieved by decomposing the maintenance in the three dimensions physical, action, and process, defining modules as the function of the maintenance in the three dimensions and the interfaces as the connection between the functions across the three dimensions. The developed modularization approach was applied in a case company where the modular maintenance was structured into an application. The application was used to identify opportunities within a shorter timeframe and with a larger amount of configurable modules identified than the work done by the company experts.

The maintenance module definition achieved in this paper was heavily influenced by the definition from service modularization. Services and maintenance are similar in that they seek to deliver an intangible value that requires the connection between multiple dimensions to achieve (Løkkegaard *et al.*, 2016; de Mattos *et al.*, 2021; Sigsgaard, Soleymani, *et al.*, 2021). Dimensions in services and maintenance are also similar, where services span service, process, physical and human interaction dimensions, the architecture definition by Sigsgaard, Soleymani, et al. (2021) that was used in this study proposes the dimensions physical, action, and process. Where the domains of services and maintenance starts to differ is in the recipient of the value and in the dynamic nature of maintenance. Where the recipient of a service is a client or a customer (de Mattos *et al.*, 2021), the recipient of value in maintenance is the operator of the facilities (Sigsgaard, Soleymani, *et al.*, 2021). As the requirements to keep equipment in a production context so are the module variants, i.e. the contents of the maintenance modules meaning aspects such as maintenance objective, maintenance instructions, planned hours, production impact, and so forth. Where in service and product modularization a benefit is reuse and repeatability (de Mattos *et al.*, 2021), the goal of maintenance modularization is more focused on standardized connections across maintenance modules. The application based on the



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modularized maintenance was a clear improvement on both the time spent and the amount of identified opportunities. However, the results of this study are tentative and case dependent, as this study is a case based implementation of approaches from product and service architecture and modularization in maintenance. The findings are an indication of the benefits of applying modularization techniques when clarifying maintenance impact on production, but more studies in other application areas, companies, and industries is required to further build the definitions of modular maintenance. Future studies should focus on the module and interface definition, as well as the ability for decomposition in the same way in other contexts.

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