Effective Maintenance: A Configuration Approach

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Effective Maintenance: A Configuration Approach

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Effective Maintenance:
A Configuration Approach

by

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for the fulfillment of the degree of PhD

Department of Civil and Mechanical Engineering

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Abstract

This thesis addressed the industrial need for effective and efficient maintenance of assets using an approach that leverages historical data and mass customization concepts. The primary objective of this research was to improve maintenance preparation and execution by emphasizing the importance of clear, visual, and easily understandable information for decision-making. The research also aimed at eliminating low-value activities, reusing value-adding activities, and learning from past equipment failures and maintenance practices to drive improvements.

The study incorporated the principles of modularization, which involved decomposing maintenance activities into independent modules that represented specific tasks, such as repairs or replacements. This collection of well-defined and value-adding modules meets the maintenance needs of companies by allowing for customization and configuration.

The research methodology involved studying a maintenance-performing company and exploring the role and value of data in maintenance preparation. It investigated the potential for reusing historical data and structuring and organizing it using the modularization approach. Furthermore, the research examined the purposeful development of configurators. Models and methods were developed to structure, organize, and synthesize historical data for decision-making; modularize maintenance activities and instructions based on historical data; and evaluate configurator projects in alignment with development objectives and requirements.

The key findings of this research revealed that valuable insights for maintenance preparation could be derived from data on equipment failures and maintenance activities. Moreover, historical data could be effectively utilized for the modularization of maintenance, resulting in a significant reduction in non-value-adding variety and an enhancement of value-adding variety. Furthermore, the incorporation of effective performance assessments in configurator development projects could steer these projects toward achieving their targets. By effectively configurating maintenance activities, significant improvements were achieved, including error rate reductions from above 4% to below 1% and a time reduction of 75%–92% compared to traditional methods.

This thesis underscores the value of modularization and architectural principles, traditionally applied in product domains, within the context of maintenance. The research demonstrates the value of data-driven approaches, modularization principles, and information accessibility in enhancing maintenance preparation. By leveraging historical data, implementing modularization, and utilizing configurators, companies can tackle industry challenges more effectively.

Resumé

Denne afhandling adresserede det industrielle behov for effektivt vedligehold af aktiver ved hjælp af en tilgang, der udnytter historiske data og massetilpasningskoncepter. Det primære formål med denne forskning var at forbedre forberedelsen og udførelsen af vedligeholdelse ved at understrege vigtigheden af klar, visuel og let forståelig information for beslutningstagning. Forskningen havde også til formål at eliminere aktiviteter med lav værdi, genbruge værdiskabende aktiviteter og lære af tidligere udstyrsfejl og vedligeholdelsespraksis for at fremme forbedringer.

Undersøgelsen inkorporerede modulariseringsprincipper, som indebar at dekomponere vedligeholdelsesaktiviteter i uafhængige moduler, der repræsenterede specifikke opgaver, såsom reparationer eller udskiftninger. Denne samling af veldefinerede og værdiskabende moduler opfylder virksomhedernes vedligeholdelsesbehov ved at tillade tilpasning og konfiguration.

Forskningsmetodikken indebar at studere en vedligeholdelsesudførende virksomhed og udforske rollen og værdien af data i vedligeholdelsesforberedelse. Den undersøgte potentialet for at genbruge historiske data og strukturere og organisere dem ved hjælp af modulariseringstilgangen. Desuden undersøgte forskningen den målrettede udvikling af konfiguratorer. Modeller og metoder blev udviklet til at strukturere, organisere og syntetisere historiske data til beslutningstagning; modularisere vedligeholdelsesaktiviteter og instruktioner baseret på historiske data; og evaluere konfiguratorprojekter i overensstemmelse med udviklingsmål og -krav.

De vigtigste resultater af denne forskning afslørede, at værdifuld indsigt til brug i vedligeholdelsesforberedelse kunne udledes af data om udstyrsfejl og vedligeholdelsesaktiviteter. Desuden kunne historiske data effektivt udnyttes til modularisering af vedligeholdelse, hvilket resulterer i en betydelig reduktion i ikke-værdiskabende variation og en forbedring af værdiskabende variation. Desuden kan inkorporering af effektive præstationsvurderinger i konfiguratorudviklingsprojekter styre disse projekter mod at nå deres mål. Ved effektivt at konfigurere vedligeholdelsesaktiviteter blev der opnået betydelige forbedringer, herunder fejlprocentreduktioner fra over 4 % til under 1 % og en tidsreduktion på 75 %-92 % sammenlignet med traditionelle metoder.

Denne afhandling understreger værdien af modularisering og arkitektoniske principper, traditionelt anvendt i produktdomæner, i forbindelse med vedligeholdelse. Forskningen demonstrerer værdien af datadrevne tilgange, modulariseringsprincipper og informationstilgængelighed for at forbedre vedligeholdelsesforberedelsen. Ved at udnytte historiske data, implementere modularisering og bruge konfiguratorer kan virksomheder tackle industrielle udfordringer mere effektivt.

Preface

Welcome, readers, to my thesis! Over the past few years, I have studied the phenomenon of asset maintenance. Although the topic may not be as complex as rocket science, it can still be complicated to understand. To better guide your reading and understanding of the thesis, I will begin by framing the research through two stories.

The first story, of Italian artist Gianluca Gimini, who in the period from 2009 to 2016 asked hundreds of people to sketch a bicycle, captures the essence of this thesis[1]. Out of the nearly 400 drawings he collected, only a handful accurately depicted a bicycle that was functional. Although a bicycle is a common object, people forgot some of its essential components, such as the pedals or the chain, or constructed the frame in peculiar ways. This simple experiment shows that regardless of one's familiarity and experience with a principle or object, accurately designing it does not always guarantee something that is functional or optimal.

For the second story, during the 1980s, members of Ford delegations were struck by the level of assembly precision they observed during visits to Toyota in Japan[2]. The story goes that these executives and managers were dumbfounded not to find any rubber mallets in the final assembly area. At Ford, these were commonly used to tap doors to make them fit perfectly, but at Toyota, the doors just snapped into place and fitted perfectly. This experience resulted in reflections on the level of product quality and manufacturing efficiency in the US, which in turn led to a global shift in car production according to Toyota's methods.

These stories shape the core of this thesis: Its central focus is to improve the maintenance process and the "sketching," or designing, of maintenance solutions, the aim being to help maintenance decision-makers to sketch functional, high-quality solutions that fit perfectly, eliminating the need for the metaphorical rubber mallets. To achieve this, the thesis explores a company's historical data of maintenance to gain insights into past successes and failures and investigates the use of configurators to aid the decision-making process and generate effective designs for maintenance solutions.

Central to this exploration is the concept of modularization. As a quote from the cult Danish TV series *The Julekalender* puts it: "*That's a good* vending *[phrase]! Maybe we can use that in another* afsnit *[episode]?*"; this line not only relates to the process of writing this thesis but also to modularization. The fundamental idea of modularization is the reuse of excellent content, or modules, to generate a wide range of customized solutions. For instance, car manufacturers employ this concept to offer and construct many different variants of vehicles using a defined set of mass-produced high-quality modular components. Another simple example of modularization can be illustrated by something we all use—the alphabet. The English alphabet consists of 26 letters. With these letters, we can form words and sentences, enabling effective communication through reading and writing. Without a modular alphabet, I

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[1] Gimini, G. (n.d.). *Velocipedia*. Retrieved May 13, 2023, from https://www.gianlucagimini.it/portfolio-item/velocipedia/

[2] Sullivan, L. P. (1984). Reducing Variability: A New Approach to Quality. *Quality Progress*, *17*(7), 15–21.

would not be able to compose this thesis, and you would not be able to read it. The English vocabulary includes roughly 1 million words[3], all composed of these 29 letters. Imagine if we had to learn and remember unique symbols for each word—it would result in utter chaos, impeding effective communication. Instead, we can generate these words using a predefined set of letters, or modules.

In this thesis, I aim to show that the principles of modularization can enhance the quality of maintenance. This involves investigating and defining the modules that can be efficiently combined to generate effective "sketches" (designs) of maintenance solutions.

I would like to take this opportunity to thank the crucial people involved in conducting the work and the completion of this thesis. First, I would like to thank Niels Henrik Mortensen, a professor and my main supervisor, and Lars Hvam, a professor and my co-supervisor, for their guidance and support throughout the research project. Their expertise and mentorship have been invaluable.

I would also like to acknowledge my colleagues at DTU, particularly my close colleagues in our research team, Julie, Jingrui, Simon, Christian, and Kristoffer. Our collaboration and discussions have provided valuable insights and perspectives.

Furthermore, I would like to thank everyone involved in the industrial partnership, particularly Kim Nielsen and Sebastien Perrier. Kim's support and collaboration have been paramount in the success of this research. Sebastien's support and trust in the potential of this research has created a space for exploring, researching, and innovation.

Lastly, I would like to thank my family and friends for their support.

I hope you will enjoy reading this thesis,

Kasper Barslund Hansen

Copenhagen, June 2023

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[3] Merriam-Webster. (n.d.). *How many words are there in English?* Retrieved May 13, 2023, from https://www.merriam-webster.com/help/faq-how-many-english-words

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Included Publications

Paper A

Didriksen, S., **Hansen, K. B.**, Sigsgaard, K. V., Mortensen, N. H., Agergaard, J. K., & Ge, J. (2022). Utilising failure history to improve maintenance planning. *Proceedings of NordDesign 2022 (Vol. DS 118)*. https://doi.org/10.35199/NORDDESIGN2022.42

Paper B

Hansen, K. B., Vandrup Sigsgaard, K., Agergaard, J. K., & Henrik Mortensen, N. (2021). Visualize maintenance data to identify safety issues and opportunistic maintenance possibilities. *2021 Annual Reliability and Maintainability Symposium (RAMS)*, *May 2021*. https://doi.org/10.1109/RAMS48097.2021.9605777

Paper C

Hansen, K. B., Sigsgaard, K. V., Mortensen, N. H., Agergaard, J. K., Ge, J., & Didriksen, S. (2022). Improve maintenance by reusing and refining previous maintenance cases. *2022 6th International Conference on System Reliability and Safety (ICSRS)*, 310–317. https://doi.org/10.1109/ICSRS56243.2022.10067286

Paper D

Hansen, K. B., Mueller, G. O., Mortensen, N. H., Sigsgaard, K. W., Agergaard, J. K., Ge, J., Didriksen, S., & Jespersen, C. B. An investigation into how modularization principles can be applied to maintenance and commissioning services. Submitted for publication to the journal *Concurrent Engineering: Research and Applications*.

Paper E

Sigsgaard, K. V., Agergaard, J. K., Mortensen, N. H., **Hansen, K. B.**, & Ge, J. (2023). Modular maintenance instructions architecture (MMIA). *Journal of Quality in Maintenance Engineering*, *29*(5), 50–67. https://doi.org/10.1108/JQME-08-2021-0063

Paper F:

Hansen, K. B., Ge, J., Haug, A., Hvam, L., Mortensen, N. H., Sigsgaard, K. W., Agergaard, J. K., Didriksen, S., & Jespersen, C. B. Applying performance measures before, during, and after configurator development. Submitted for publication to the journal *Computers in Industry*.

Supplementary Publications

Agergaard, J. K., Sigsgaard, K. V., Mortensen, N. H., Ge, J., & **Hansen, K. B**. (2023). Quantifying the impact of early-stage maintenance clustering. *Journal of Quality in Maintenance Engineering*, *29*(5), 1–15. https://doi.org/10.1108/JQME-07-2021-0056

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Agergaard, J. K., Sigsgaard, K. V., Mortensen, N. H., Ge, J., & **Hansen, K. B**. (2022). Systematic maintenance action modularization for improved initiative prioritization. In N. H. Mortensen, C. T. Hansen, & M. Deininger (Eds.), *Proceedings of NordDesign 2022 (Vol. DS 118)*. The Design Society. https://doi.org/10.35199/NORDDESIGN2022.39

Agergaard, J. K., Sigsgaard, K. V., Mortensen, N. H., Ge, J., & **Hansen, K. B**. (2022). Modularizing Maintenance for Improved Production Impact Clarification. *Proceedings of the Design Society*, *2*, 2413–2422. https://doi.org/10.1017/pds.2022.244

Sigsgaard, K. V., Soleymani, I., Mortensen, N. H., Khalid, W., & **Hansen, K. B**. (2022). Toward a framework for a maintenance architecture. *Journal of Quality in Maintenance Engineering*, *28*(2), 474–490. https://doi.org/10.1108/JQME-01-2020-0004

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Abbreviations and Glossary

ARC	Areas of Relevance and Contribution
CMMS	Computerized maintenance management system
DRM	Design Research Methodology
DTU	Technical University of Denmark
DUC	Danish Underground Consortium
ERP	Enterprise resource planning
FMEA	Failure mode and effects analysis
MBSE	Model-based systems engineering
SDU	University of Southern Denmark
OEM	Original equipment manufacturer
RCM	Reliability-Centered Maintenance
RQ	Research question
TPM	Total Productive Maintenance

Stages of the Design Research Methodology

RC	Research clarification
DS I	Descriptive study I
PS	Prescriptive study
DS II	Descriptive study II

1

Introduction

The primary focus of this PhD thesis is to improve maintenance practices and contribute to the existing research knowledge in this domain. The research specifically focuses on the maintenance of offshore oil and gas production in the Danish sector of the North Sea. In the following sections, the research is introduced, and an overview is provided of the challenges addressed, the scope of the research, and the research questions, purpose, and aims.

1.1 Background and Industrial Challenges

Maintenance is crucial to ensure equipment reliability and availability, promote safety, ensure regulatory compliance, reduce costs, and extend the lifetime of assets (De Jonge & Scarf, 2020; Deighton, 2016; Kelly, 2006a; Kister & Hawkins, 2006; Petchrompo & Parlikad, 2019). Through activities such as inspections and repairs, maintenance aims to identify and address current issues before they escalate, ensuring the proper functioning of equipment and systems (European Standard, 2017a), Additionally, identify and address potential safety issues that could result in accidents or injuries, thereby mitigating risks, protecting employees, and preventing any impact on the surrounding environment(European Standard, 2017b). Various industries require compliance with regulations and standards related to occupational safety and environmental impact. Maintenance is vital to adhere to these requirements and ensure operations are within the guidelines (European Standard, 2010). Implementing effective maintenance strategies can reduce operational costs by preventing and avoiding unnecessary shutdowns and expensive repairs. Assets are a significant investment, and proper maintenance can extend their lifetime (McKinsey & Company, 2015).

1.1.1 Challenges and Outlook in Offshore Oil and Gas

Insufficient maintenance can lead to disastrous consequences. The Deepwater Horizon accident in 2010 stands as an example, being one of the most catastrophic incidents in history in terms of human fatalities and being the largest offshore oil spill. The accident was partly a result of neglect and inadequate maintenance practices (BP, 2010; Reuters, 2010). Subsequent analysis of maintenance records revealed non-compliance with the company's maintenance policies, a backlog of thousands of hours of overdue maintenance tasks, and a lack of robust maintenance management. This highlights the critical importance of proper asset maintenance.

Introduction

Since the accident, projected returns in the oil and gas industry have declined, and the world is now transitioning toward a low-carbon future. An illustration of this was the sharp increase in bankruptcies within the oil and gas sector in 2020 in North America (McKinsey & Company, 2021). In the North Sea, many offshore production platforms continue operating well beyond their original design life, necessitating increased maintenance and asset integrity efforts to support production. Consequently, operational expenditures have risen (McKinsey & Company, 2014a).

The combination of a shrinking industry, aging and depreciating infrastructure, and high maintenance costs is discouraging further investments in upkeep. A case in point is the massive oil spill near Los Angeles in 2021, which shed light on the challenges posed by California's aging oil infrastructure (Gammon, 2021). California has ambitious climate goals and is gradually phasing out infrastructure associated with fossil fuel extraction in favor of greener technologies. However, some old oil rigs are still in operation, and companies may be hesitant to invest in a sector that is gradually being discontinued. Dr. Daniel Kammen, a Nobel Peace Prize winner for his work on the climate crisis at the University of California, Berkeley, expressed concerns about future spills, emphasizing the expense of operations and maintenance, particularly in an industry with a shrinking future (Gammon, 2021). He urged focus to be placed on sustaining incentives for responsible operations and maintenance until the end of life of existing infrastructure, thereby avoiding underinvestment in upkeep. In this context, McKinsey & Company (2021) argued that companies must strive to continually improve their capital returns and operating performance while simultaneously reducing operational carbon emissions. This necessitates cost-effective and risk-mitigating maintenance to ensure prioritization of maintenance activities and bridging toward greener energy alternatives.

So far, the consequences seen in North America have not been observed in the North Sea and Denmark. Currently, both the renewable energy industry and the oil and gas industry in the North Sea receive equal investments (International Energy Agency, 2018). There are projections indicating a gradual shift toward increased investment in new renewable energy projects, while investment in oil and gas projects is forecast to remain stable in the near term (International Energy Agency, 2018). Short-term investments from the UK and Norway are even expected to rise by 20–30% until 2025 (Rystad Energy, 2023).

In Denmark, all Danish oil and gas facilities will cease production no later than 2050, and all upcoming bidding rounds that promote exploration for more oil in the Danish part of the North Sea have been cancelled (Danish Energy Agency, n.d.-b). The decommissioning process of platforms will be initiated in the near future, gradually removing them from service. The estimated cost of decommissioning will exceed $100 million per platform (Andersen, 2012), totaling $100 billion in the North Sea alone—a figure that could double or triple (Oudenot et al., 2017).

Carbon capture and storage, where CO_2 is captured and stored underground, represent potential future prospects. They will play a crucial role in reaching Denmark’s climate goals, and permits have already been awarded to initiate their development (Danish Energy Agency, n.d.-a; State of Green, 2022). The objective is to reuse existing infrastructure, utilizing the existing pipelines and facilities to transport CO_2 to the platforms, which emphasizes the need for well-kept and maintained facilities (International Energy Agency, 2018).

Oil and gas will continue to be part of the energy mix, albeit under increasing pressure due to the gradual shift toward greener renewable energies. This shift, coupled with limited investment, presents challenges to the upkeep and safety of platforms and infrastructure in the oil and gas industry. The imminent and costly decommissioning of platforms also raises concerns that maintenance activities may be deprioritized. However, as platforms age, they become more prone to failures and require additional maintenance attention. Moreover, these platforms and infrastructure may need to be repurposed for carbon capture and storage. This situation necessitates more cost-effective and safety-focused maintenance practices.

This all raises questions: Are companies capable of handling these maintenance challenges, and can they effectively address the maintenance needs under these circumstances?

1.1.2 The State of Offshore Maintenance

Maintenance of offshore equipment has always been challenging. The machinery is constantly exposed to corrosive saltwater and subjected to intense operational demands. Essential spare parts may be located far away, and frequent shift changes result in multiple workers handling a single position within a month. Consequently, equipment breakdowns and both planned and unplanned maintenance interventions impose substantial costs on the industry (McKinsey & Company, 2014b).

The North Sea presents significant operational challenges for the companies operating in the region (McKinsey & Company, 2014b). The basins are some of the most mature globally, and the platforms and infrastructure are aged, with some platforms in Danish waters having operated since 1972 (Danish Energy Agency, n.d.-b). Over the past 50 years, as production has expanded, additional platforms and infrastructure have been established, resulting in a diverse range of physical systems, approaches, and solutions (McKinsey & Company, 2014a). This also extends to maintenance practices, which are defined and carried out differently across companies, assets, and platforms.

Operating and development costs have seen a considerable increase (McKinsey & Company, 2014a). From 2003 to 2013, lifting costs increased by on average 10% per year, significantly surpassing inflation rates. At the same time, production efficiency declined by 1% per year (McKinsey & Company, 2014b), and the average time used for carrying out a broad range of standard procedures doubled (McKinsey & Company, 2014a). The wrench time of a technician, being the actual time when maintenance is performed, corresponds to only 38% of the total time available, or approximately 4.5 hours of a 12-hour shift. The lower productivity is believed to be partly due to less experienced crew (McKinsey & Company, 2014a).

The industry currently demands maintenance practices that are effective, cost-efficient, and highly productive. However, the current trend indicates the opposite, presenting a challenge to meet these expectations.

1.2 Academic Challenges

Over the years, several approaches have been introduced to enhance maintenance management, improve equipment reliability, minimize downtime, and optimize maintenance efforts. These include; Total Productive Maintenance (TPM), which aims to maximize equipment effectiveness (Chaurey et al., 2023); Reliability-Centered Maintenance (RCM), which optimizes maintenance based on reliability requirements and risk assessments (Geisbush & Ariaratnam, 2022); and Condition-Based Maintenance, which focuses on performing maintenance tasks, when necessary, based on the actual equipment condition and typically relying on real-time monitoring (Firdaus et al., 2023). The exploration and advancement of these methodologies have been a recurring theme in research (Chaurey et al., 2023; Firdaus et al., 2023; Geisbush & Ariaratnam, 2022).

In recent years, predictive and proactive maintenance have gained interest in maintenance research (Psarommatis et al., 2023). The integration of advanced monitoring technologies with the vast amount of data generated by Industry 4.0 innovations has led to the development of artificial intelligence algorithms for big data analytics. These algorithms can extract crucial insights, including failures and degradation trends, from large monitoring datasets (Psarommatis et al., 2023). This new paradigm focuses on diagnosing the condition of equipment and implementing timely maintenance, leading to consideration of the implications for decision-making (Silvestri et al., 2020).

Decision-making within maintenance management is not without its challenges. A recent literature review of these new technological advancements in maintenance revealed a lack of clarity with regard to accountability and that a significant portion of research has neglected to specify who is responsible for taking maintenance decisions and planning maintenance (Psarommatis et al., 2023). Considering this, the literature review by Sheikhalishahi et al. (2016) revealed that human factors such as knowledge, experience, and communication are closely tied to the efficiency and effectiveness of maintenance. Poor-quality documentation and procedures were identified as factors contributing to human error. Moreover, a review of the literature by Phogat and Gupta (2017) highlighted lack of communication and information as prevailing issues in maintenance. To mitigate these challenges, Sheikhalishahi et al. (2016) proposed the development of "intelligent decision aid systems."

These challenges in maintenance are further complicated by a lack of systems to harness the knowledge-related information in the industry, as recognized by Jardine et al. (2006). Their suggestion for developing methods or tools for managing this information in maintenance continues to be relevant, especially in the context of determining maintenance actions. As Villani et al. (2018) noted, only a limited number of employees possess the necessary knowledge required to determine the appropriate maintenance tasks in certain industrial cases. This lack of organization-wide knowledge sharing, coupled with insufficient guidelines, gaps in training, and documentation unavailability, is a cause of operational mistakes that adversely impact quality and cause delays (Belkadi et al., 2019).

This emphasizes the need for a knowledge-based approach to maintenance tasks. To enhance system reliability, prevent failures, and reduce costs, maintenance actions should be customized based on factors such as equipment criticality, required shutdowns for maintenance, age and repair limits, and failure rates (Wang, 2002). The value of such an approach should not just be theoretical. Parida and Chattopadhyay (2007) argued that the effectiveness and quality of maintenance need to be measured to justify investment. However, only limited work has been conducted on the actual design of performance measurement systems for maintenance (Parida et al., 2015).

In improving maintenance through technological advancements, focus is not given to the planning and preparation of maintenance (Psarommatis et al., 2023). This lack of focus is surprising, given the potential impact that effective planning and decision-making, namely, addressing issues in communication, documentation, and information, as well as optimizing human factors, can have on the overall success of maintenance efforts.

Several researchers have argued that a significant portion of the research on maintenance focuses primarily on mathematical analysis and techniques, instead of utilizing empirical evidence to address real-world industrial problems (Fraser et al., 2015). Zio (2009) argued that the maintenance literature heavily leans toward developing novel computational methods, the practical value of which remains questionable. In this regard, Veldman et al. (2011) urged academics to investigate the real-world application of maintenance models in different industrial contexts, thereby assisting industries in reaching their operational objectives.

1.3 Research Context

This PhD project, which has received support and funding from the Danish Offshore Technology Centre, aims to investigate and tackle the challenges associated with offshore operations in the North Sea. The objective is to provide valuable insights in this field.

1.3.1 Danish Offshore Technology Centre

The Danish Offshore Technology Centre (DTU Offshore), formerly known as the Danish Hydrocarbon Research and Technology Centre (DHRTC), was established in 2014 as part of Denmark's long-term national energy strategy and serves as the country's national R&D center for offshore technologies (DTU Offshore, n.d.). The center, operating as a public-private partnership involving the Technical University of Denmark, the University of Copenhagen, Aarhus University, Aalborg University, and GEUS, develops research-based technology solutions for the offshore industry. Financial support for the center comes from the Danish Underground Consortium (DUC), a joint venture between TotalEnergies, BlueNord, and Nordsøfonden, accounting for the largest share of Danish oil and gas production (Nordsøfonden, n.d.). The center's research is structured into programs, where researchers and industry collaborate to address specific challenges in the Danish sector of the North Sea. Figure 1-1 provides an overview of the center's ten research programs. This PhD project is part of the "Operations and Maintenance Technology CTR1" program, which aims to reduce the operating costs of offshore production facilities while minimizing their environmental impact through the development of technology to streamline production operations.

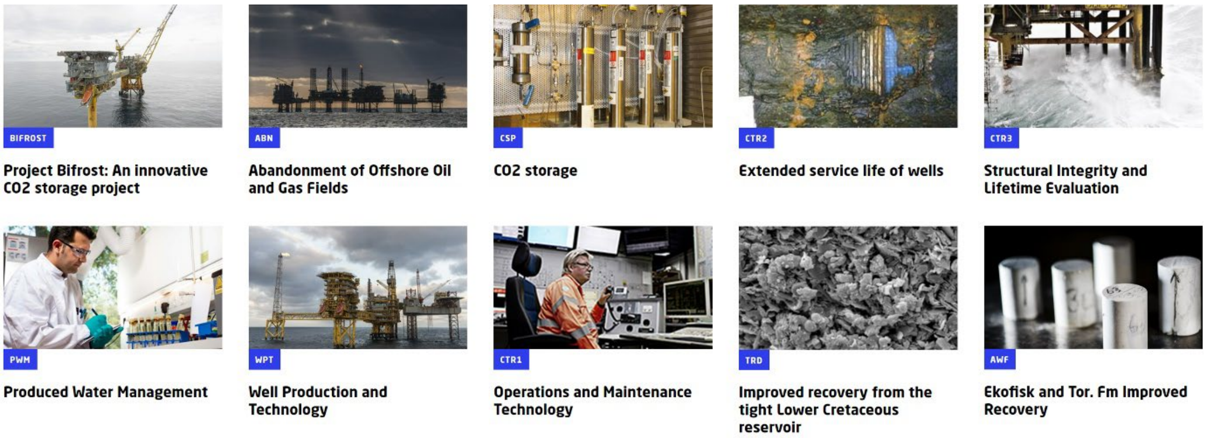


Figure 1-1. The research programs of the Danish Offshore Technology Centre (DTU Offshore, n.d.)

1.3.2 Collaboration with Industry – the Primary Case Company

As the research for this PhD project has been supported and funded by the Danish Offshore Technology Centre, the primary objective is to investigate and address the challenges related to offshore operations in the North Sea. The aim is to make valuable research contributions that align with the needs of industry practitioners.

The author’s research group has established a strong collaboration with an offshore operator in the Danish sector of the North Sea that is responsible for the development, operation, maintenance, and decommissioning of 50 offshore installations. The operator is an affiliate of a large global corporation with 100,000 employees that encompasses the entire value stream of oil and gas production, as well as other energy products, with affiliates around the world. The Danish affiliate and operator, (hereinafter referred to the case company) employs 1500 people.

The case company has ambitions to optimize maintenance and productivity to address the challenges in the industry of ensuring effective maintenance in terms of quality, safety, reliability, and costs.

The long-lasting collaboration has granted the research project physical entry into company buildings as well as access to the company’s intranet and servers. Furthermore, the project has been given access to and permission to utilize all formal maintenance procedures and instructions available on these servers. More than 10 years’ worth of historical maintenance records from the enterprise resource planning (ERP) system have also been made available. Additionally, the project can document current practices and informal procedures through interviews and workshops conducted with employees across the company.

Throughout the research work of this PhD project, discussions and presentations of results have also been conducted with other affiliates and companies. These affiliates adhere to similar internal standards and procedures, which have been adapted to meet regional operating conditions and legislative requirements. The industry as a whole is highly regulated through industry standards and legislation pertaining to maintenance (i.e., maintenance terminology, processes, and reliability analyses; European Standard, 2017a, 2017b; IEC, 2018), offshore operation and safety (i.e., the European Offshore Safety Directive; Directive 2013/30/EU, n.d.), and oil and gas production (i.e., maintenance data collection; ISO, 2016). Based on these observations, it can be assumed that there is a certain level of homogeneity within the company and across the industry. As a result, the research findings of this PhD project hold potential transferability and generalizability.

1.4 Scoping the Research

Indications of potential directions for optimizing maintenance and productivity can be identified from a survey conducted by McKinsey & Company (2014a, 2014b) among North Sea operators. For high performance, the survey highlights the importance of maintaining clear, visual, and easily understandable written standards aimed at minimizing the risk of equipment damage. Moreover, it emphasizes the need to eliminate low-value or value-destroying activities and optimize the planning and execution of activities, requiring a rigorous analysis of all types. Additionally, adopting a continuous improvement mindset is essential, learning from past failures and maintenance practices to implement the appropriate changes.

Furthermore, it is vital to understand that offshore operations are where value is created, whereas the sole purpose of onshore functions and facilities is to support the offshore execution, and that the operator is vital in promoting these principles and should lead their adoption and implementation.

These improvement directions, from well-written and value-creating standards and activities, and the focus on learning from the past to improve form the basis for the research scope.

1.4.1 Optimizing and Leveraging Maintenance

Maintenance is widely recognized as a crucial necessity. However, it often suffers from a negative perception and is occasionally seen as a necessary evil (Takata et al., 2004). This perception is partly influenced by the substantial portion of operational costs that maintenance entails. Across different industries, maintenance consistently represents a significant proportion, ranging from 15% to 75% of the overall life cycle costs associated with equipment and production (Bevilacqua & Braglia, 2000; Dhillon, 2006; Mobley, 2002).

Nevertheless, it is crucial to shift the perspective of maintenance, considering it not as a burden but as an approach to optimize operational efficiency, minimize downtime, and maximize the lifespan of assets or equipment. Improving maintenance should be seen as a means to not only optimize its cost but also its impact on production. By effectively leveraging maintenance, production output can be increased, and defects reduced, for example, thereby improving overall production performance. Organizations are increasingly realizing that they can improve their efficiency and reliability through proper maintenance (De Jonge & Scarf, 2020), and maintenance is now generally seen as a value-adding business activity (A. Sharma et al., 2011).

Effective maintenance requires excellent decision-making regarding the maintenance to be performed and the resulting value-creating activities. The process of maintenance preparation plays a crucial role in this regard. During maintenance preparation, the activities, instructions, and resources and tools required for different tasks are determined and defined based on the needs that have been identified (European Standard, 2017b).

Maintenance preparation greatly influences the outcome of maintenance (Palmer, 2019). Suboptimal or costly maintenance can often be traced back to this step and the decisions made. To effectively tailor maintenance, it is crucial to have a clear understanding of the system to maintain and how to maintain it. This understanding can be achieved through various means, including experience and training, and from information such as system drawings, equipment classifications, reliability analyses, and data on past events. However, the information is often fragmented. The decisions of the maintenance preparers are based on the information they have available and their ability to process it.

1.4.2 Information as a Resource

Ensuring optimal asset performance is challenging for all organizations with asset-intensive operations. Thus, the availability of high-quality information and use of digitalized data-driven initiatives become vital (Woodall et al., 2012). Information is a crucial asset within a company, the effective utilization of which contributes to operational efficiency and effectiveness by providing access to relevant data for informed decision-making (Krcmar, 2015). This includes assessing the current state, evaluating options, and predicting potential outcomes.

Although companies possess a vast amount of information, ranging from documents and databases to ERP systems, only a fraction of it is needed for any single decision. Nevertheless, it needs to be precisely the right information for the decision at hand, and individuals can struggle to filter, prioritize, and extract relevant insight due to the overwhelming volume of information that exceeds their capacity to use it. Hence, the value of information (Krcmar, 2015, p. 117) lies in having,

- *the right information* that is required and understood by the recipient,
- *at the right point in time* for decision-making,
- *in the right quantity* (as much as necessary or as little as possible),
- *in the right place* for the recipient,
- *and of the required quality* (sufficiently detailed, correct, and immediately usable).

This emphasizes the need for effective information management strategies. To extract its value, information should be considered a resource that is supplied to meet the needs of decision-making and that needs to be structured and organized for reuse. Here, it is important to understand the needs of the decision-maker so that the information supply is catered to them.

In the context of maintenance, several information sources, such as equipment master data, system drawings, performance dashboards, and condition monitoring, are used to inform decision-making. A common practice involves the use of a computerized maintenance management system (CMMS), which is often a subsystem of ERP systems. CMMSs facilitate an organized workflow, capturing, entering, and storing a variety of data that pertain to system maintenance and encompass historical data and maintenance records (Gunay et al., 2019; Mahlamäki & Nieminen, 2019).

The use of CMMSs has been widely adopted, serving as a repository of past events, including failures, solutions, performance, decisions, workflows, and processes over time (Gunay et al., 2019; Mahlamäki & Nieminen, 2019). This extensive amount of historical data is relevant to maintenance preparers. For instance, such data can help in understanding the past maintenance events of a specific piece of equipment. However, the retrieval of this information can be a challenge for maintenance preparers due to data fragmentation, necessitating synthesis from several sources. Moreover, understanding potential maintenance actions and identifying the best performers becomes a practically impossible task for maintenance preparers. It requires substantial effort in data extraction, cleaning, and analysis, given that the preparer possesses the necessary capabilities.

To improve the preparation of maintenance activities and facilitate informed decision-making by maintenance preparers, the historical data should be explored, structured, and organized. Considering these data as a valuable information resource has the potential to improve the maintenance process and overall operational efficiency and effectiveness.

1.4.3 Maintenance Preparation as a Design Activity

Similarities between design activities and preparation of maintenance have been observed by the present author, who possesses a background in product design and development. Maintenance preparation can be regarded as the design of maintenance activities. Preparation of maintenance is, by design, a knowledge-intensive, purposeful, and cognitive activity in a dynamic context, with the aim of "*changing existing situations into preferred ones*" (Blessing & Chakrabarti, 2009; Simon, 1981). Designing is acknowledged as complex and multifaceted, involving people; a product to be developed; a process encompassing numerous activities and procedures; a wide variety of knowledge, tools, and methods; and organization (Blessing & Chakrabarti, 2009). It entails addressing and balancing the goals, structures, and cultures associated with these different factors.

1.4.4 Quality of Maintenance Activity and Instruction Descriptions

Maintenance preparation involves the design of maintenance activities and instructions. Studies have demonstrated that precise, consistent, and high-quality instructions empower technicians with less experience to execute maintenance tasks that would otherwise demand those with more skills (Harris, 1994). The correlation between data quality and the resources required to create, deal with, and use data has been studied (Hvam et al., 2008). As illustrated in Figure 1-2, research has indicated that if the correctness of data declines to 92%, the activities relying on these data require twice as many resources as if the correctness were 100%. A further decline in quality results in the need for significantly more resources. These additional resources required to handle low-quality data do not contribute any value. This highlights the importance of adopting approaches to ensure high-quality descriptions of maintenance activities and instructions, on which maintenance process greatly relies. Therefore, if the quality of these descriptions is low, the efforts and resources required for the maintenance will likely increase. Additionally, the overall quality of the maintenance performed will be affected, leading to potential impacts on costs, risks, and reliability.

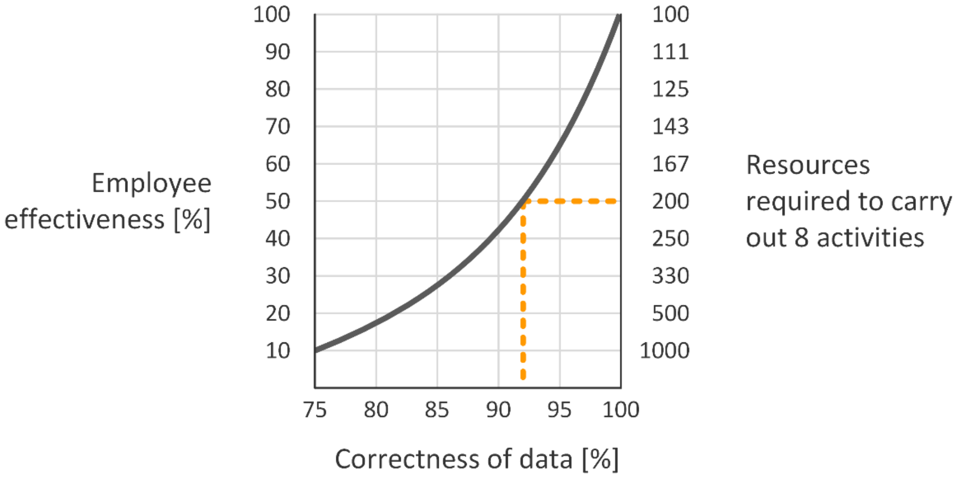


Figure 1-2. Relationship between data correctness and resource consumption, redrawn from Hvam et al. (2008)

1.4.5 Mass Customization Strategy

Mass customization is a strategy for effective design and development (Hvam et al., 2008). The mass customization strategy combines the benefits of mass production and customization, offering a wide range of personalized products while having the efficiency and economies of scale associated with mass production. Additionally, the concepts of mass customization also facilitate the high quality of product data and of the products and services produced.

Modularization is a key aspect of mass customization that involves breaking down a product into independent modules (Baldwin & Clark, 2000; Mikkola, 2006). These modules can be mixed-matched to create different variations and configurations, providing flexibility and customization. They are constrained and guided by interfaces, ensuring compatibility and enabling seamless interchangeability.

Architecture plays a crucial role in facilitating mass customization. It defines the overall framework and connectivity between the modules, establishing the structure and rules for how they interact (Harlou, 2006). Well-designed architecture enables the easy configuration of modules, ensuring that they can be efficiently combined to create customized products.

To effectively manage the architecture and facilitate the configuration of module combinations for different products, configuration systems, commonly known as configurators, can be utilized (Hvam et al., 2008). These are software applications that guide users through the customization process. They present the available options, guide selections, and ensure that the chosen configurations align with the defined dependencies and constraints set by the architecture. Configurators use the selected options to configure the product or service based on the available modules, ensuring valid and feasible combinations.

Leveraging a configuration system can significantly enhance the quality of product or service data (Hvam et al., 2008). This is partly due to the “cleaning up” process associated with modularization and configuration projects that ensures that data and rules are well-organized and precise. Additionally, the use of configuration systems minimizes human errors, leading to more reliable and correct data output, such as error-free offers, parts lists, and operation lists, from the system.

For the present research, the principles of mass customization have been used as inspiration to improve the process of maintenance preparation and ensure effective maintenance. By leveraging the principles, maintenance activities can be broken down into independent modules that represent specific activities, such as repairs, or replacements. By having a predefined set of modules, they can be mixed-matched based on specific maintenance needs. The definition of modules and architectures ensures compliance with best practice, standards, and regulations. A configurator will allow maintenance preparers to select and combine the appropriate modules to create customized, effective, and compliant maintenance, ultimately enhancing the maintenance preparation process and outcomes.

1.5 Research Purpose

The purpose of the present study is to improve the process of maintenance preparation by considering historical data of past maintenance events as valuable information resources, viewing maintenance preparation as a design activity, and applying principles from mass customization, thereby aiming to improve the overall productivity and effectiveness of maintenance.

The objective is to explore the historical data of a maintenance-performing company and investigate their relevance to the preparation of maintenance activities. Additionally, the study aims to actively structure, organize, and reuse these data using the concepts of modularization and architecture. Furthermore, it will pursue an exploration of alignment between the development of a configurator and performance objectives. The goal is to advance the understanding of historical data and their utilization in maintenance preparation.

1.6 Research Framework and Questions

The research framework, as depicted in Figure 1-3, formalizes the study’s purpose and objectives. This figure visually presents the integration of historical data and their implications for maintenance preparation, including considerations of architecture and configuration systems and their impacts on performance. Also featured in Figure 1-3 are the research questions of the thesis, further illustrating their connection to the framework.

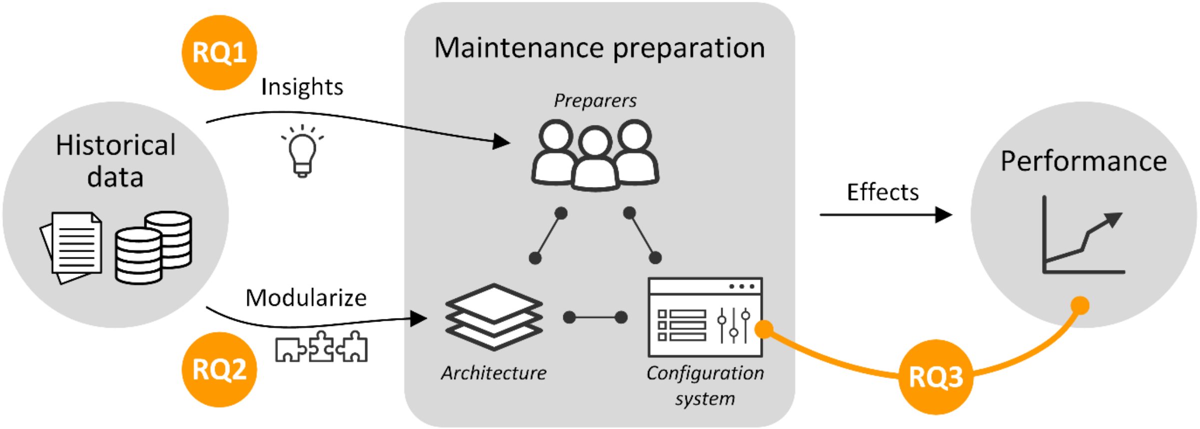


Figure 1-3. The research framework and the related research questions

The research questions are defined and clarified below.

RQ1: ***How can data on failures and maintenance activities be utilized for maintenance preparation?***

This question explores the role and value of data in maintaining complex industrial systems, with a particular focus on how insights can be derived and utilized to enhance maintenance preparation.

RQ2: ***How can historical data be utilized for the modularization of maintenance?***

This question examines the potential for reusing historical data within a maintenance-performing company, with a view to structuring and organizing the data using the modularization approach. The aim is to investigate how a company can leverage past and existing services, represented in the historical data, to modularize its maintenance services.

RQ3: ***How can development and performance assessments be aligned in configuration system development projects?***

This question examines the purposeful development of configuration systems with performance objectives such as reducing preparation errors, improving compliance, decreasing time consumption, and aligning the development and performance assessment early in a configurator development project.

1.7 Research Aim

This research seeks to improve operations by leveraging insights from historical data and enhancing maintenance processes. Additionally, it aims to extend understanding of the value and utilization of historical data, particularly in the context of maintenance preparation, benefiting both researchers and practitioners.

By delving into these areas, this study aims to contribute valuable knowledge and guidance for optimizing maintenance preparation processes. The overall aim is to explore and understand the principles and requisites for configuring maintenance, particularly providing insights for the preparation of a maintenance-performing company to achieve this.

1.7.1 Areas of Relevance and Contribution

Significant research results often occur when different research fields intersect and when knowledge, ideas, and methods are transferred from one area to another (Blessing & Chakrabarti, 2009). To identify and define relevant research areas for the present research and where contributions are made, the Areas of Relevance and Contribution (ARC) diagram has been used. The diagram has been useful for clarifying the foundational basis of the research as well as the areas of contribution by exploring the theories, models, background information, and more of various disciplines to draw inspiration or make contributions. Figure 1-4 shows the ARC diagram for the present research, distinguishing between areas that are useful, essential, and where contributions are made.

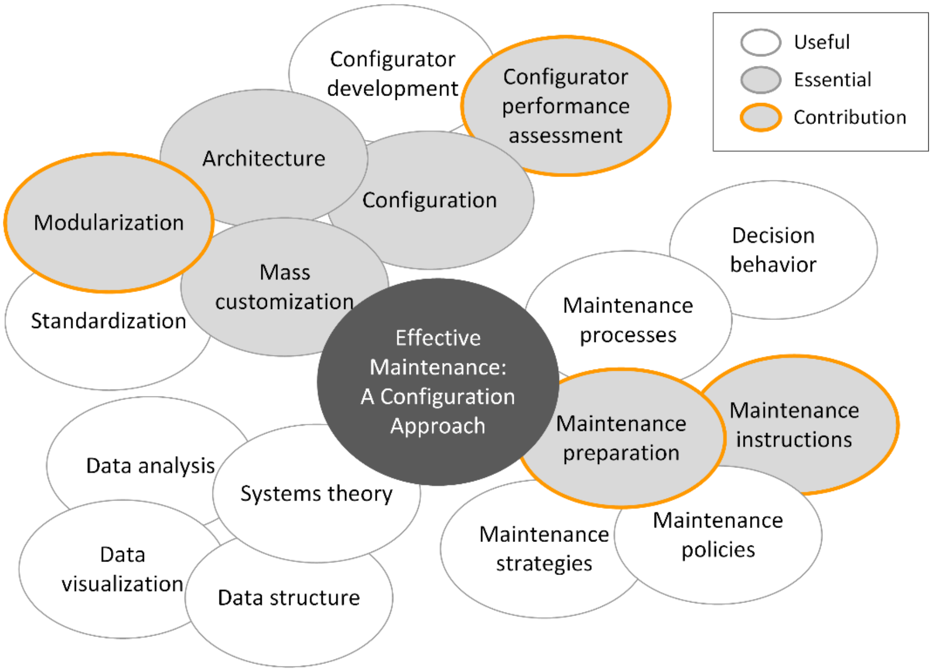


Figure 1-4. Areas of relevance and contribution of the PhD project

1.8 Outline of the Thesis

This paper-based PhD thesis features a collection of research publications and is a coherent synopsis on the findings and individual contributions from these publications. The remainder of the thesis is structured as follows:

2	*Research Methodology*	introduces the research methodology, methods, and activities employed
3	*Theoretical Basis*	presents the theoretical underpinnings of the research
4	*Results*	presents the individual contributions and methods of the included publications
5	*Conclusions*	summarizes the findings of the research, answers the research questions, and discusses the research limitations
6	*Further Research Suggestions*	proposes topics and directions for further research
7	*Supplementary Results*	summarizes the results of the supplementary publications

The included publications are appended at the end of the thesis.

2

Research Approach

To answer the research questions, the present thesis aims to balance the notions of rigor and relevance; that is, relevance in the form of addressing real-world problems and providing insights that are useful and meaningful, and rigor in terms of applying research methods and principles to ensure the validity and reliability of the research process and results. For this, design research has been applied as the overarching research approach, addressing both the academic and industrial ambitions of this PhD project.

2.1 Design Research Methodology

Design research encompasses two objectives, namely, the formulation and validation of models and theories regarding phenomena and the development and validation of support based on these models and theories, with the aim being to improve design practice and its outcomes (Blessing & Chakrabarti, 2009). Design research methodology (DRM), as presented by Blessing and Chakrabarti (2009), has been adopted to guide the research of this PhD project. DRM recognizes the significance of design research in providing understanding and developing support, serving as the underlying framework of this project. DRM is a stepwise approach and consists of four stages:

- **Research clarification (RC):** This stage aims to clarify the aim, focus, and scope of the research project; outline the overall research aim; develop a research plan; and provide a clear direction for the subsequent stages.
- **Descriptive study I (DS I):** This stage aims to enhance understanding of the studied phenomena. Through investigation, valuable insights are gained to inform the development of support.
- **Prescriptive study (PS):** Building upon the results obtained from the descriptive study, this stage focuses on systematically developing support.
- **Descriptive study II (DS II):** In this stage, the resulting support is evaluated. The emphasis is on assessing the usability, applicability, and overall usefulness of the developed support, ensuring it meets the intended objectives.

These stages are depicted in Figure 2-1. A detailed description of each stage in relation to the present research is provided in later sections.

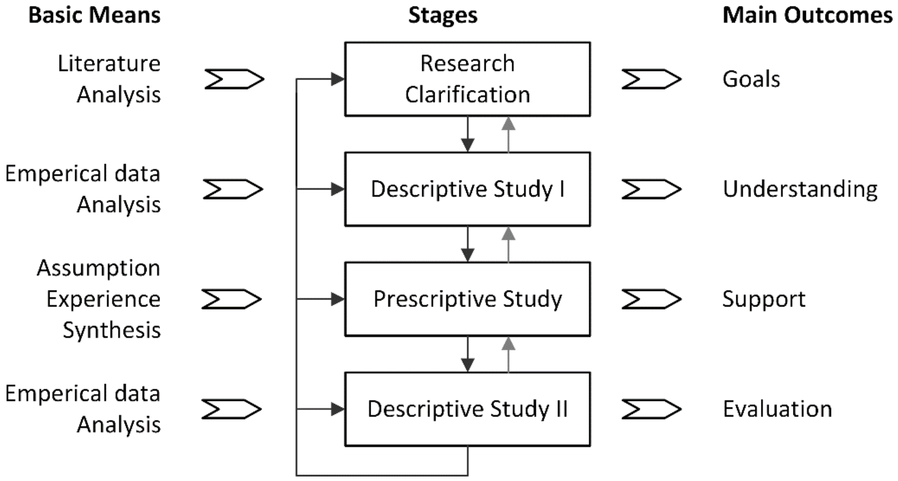


Figure 2-1. The four stages of design research methodology, redrawn from Blessing and Chakrabarti (2009)

2.1.1 Model-Based Problem-Solving

The objective of DRM is to improve a current situation into a desired situation (Blessing & Chakrabarti, 2009). The methodology highlights the importance of gaining an understanding of a situation before developing support to improve it. To further clarify and strengthen this relationship, the model-based problem-solving approach of Leimeister (2012) has supplemented the present study. This approach is illustrated in Figure 2-2. The basic notion of the approach is that a direct modification of the current state to a target state cannot be performed. To reach the target state, the existing state with the initial problem has to be modelled. Within the framework of the model, the problem is formulated, analyzed, and solved. The solution is then implemented as modifications in the model. The emerging prescriptive model can subsequently be used to test the modifications through application, and an improved state is eventually reached.

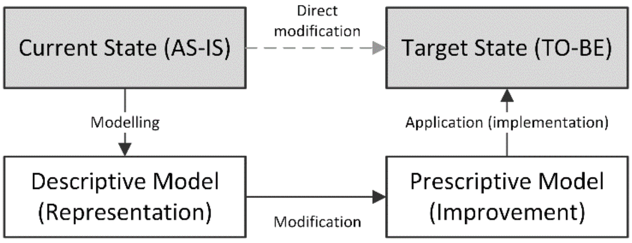


Figure 2-2. Model-based problem-solving, adapted from Leimeister (2012)

2.1.2 Working Paradigms

To underline and support the ambition of this PhD project to contribute to both researchers and practitioners alike, the scientific working paradigms set forward by Jørgensen (1992) have guided the research. The objective is to bridge and combine the two fundamental paradigms of conducting problem-oriented research and carrying out innovative theory-based research, as illustrated in Figure 2-3. Jørgensen (1992) argued that these should be performed jointly, forming a derived problem-based and theory-based working paradigm. This is to both anchor the research in a practical reality and process the research results that emerge for practical applications as well as to both test new scientific realizations' applicability in practical reality and ensure the grounding of the work in state-of-the-art research.

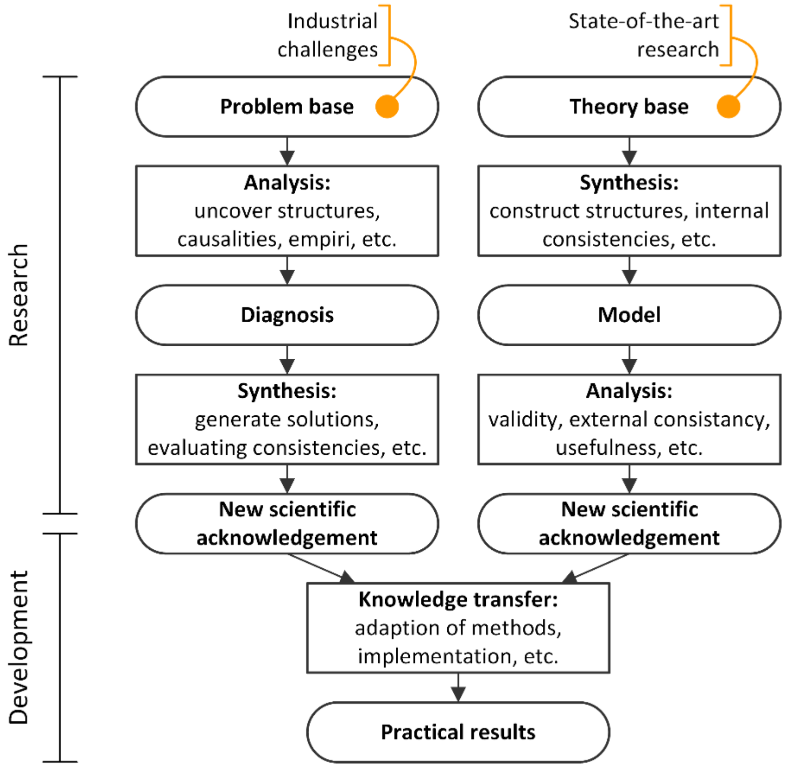


Figure 2-3. The problem-based and theory-based working paradigm, based on Jørgensen (1992)

2.2 Research Methods

In this work, several research methods have been applied, each with its own limitations and flaws (Turner et al., 2017). Nevertheless, these limitations can be addressed by combining different methods to obtain more comprehensive insights into the research questions. By employing multiple methods, the understanding of the studied phenomena can be broadened and deepened (Turner et al., 2017).

In the present research, literature studies, case studies, and action research have been employed as primary research methods, using both qualitative and quantitative data. Here, the distinction between case studies and action research lies in the role assumed by the researcher. In case studies, the researcher primarily assumes the role of observer, while in action research, they actively engage with the case company. Nevertheless, it is possible to concurrently apply action research and case studies, allowing for a combination of observation and interaction. The following section elaborates on the primary methods of the present research.

2.2.1 Literature Study

Literature studies have been utilized to explore and examine the existing body of knowledge present in the research literature. This is valuable to gain a comprehensive understanding of the subject matter, position the research within the literature, make contributions, and build upon and extend the state-of-the-art. In the research clarification stage, studies of literature are used to frame the research and guide subsequent work. In the descriptive studies, literature studies have been used to synthesize existing knowledge to support and further clarify the findings. Additional literature reviews have been used in other studies to investigate various aspects.

2.2.2 Case Studies

Case studies are appropriate and valuable for studying complex issues within their real-life contexts, particularly when investigating "how" and "why" research questions (Yin, 2009). On this basis, case studies have been conducted for the present research project.

A case study involves investigating the history of a past or present phenomenon using various sources of evidence (Leonard-Barton, 1990). Case studies are well-suited for capturing behaviors that occur in authentic contexts (Turner et al., 2017), allowing a phenomenon to be studied in its natural setting and enabling the generation of meaningful, relevant theory from the gained understanding (Meredith, 1998).

Case research can have a significant impact because many substantial concepts and theories may emerge from it (Voss et al., 2002). However, drawing generalizable conclusions from a limited set of cases and ensuring rigorous research can be a challenge. To address this, multiple case studies can be utilized for more claims regarding generalizability (Turner et al., 2017), and validity can be further enhanced by triangulating multiple methods of data collection (Voss et al., 2002). It is also possible to examine different issues within the same company using various cases or to investigate the same issue across various contexts in the same firm (Voss et al., 2002).

In the present research project, one case company has been primarily studied, although it provides the basis for six different case studies. These studies approach different issues within different contexts. Table 2-1 presents the case studies, their objectives, their data collection methods, and the corresponding papers in which they are discussed. Notably, Paper D includes an additional case study from a different case company to increase generalizability. To enhance rigor, multiple data sources are used for the studies, including semi-structured interviews, personal observations during meetings and workshops, and the collection and analysis of documents and data.

Table 2-1. Overview of the case studies

Paper	Cases	Case study objective	Data collection methods
A	1	Retrospective study of the application of a principle for using historical data that presents three different scenarios of future use.	- Collection and analysis of maintenance records
B	1	Demonstrate, test, and evaluate the applicability of a method to incorporate data into decision-making.	- Equipment master data, maintenance records, and system drawings - Observations, meetings, and semi-structured interviews
C	1	Investigation of the feasibility and applicability of a proposed method, including the usability of historical data.	- Maintenance records - Observations, meetings, and semi-structured interviews
D	2	Examine maintenance and commissioning services, apply service modularity concepts, and evaluate the prospective benefits.	- Historical service design data from service planning documentation and enterprise resource planning (ERP) systems - Observations, meetings, workshops, and semi-structured interviews
E	1	Systematic analysis of maintenance instruction and testing the applicability of a model to modularize these, including the validation of findings.	- Internal documents and data extractions from CMMS - Workshops, meetings, and semi-structured interviews
F	1	Longitudinal study to evaluate a proposed approach following the development of a configuration system at a company during which the researchers conducted performance assessments.	- Data extractions from enterprise IT systems and from a configuration system event log - Semi-structured interviews and participatory observations during meetings and a workshop

2.2.3 Action Research

In this research project, action research has been employed in the prescriptive stages. Fundamentally, action research is about driving change (Shani & Pasmore, 1982). The researcher takes an active role with the dual goals of exploiting an opportunity or solving a problem and making meaningful contributions to research (Gummesson, 2000). This process is highly interactive.

In contrast to traditional positivist science, which solely aims to create knowledge, the outcome of action research includes both action-oriented results and research-based knowledge (Coughlan & Coghlan, 2002). A distinguishing characteristic of action research is its focus on working with people and organizations, rather than on or for them (Coughlan & Coghlan, 2002; Shani & Pasmore, 1982). Action research has considerable relevance for practitioners because, while it contributes to research theory, it can produce actionable knowledge (Coughlan & Coghlan, 2002).

Data gathering in action research can utilize a wide range of methods, allowing for comprehensive exploration (Gummesson, 2000). Unlike much qualitative research that focuses on past events, action research involves researching in the present tense (Coughlan & Coghlan, 2002). It builds on historical data and takes place in the present with the objective of shaping the future.

Action research positions itself in relation to the needs of both industry and research. It aims to resolve real-world issues with uncertain outcomes, facilitated by physical access to data collection and the organization (Coughlan & Coghlan, 2002).

In relation to the PhD project, action research is a fitting method due to the significant collaborative relationship with the primary case company and the presence of a real-world issue requiring resolution. This method allows for the contribution of actionable knowledge for practitioners through the research project, as well as the generation of emergent research theory.

2.3 Research Design and Activities

The research design of the PhD project is illustrated in Figure 2-4, which depicts the DRM research stages undertaken and the corresponding research methods employed to address each research question. Additionally, it indicates the specific research question to which the findings of the included papers contribute. The subsequent sections describe the activities carried out during the DRM stages.

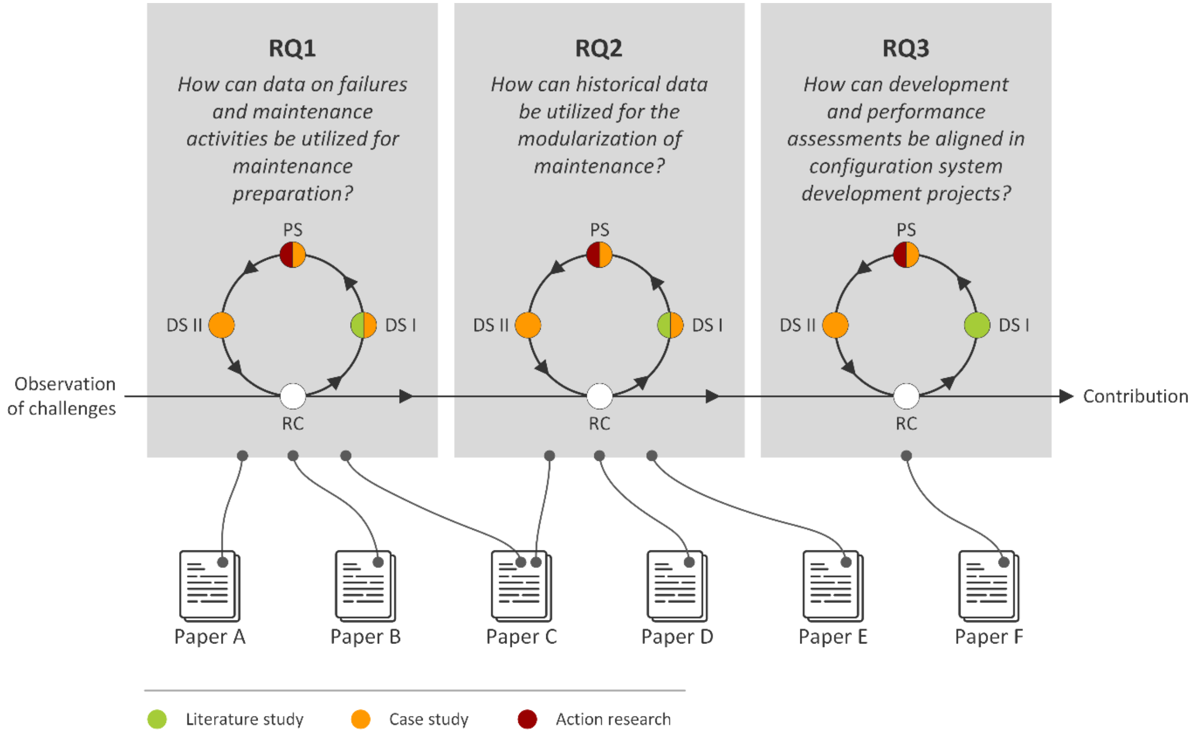


Figure 2-4. The research design of the PhD project

2.3.1 Research Clarification

All studies were initiated based on observations of challenges encountered in industry. These observations were further clarified by examining the existing literature. This involved investigating whether these challenges had been previously described or solved as well as exploring how similar challenges had been addressed in different domains, with the aim of drawing inspiration and insights. Furthermore, the initial potential for adapting concepts, methods, and frameworks from the literature to address industrial challenges was explored.

The understanding derived from these observations and the initial clarifications were used to position the studies within the context of the existing literature and industrial challenges. This involved clarifying the involved domain areas and determining the expected contributions. As a result, the research goals were identified and defined, and the focus of the studies, including the research problem, was also defined.

This preliminary clarification serves as the foundational basis for the following stages.

2.3.2 Descriptive Study I

A greater understanding of the situations requiring improvement was to be gained during the DS I stage. The factors influencing the situations were to be identified and clarified in more detail.

In the studies of this project, this was conducted through literature reviews and case studies. The existing body of literature was reviewed to extend the initial understanding. Case studies were used to obtain empirical data if the literature showed a lack of understanding of the topic. This involved collecting and analyzing empirical data and conducting interviews with key people to gain insight into the results. The aim was to investigate the extent to which phenomena occurred and to examine the nature of the phenomena.

The goal was to identify the most suitable factors to address and provide a foundation for the effective development of support,

2.3.3 Prescriptive Study

Based on understanding the factors that needed to be addressed, support was to be developed and realized that would address these. The support should be systematically developed with a focus on these factors and with enough detail to evaluate its impact. The goal was to improve the existing situation to a desired situation.

Each study described in the included papers proposed a method, concept, or framework aimed at improving the situations. These studies employed a combination of action research and case studies. Action research was used as an approach to take an active role in facilitating changes in the situations, while case studies were employed to observe the implementation process and assess the progress made.

2.3.4 Descriptive Study II

In this stage, the objective was to determine whether the applied support had the desired impact. Empirical studies are commonly conducted during this stage. In the studies of this research project, case studies were employed to observe and investigate the impact and effects of the proposed supports. The aim was to evaluate whether the introduction of the support had improved the existing situation and whether the support was as intended. Additionally, the focus was on assessing whether the process of applying the support aligned with the expectations.

This stage was essential because the support had been developed based on assumptions, even though these assumptions were thoroughly investigated. Therefore, the actual impact and effects of the proposed and applied support were unknown, and evaluation was needed. Furthermore, the studies conducted sought to investigate necessary improvements if the support was not as expected.

2.4 Other Research Activities

Other research activities, such as attending courses, sharing and dissemination of knowledge, and collaborating with students, were conducted throughout the PhD project.

2.4.1 Academic Courses

The following courses, on modularization, architecture, maintenance, and research design and methodologies, were attended and completed as part of this PhD project.

- Product Platform and Product Family Design: From Strategy to Implementation
  Massachusetts Institute of Technology, USA
    - Course on site at the MIT campus with a focus on the strategic and implementation aspects of modular architectures, covering the latest theory as well as case studies.
- RAM&PHM 4.0: Advanced Methods for Reliability, Availability, Maintainability, Prognostics, and Health Management of Industrial Equipment
  Politecnico di Milano, Italy
    - Course on the newest advancements within the maintenance field with a focus on advanced techniques within data analytics.
- WCM Summer School on Maintenance Management & Engineering
  World Class Maintenance, The Netherlands
    - Course bringing together young professionals and PhD students to solve a real-world case and including lectures within the maintenance field from both academia and industry.
- EDEN Doctoral Seminar on Research Methodology in Operations Management
  European Institute for Advanced Studies in Management (EIASM), Belgium
    - Course bringing discussions and insights into the characteristics of different research methodologies.

- EurOMA Doctoral Seminar: Research Design in Operations Management
  University of Warwick, United Kingdom
    - A seminar that provided the opportunity to present and discuss the research of this PhD project and receive feedback from established renowned researchers and peers.
- Sustainability Evaluation and Communication (42750)
  Technical University of Denmark, Denmark
    - Course at DTU with the aim of enabling the achievement of sustainability goals by providing an understanding of sustainability and sustainable development for use in PhD studies.
- Architecture and Systems Engineering: Models and Methods to Manage Complex Systems
  Massachusetts Institute of Technology, USA
    - Online four-course program to explore state-of-the-art models and methods to manage complex systems through industry case studies and the latest thinking from MIT.

Besides these courses, there was also participation in a book club, where three books on the subject of data intelligence were read and discussed.

2.4.2 Knowledge Sharing and Dissemination

The following presents an account of the key knowledge dissemination activities carried out throughout the PhD project. The activities included presentations, pitches, guest lectures, and posters for and discussions with both academia and the industry concerning the results and findings of this PhD project.

Conferences Attended

- DHRTC Technology Conference 2019 and 2021, Kolding, Denmark
    - Poster about the research project.
- DHRTC Young Researcher's Day 2020
    - Online presentation of the research project.
- NordDesign 2020
    - Co-authored several papers and participated in the conference.
- The 2021 Annual Reliability and Maintainability Symposium (RAMS), Florida, USA
    - Presentation of the research results (attended online due to Covid-19)
- DHRTC Young Researcher's Day 2022
    - Poster and pitch presentation on the research project.
- Danish Offshore Technology Conference 2022, Kolding, Denmark
    - Co-authored a poster.
- The 2022 6th International Conference on System Reliability and Safety (ICSRS 2022), Venice, Italy
    - Online presentation of the research results.
- EuroMaintenance 2023, Rotterdam, the Netherlands
    - Participated at Europe's largest maintenance congress.

Guest lectures

- 41083 Technology Platforms and Architectures, DTU (2020, 2021, 2022)
- 41637 Mass Customization – Application of Product Configuration, DTU (2022)
- DTU Executive MBA (2023)

Other dissemination activities

- Held a webinar for members of the Danish Maintenance Society (DDV) on the value to be found in historical data and maintenance records (2020).
- Prepared a presentation for the Maintenance Excellence network of the DDV on the configuration of maintenance (2023)
- Presented the research at the Maintenance NEXT 2023 industrial exhibition in Rotterdam, the Netherlands.
- Partook in the planning and creation of a video to promote a successful academic and industrial collaboration between DTU and TotalEnergies covering aspects of the research in this PhD project (2022–2023)
- Besides collaboration with TotalEnergies E&P Denmark, I have presented and discussed my research with other affiliates -, including research on digital innovation in France, operational excellence with affiliates in Qatar and United Kingdom, and on new developments with those in Uganda and Angola.
- Throughout the project, presentations and discussions were held with various European companies. However, the company names cannot be disclosed due to confidentiality.

2.4.3 Awards

Winner of the TotalEnergies Best InnoCop Award 2023

For recognition of the industrial results, the "Best InnoCop" was awarded for the associated work of this PhD project. The award is a recognition from the entire global exploration and production segment of the TotalEnergies group and given to teams or individuals for their ability to adapt concepts or techniques existing in other domains or industries originally dedicated to other use cases and transform them to new needs to create value. Specifically, we were acknowledged for successfully employing the principles of mass customization and configuration to transform maintenance operations.

First Place at TotalEnergies NSR Innovation Awards 2022

The research findings from this PhD project, the derived results at TotalEnergies, and the collaborative efforts of TotalEnergies and DTU were recognized at the TotalEnergies NSR Innovation Awards (now named Europe Innovations Awards). The project was nominated, selected as a finalist, and ultimately won first place in the "Continuous Improvement and New Approaches" category out of 44 nominated projects from the UK, the Netherlands, Russia, Norway, and Denmark. In the words of the jury: "*The first place is clearly contributing to the digital transformation of our production operations. Thanks to these new and disruptive approaches, what used to require several hours to prepare now takes only a few minutes, while* *job quality and pertinence have improved. It is really, really, really impressive! Some key words: simplification, acceleration, and excellence. The first place goes to …*"

Excellent Oral Presentation at ICSRS 2022

The paper entitled "*Improve Maintenance by Reusing and Refining Previous Maintenance Cases*" was recognized as one of the top presentations at the 2022 6th International Conference on System Reliability and Safety (ICSRS 2022) and received recognition as an "Excellent Oral Presentation."

Best Poster Award at the Danish Offshore Technology Conference 2022

Part of the winning team of the conference poster award for the poster "*Industrialization of Maintenance by Means of Intelligent Automation*," which highlighted the contributions of this thesis as well as the work of the other co-authors. The conference was organized and hosted by DTU Offshore with the participation of more than 270 academic and industry experts.

2.4.4 Collaboration with Students

Throughout the PhD project, several student projects have been co-supervised at the Technical University of Denmark (DTU). These projects were related to the scope of this PhD project, and all were carried out in collaboration with the main case company.

- Data Visualization of Failure History for Industrial Maintenance
  Co-supervision of project course (2021)
- Using Machine Learning to Predict Work Hours in Corrective Maintenance Work
  Co-supervision of bachelor's thesis (2021)
- Modularization-Based Optimization of Materials Management in the Maintenance of Complex Systems
  Co-supervision of master's thesis (2022)
- Automation of Work Permits Based on Modularization
  Co-supervision of project course (2022)

3

Theoretical Basis

This section establishes the theoretical basis upon which the present research was developed. It encompasses several key topics, namely systems theory for the fundamental understanding of systems; asset maintenance, and how it is conducted; and the strategy of mass customization, including the topics of modularization, architecture, and configuration. Additionally, a reflection is included on how these theories have contributed to the present research.

Each paper included in the thesis aligns itself with this theoretical basis and, in addition, includes a review of the relevant literature.

3.1 Systems Theory

This thesis delves into the study of systems, which can be a multitude of things. According to Crawley et al. (2016), a system is "*a set of entities and their relationships, whose functionality is greater than the sum of the individual entities*." From this definition, two central points are implied. First, a system is composed of entities that interact or are interrelated. Second, when these entities interact, a function emerges that is greater than, or distinct from, the functions of the individual entities.

Systems theory, as used in design theories, serves as an approach for the analysis and synthesis of complex systems (Andreasen et al., 2015). Through this theory, systems can be modelled as objects composed of elements and their respective relationships, thereby forming a structure with certain behaviors. The basic modelling concepts are illustrated in Figure 3-1.

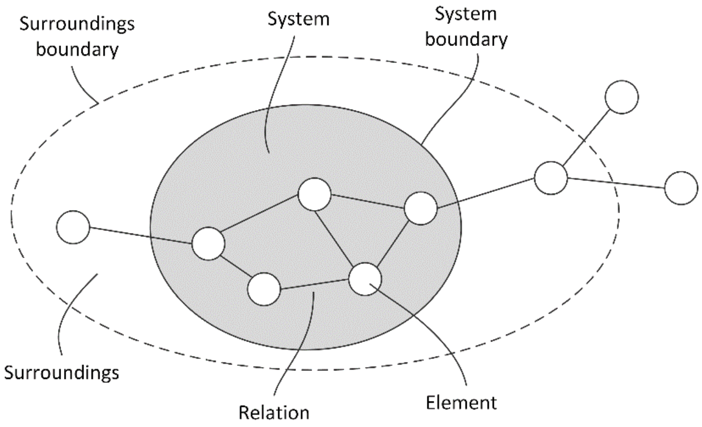


Figure 3-1. The basics concepts of modelling systems, adapted from Andreasen et al. (2015, p. 197)

A unanimous consensus on the definition of system complexity is lacking (Sitte, 2009). According to Crawley et al. (2016) complex systems are characterized as having "*many elements or entities that are highly interrelated, interconnected, or interwoven*." Consequently, complexity can be characterized by the number of distinct elements and the number of relations among them. The interactions between these elements lead to emergent properties and potentially unpredictable behavior (Sitte, 2009). The related term "complicated" refers to the human ability to perceive and understand complexity (Crawley et al., 2016). Thus, greater system complexity also implies greater strain on our ability to comprehend it in terms of the elements, their interrelations, the emergent properties, and unpredictable behavior.

This thesis focuses on technical and transformational systems, drawing from the theory and definitions provided by Hubka and Eder (1988) in the field of engineering design. According to Hubka and Eder (1988), technical systems are artificial systems that include "*all types of man-made artifacts, including technical products and processes*." Hubka and Eder (1988) defined different degrees of complexity for technical systems, as described in Table 3-1, giving a greater perspective on what constitutes a complex system.

Table 3-1. The degrees of complexity of technical systems, adapted from Hubka and Eder (1988, p. 97)

Level of complexity	**Technical system**	**Characteristic**	**Examples**
I (simplest)	Part, component	Elementary system produced without assembly operations	Bolt, bearing sleeve, spring, washer
II	Group, mechanism, sub-assembly	Simple system that can fulfill some higher functions	Gearbox, hydraulic drive, spindle head, brake unit, shaft coupling
III	Machine, apparatus	System that consists of subassemblies and parts that perform a closed function	Lathe, motor vehicle, electric motor
IV	Plant, equipment, complex machine unit	Complicated system that fulfills a number of functions and that consists of machines, groups, and parts that constitute a functional and spatial unity	Hardening plant, machining transfer line, factory equipment

3.1.1 Transformational Systems

Hubka and Eder (1988) described the workings of a system through the concept of a transformational system. This encompasses all elements, influences, and their interrelationships that are involved in the process of transformation. Essentially, transformational systems have the purpose of changing a starting state to a final state, where the operands typically are material, energy, or information. The system includes the structure of the operations; their sequence, which accomplishes the transformation of the operand and aids in assisting humans to perform these operations; and the management and control mechanisms that guide the transformational system. Figure 3-2 illustrates the general model of a transformational system.

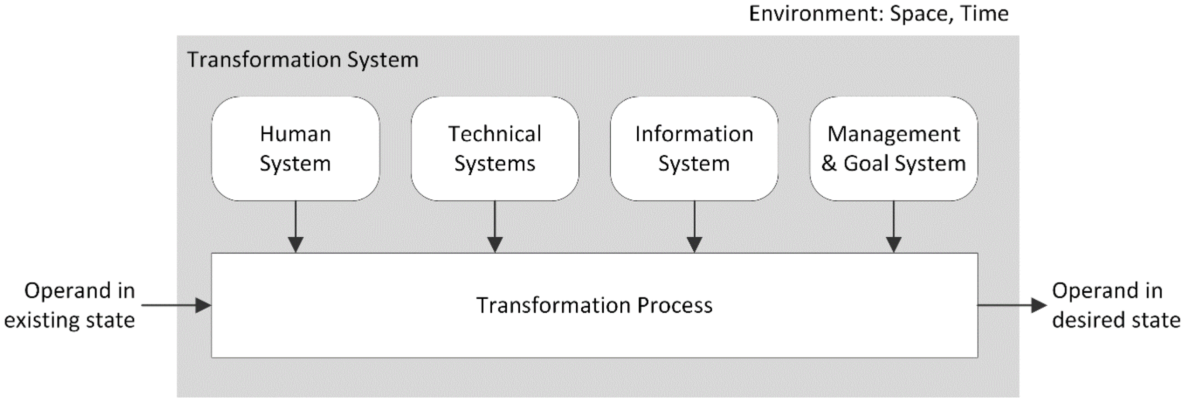


Figure 3-2. Model of a transformational system, adapted from Hubka and Eder (1988, p. 24)

Design as a Transformational System

In the process of designing, a transformational system transforms a set of needs to a description of a design. The information about a need or the direct requirements for a product or service is transformed via a design process into a complete description of the design to address those needs. As shown in Figure 3-3, Hubka and Eder (1988) applied the transformational system model to the design process. This model encompasses the design process itself, the object to be designed as the operand, designers as human operators, technical systems as their working tools, information and management systems as the aid and context, and the environments as the time and place.

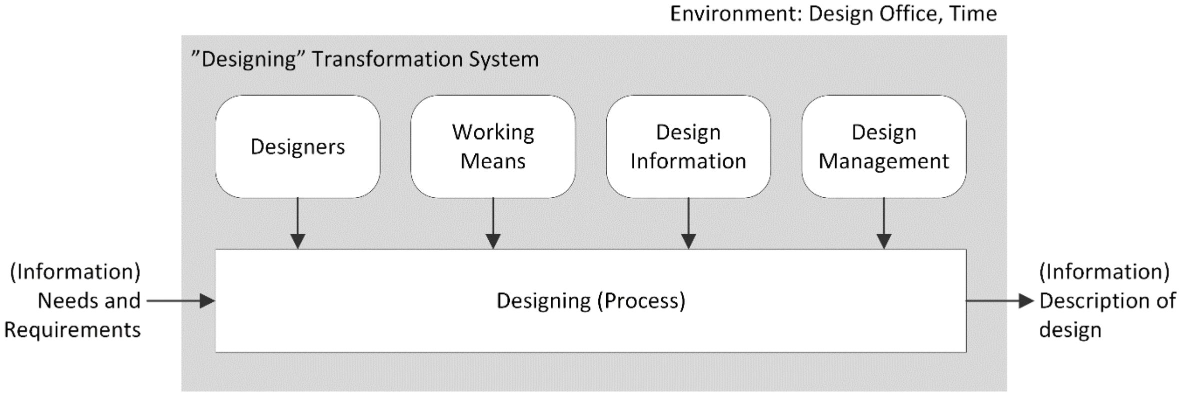


Figure 3-3. Model of design process, adapted from Hubka and Eder (1988, p. 215)

3.1.2 Model-Based Systems Engineering

Engineers often face challenges in finding the information they need, especially given the increasing complexity of systems (A. Madni & Sievers, 2018). This has made it more difficult to use and manage document-centric approaches, due to the effort needed and because critical information can easily be overlooked. As a result, model-based approaches such as model-based systems engineering (MBSE) have been introduced (A. Madni & Sievers, 2018).

To ensure that organizations are effective, it is crucial that everyone "speaks" the same language and works on the same "matter" (Ramos et al., 2012). MBSE and the model-centric approach revolve around having a unified and coherent central model that promotes transparent and traceable design (Friedenthal et al., 2015; A. Madni & Sievers, 2018). This model serves as the system's sole source of truth and fosters a shared understanding within the organization.

The value of MBSE lies in its ability to store and manage all system-related information in a centralized repository, replacing the need to manage numerous documents with a controlled model of the system (A. Madni & Sievers, 2018; Ramos et al., 2012). This facilitates efficient information retrieval and automatic propagation of design changes, leading to potential cost reductions and quality improvements (Madni & Sievers, 2018).

Model-based approaches are essential to leverage technological advancements such as digital twins (A. Madni et al., 2019).

3.2 Asset Maintenance

The introduction of this thesis (see Section 1.1-1.2) provided a discussion on the challenges associated with the maintenance of complex systems. In this section, the theory and nomenclature of maintenance are clarified.

The maintenance of assets is vastly different from simple common maintenance, such as maintaining one's own bike. Rather, it involves maintaining intricate multiunit systems consisting of numerous interconnected and interdependent components (Petchrompo & Parlikad, 2019). The complexity of these systems may also derive from them being difficult to reach, such as offshore unmanned platforms, or covering vast areas, such as a railroad network. Consequently, this complicates the performance of maintenance. Therefore, the maintenance of assets requires structured organization and established processes to monitor, prioritize, plan, and implement maintenance operations. For the purpose of this thesis, asset maintenance is simply referred to as "maintenance."

Maintenance can be defined as the "*combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function*" (European Standard, 2017a). Similar definitions exist in several industrial standards (IEC, 2015; ISO, 2016).

Maintenance is a critical component of asset management (Petchrompo & Parlikad, 2019). It enables organizations to derive value from their assets while achieving their organizational objectives. In this regard, maintenance significantly contributes to asset dependability, defined as the ability to perform as and when required (European Standard, 2017a; ISO, 2014). Dependability is achieved through the effective planning and implementation of dependability activities, with maintenance playing a crucial role (IEC, 2004, 2014).

3.2.1 Maintenance Types and Actions

In general, maintenance can be classified into two main types: preventive and corrective maintenance. Figure 3-4 illustrates the different types of maintenance, synthesized from EN 13306:2007 and IEC 60300-3-14:2004. The following provides a description of the maintenance types and actions based on those standards.

Corrective maintenance is performed after a fault has been observed and recognized. The purpose of this maintenance type is to restore equipment to a state in which it can perform the required function. Preventive maintenance is conducted proactively to prevent the occurrence of failures. This type of maintenance is used to assess and mitigate degradation and reduce the likelihood of failures. Preventive maintenance can be carried out in two ways: through predetermined time intervals or usage-based intervals or through condition monitoring to assess the conditions of equipment. Condition-based maintenance can further be divided into predictive and non-predictive approaches. Predictive maintenance involves repeated analysis and forecasting, often involving sensors and advanced algorithms, whereas non-predictive maintenance often involves hands-on monitoring of the condition.

Regardless of the type of maintenance required, maintenance actions need to be conducted. These actions include both passive actions, such as observing and analyzing the equipment's state (e.g., inspection, monitoring, testing, diagnosis, or prognosis), and active maintenance actions (e.g., repair, refurbishment).

This thesis does not address improvements and modifications to systems or equipment, which can be classified as a separate type of maintenance.

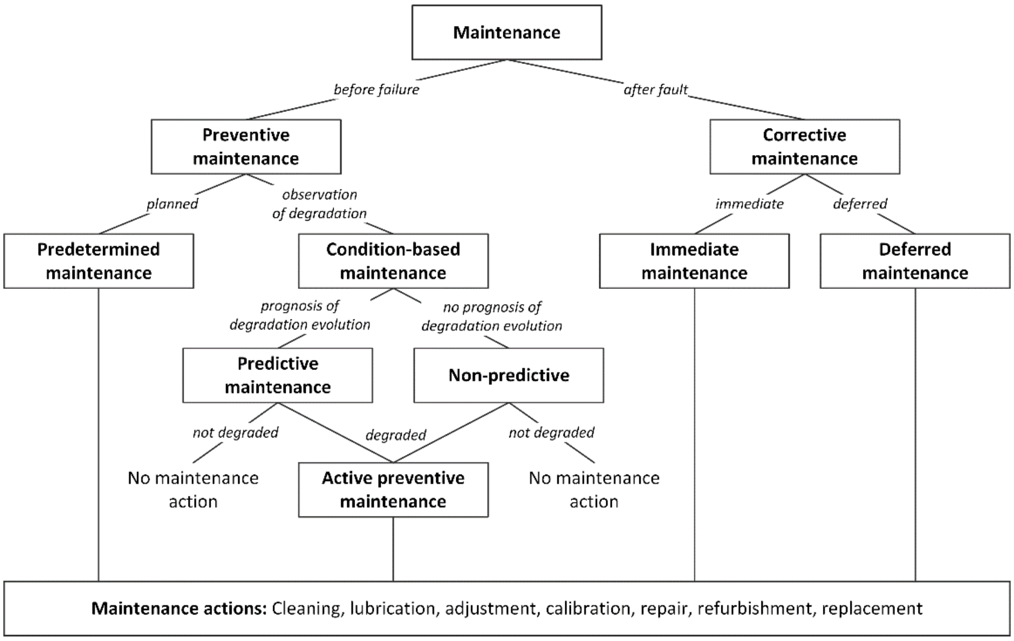


Figure 3-4. Maintenance types and actions, based on EN 13306:2007 and IEC 60300-3-14:2004

3.2.2 Maintenance Strategies and Policies

Maintenance strategies and policies are fundamental concepts in the field of maintenance. Maintenance strategies encompass the overall approach or plan that an organization adopts to effectively manage its maintenance operations. This involves making decisions related to maintenance methodologies, setting up a suitable maintenance organization, and implementing systems to direct maintenance efforts (Kelly, 2006a). Maintenance strategies also consider the objectives, goals, budgets, available resources, and assets and systems to be maintained.

Numerous strategies have been developed to improve maintenance beyond the traditional reactive firefighting approaches (R. K. Sharma et al., 2005). The most commons ones include the following:

- *Total Productive Maintenance (TPM)*: This is a maintenance philosophy developed based on Japanese manufacturing principles, particularly LEAN processes (Ahuja & Khamba, 2008). TPM emphasizes the implementation of eight pillars that encompass various aspects, such as value-creating activities, quality and defects, the promotion of autonomous maintenance by machine operators, and focused improvements. The objective of TPM is to optimize equipment effectiveness, eliminate breakdowns, and enhance overall operational efficiency (Ahuja & Khamba, 2008). It is often implemented together with other LEAN manufacturing initiatives, such as Total Quality Management and Just-in-Time (Cua et al., 2001).
- *Reliability-Centered Maintenance (RCM)*: RCM aims to optimize the maintenance program of a company or facility (Geisbush & Ariaratnam, 2022). It involves a systematic process to identify the functions of an asset, analyze the causes of failures, and evaluate the effects of those failures in the context of its operation (Ahuja & Khamba, 2008). By considering these, the most effective maintenance approach can be

determined, integrating the different types of maintenance, to ensure the desired reliability and availability of assets at the lowest cost (Geisbush & Ariaratnam, 2022).

Maintenance policies, in contrast to strategies, are the specific rules, guidelines, or procedures that dictate how maintenance activities should be conducted and provide guidance for how such activities should be prepared, planned, and executed. These policies are often company-specific and developed based on best practices, standards, regulations, and other relevant factors. The following are types of maintenance policies (Wang, 2002):

- *Age-dependent policies*: The age of equipment decides the actions to perform involving maintenance activities (i.e., after a certain age is reached).
- *Use-dependent policies*: The usage of equipment decides the actions to perform involving maintenance activities (i.e., after a certain level of utilization or operating hours).
- *Repair-cost or time-limit policies*: Maintenance activities are considered based on the cost or time required to perform them. For example, if the cost to replace equipment is below a certain predefined amount, replacement is preferred over repair.
- *Failure limit policies*: Conducting maintenance after a certain number of failures, such as replacing equipment after multiple repairs.
- *Block replacement policies*: Replacing an entire equipment package if one component fails.
- *Opportunistic policies*: Opportunities for conducting relevant maintenance concurrently, such as combining tasks under shutdowns or sharing resources.

These policies can be defined for each piece of equipment individually or on the system, asset, or company level (Bevilacqua & Braglia, 2000). By implementing appropriate maintenance strategies and policies, organizations can ensure efficient and effective maintenance.

3.2.3 Maintenance Management and Processes

Maintenance management can be defined as a combination of measures and activities employed during the operational phase of an asset's life cycle that are adopted to sustain the intended function of the asset (Manenzhe et al., 2023). Essentially, maintenance management provides a structured framework for the management and execution of maintenance tasks.

Historically, some authors have suggested different best practices, activities, sequences, and models to manage maintenance (Márquez et al., 2009). These often encompass processes or a defined workflow outlining the activities and responsibilities required to manage maintenance effectively. Various models and frameworks exist to guide the formulation of these processes.

In their view on maintenance management, Márquez et al. (2009) proposed a generic model synthesized from other models identified in the literature. The model provides a practical view of the processes needed to manage maintenance, encompassing effectiveness, efficiency, assessment, and improvement. The model helps identify decision areas where suitable methods and models can be applied. Figure 3-5 presents this model.

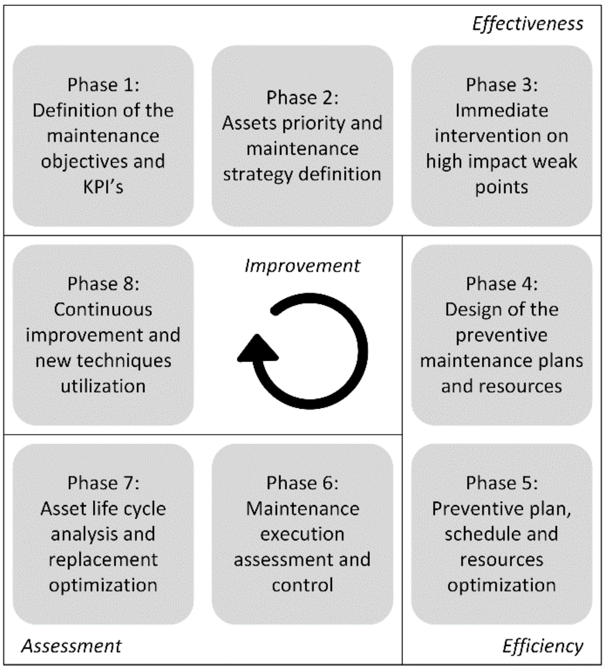


Figure 3-5. Maintenance management model, adapted from Márquez et al. (2009)

The international standard IEC 60300-3-14:2004 outlines essential processes for maintenance in dependability management (IEC, 2004). This standard emphasizes the formulation of maintenance policies, strategies, and budgeting, which leads to defining support, identifying and analyzing maintenance tasks, and managing resources effectively. The standard also recommends planning, scheduling, and resource allocation, followed by the execution of maintenance tasks with proper documentation, while adhering to safety and environmental procedures. The process then involves assessment through the rigorous evaluation of maintenance activities, resource utilization, results analysis, and equipment modification. The final step involves improvement, which entails refining the maintenance concept, enhancing maintenance procedures, and evaluating potential actions for continuous improvement.

Maintenance management also includes specific processes and workflows for conducting maintenance. Deighton (2016) developed a workflow for planning, scheduling, and executing maintenance that gives a comprehensive overview of the principal steps involved and the assignment of responsibilities. The international standard EN 17007:2017 formalizes the maintenance process through a clear breakdown of processes detailing the activities to be performed. Figure 3-6 illustrates this maintenance process.

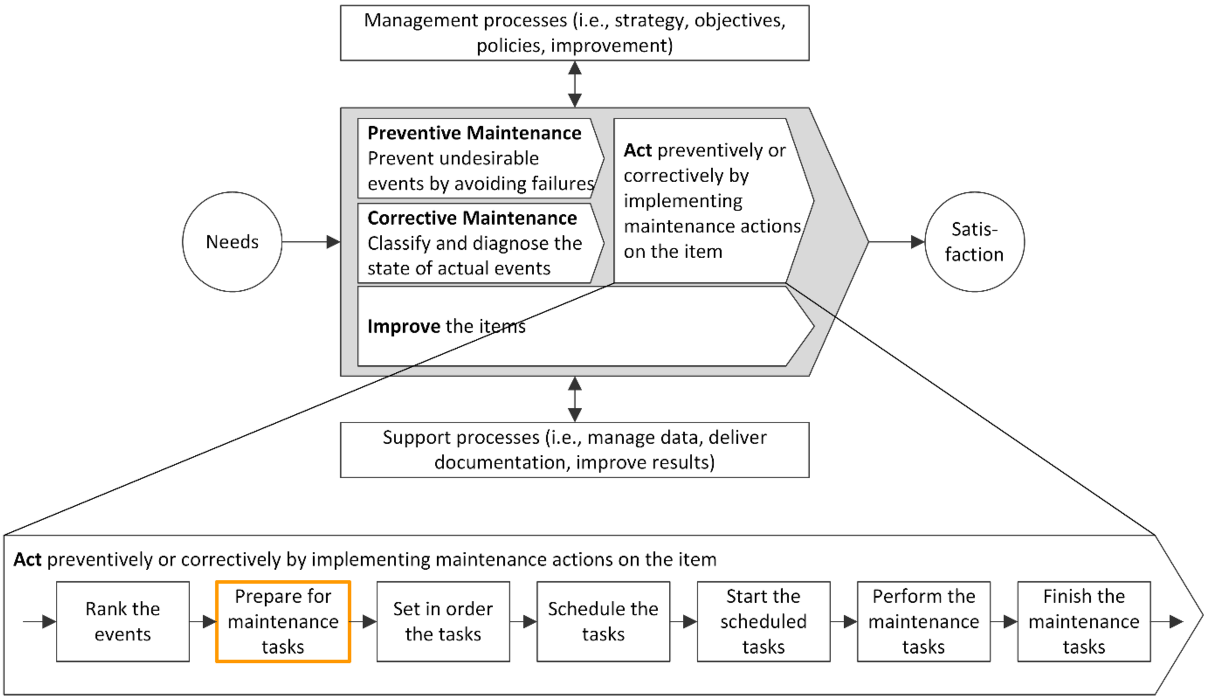


Figure 3-6. The maintenance process, adapted from EN 17007:2017 (European Standard, 2017b)

Common to these process models is the identification of an event or a request for maintenance, which is then evaluated and prioritized. Next comes planning and preparation for the necessary maintenance for the event or request, determining the necessary activities and resources. This is followed by scheduling the maintenance, setting dates, and allocating resources. After executing the maintenance, the job is closed out, and the maintenance performed is documented.

In this thesis, the focus is on the planning and preparation of maintenance, as highlighted in Figure 3-6 and established in the following section.

3.2.4 Preparing and Planning for Maintenance

The terms “maintenance planning” and “maintenance preparation” often overlap and are sometimes used interchangeably; they also at times incorporate scheduling activities. However, in this thesis, the term “scheduling” has been deliberately omitted from these definitions and is considered to be a separate process step.

Kister and Hawkins (2006) defined “maintenance planning” as “*the advance preparation of selected jobs so that they can be executed in an efficient and effective manner when the job is performed at some future date*.”

Another perspective is found in the international standard EN 13306:2017 on maintenance terminology (European Standard, 2017a). The standard describes maintenance task preparation as “*supplying of all the necessary information and identifying the required resources to enable the maintenance task to be carried out*.”

Essentially, maintenance planning and maintenance preparation are synonymous and involve determining and documenting the specific tasks, their sequence, and the necessary resources required for work. This includes the descriptions of how to perform the work, instructions, documentation, required permits, spare parts, skills needed, and tools. Additionally, maintenance preparation entails estimating the total cost and addressing essential preparatory, post-maintenance, and restart activities for both operations and maintenance. To avoid further confusion, this thesis uses the term “maintenance preparation.” The activities, inputs, and outputs associated with maintenance preparation, as outlined in EN 17007:2007 and IEC 60300-3-14:2004, are summarized in Table 3-2.

Table 3-2. The inputs, activities, and outputs of maintenance preparation

Inputs	**Activities**	**Outputs**
- General documentation and technical documentation - Item history, maintenance records, and best practices - Files from manufacturers and engineering (e.g., spare parts list) - Manufacturer recommendations - Failure mode and effects analysis (FMEA) - Experience of similar items - Regulatory requirements - Preventive maintenance plans - Diagnosis of the undesirable event - Analysis of maintenance-related risks - List of tools and support equipment	- Assessing the environmental factors and associated risks of the maintenance task and implementing appropriate mitigations. - Developing comprehensive maintenance procedures that outline the necessary actions, required resources, estimated duration, and workload. - Identifying and assigning personnel to carry out the maintenance task. - Procuring materials and spare parts either from external sources or existing inventory. - Ensuring the availability of tools, transportation, lifting, and support equipment. - Creating the necessary operating, maintenance, safety, and environmental procedures and work plans.	- Maintenance procedures, including estimated time of each task, workload, safety procedures, etc. - List of identified tools - Necessary human resources - List of spare parts needed

The planning and preparation must adhere to the maintenance strategies and policies, ensuring reliability, dependability, and availability in an efficient and cost-effective manner. Inadequacies in the availability and quality of documents and comprehensive, detailed maintenance records can affect the process of preparing for maintenance (European Standard, 2017b).

Approaches to Document and Conduct Maintenance Outside the Scope of this Thesis

The system being maintained and the industry influence the approaches taken to document and conduct maintenance. For instance, maintaining a power grid, a fleet of cargo ships, or a road network requires different strategies to maintaining a factory. Hence, there are also various heterogenous approaches to conducting maintenance. The following are a few that fall outside the primary scope of this thesis:

Operator- or technician-centric maintenance. In smaller factories, maintenance is often carried out by the operators of the manufacturing equipment or by small dedicated autonomous teams. This approach does not follow the maintenance approaches or processes discussed in this thesis.

Service manuals. The technical manuals for servicing and maintaining equipment are in some companies and industries the primary source of maintenance instructions and procedures. For example, technicians maintaining commercial two-stroke engines rely on a service manual consisting of 2000 pages (Villadsen, 2019). High-quality information in manuals is crucial for complex products (Gök et al., 2019). Research has been conducted from the perspective of original equipment manufacturers (OEMs) and product developers to ensure these manuals provide sufficient high-quality information and enable quicker and easier access to relevant documentation (Setchi et al., 2006; Setchi & Lagos, 2008). Cross-referencing with other relevant information has also been explored (Crowder et al., 1999, 2003, 2005). This approach of documenting maintenance in manuals, and the accompanying research, also falls outside the scope of this thesis.

3.2.5 Maintenance Documentation and Data

Effective maintenance requires the availability of comprehensive and relevant documentation and data. Maintenance documentation can be defined as "*Any record, catalog, manual, drawing or computer file containing information that might be required to facilitate maintenance work*" (Kelly, 2006b). Maintenance records that contain the history of all maintenance-related data for equipment and systems are an important part of maintenance documentation (European Standard, 2017a). Such documentation is used to understand system dependencies, equipment functionality, redundancies, criticality, plant history, concurrent work, and more. This enables maintenance work to be prepared accordingly.

In the petroleum, natural gas, and petrochemical industries, the internationally recognized ISO 14224:2016 standard describes a standardized format for the collection and classification of reliability and maintenance data (ISO, 2016). This standard is not limited to these industries and is widely considered to be a "strong" and well-known standard (English et al., 2022). The standard encompasses the collection and storage of various data types, including failure data, characterizing the occurrence of failure events (e.g., causes, mechanisms and consequences), and maintenance data, capturing the maintenance actions that have been planned and executed, including the resources used, maintenance consequences, and down time.

3.2.6 Maintenance Performance

Measuring, controlling, and improving maintenance performance is crucial for optimizing asset maintenance (Parida & Kumar, 2009). It is important to assess the efficiency and effectiveness of maintenance operations to determine the value created, evaluate the impact of policies and strategies, and justify investments in technological advancements (Kumar et al., 2013; Parida

& Kumar, 2006). By utilizing performance measurements effectively, opportunities for improvement can be identified, problems detected, and solutions found (Wireman, 2005).

There are two main categories of maintenance performance measurement: measuring either the process and effort put into maintenance, or the impact and results achieved by the maintenance (Kumar et al., 2013). The former includes assessing the costs associated with performing activities as well as evaluating the quality, flexibility, and other process priorities (Simões et al., 2011). The latter involves analyzing the costs associated with equipment failures and the resulting disruptions to the production plan as well as evaluating the reliability and availability of equipment (Simões et al., 2011).

3.3 Mass Customization

Mass customization refers to the ability to offer personalized and customized products and services to each customer (Davis, 1989). Various authors have defined mass customization as a system that utilizes information technology, flexible processes, and organizational structures to provide a wide range of products and services that cater to the specific needs of individual customers (Da Silveira et al., 2001).

Two essential principles of mass customization are the modular structure of products and services and the utilization of configuration systems to facilitate processes, specifically in the specification of customer-specific products or services (Hvam et al., 2008). Proper modularization can result in simpler configuration systems that are easier to maintain (Harlou, 2006).

3.3.1 Modularization

Modularization refers to an approach that efficiently organizes complex products and processes by decomposing them into simpler parts, enabling independent management while maintaining overall performance (Baldwin & Clark, 2000; Mikkola, 2006). Essentially, in this system design strategy, the smaller, more manageable parts are often referred to as modules. These modules can encompass components, processes, knowledge, and resources (Robertson & Ulrich, 1998). A module, as described by Baldwin and Clark (2000), is "*a unit whose structural elements are powerfully connected among themselves and relatively weakly connected to elements in other units*." This supports the notion that modules are independent units within a system but also jointly provide an overall system function.

Modularity is often inherent in a system's architecture, outlining the functional and structural composition of the system, including the interfaces within the system and with the external environment (Harlou, 2006; Løkkegaard, 2017). Modular architectures, as defined by Ulrich (1995), involve "*a one-to-one mapping from functional elements in the function structure to the physical components of the product, and specifies de-coupled interfaces between components*." As such, modules carry specific functionalities, and interactions between modules are well-defined and often fundamental to the primary functions of the system (Ulrich & Eppinger, 2012). The decoupling of functionality through standardized interfaces allows for the substitution of modules without causing disruptions to the entire system (Ulrich, 1995).

Implementing modular architectures in multi-product or service development enables companies to reuse knowledge, concepts, components, and processes. This reuse can significantly reduce total costs while simultaneously offering a wider product or service range (Mortensen et al., 2008).

3.3.2 Architecture

In industry and the literature, there are various definitions of architecture, and no universal consensus exists (Bask et al., 2010). The term architecture is commonly seen as synonymous with structure (Harlou, 2006). At its simplest, it is an abstract depiction of a system's entities and their relationships (Crawley et al., 2016). Architectures are valuable in articulating complex systems in a comprehendible way.

Ulrich's (1995) definition of architecture is used for the purpose of this thesis. It defines an architecture as "*(1) the arrangement of functional elements; (2) the mapping from functional elements to physical components; (3) the specifications of the interfaces among interacting physical component*."

Specifically, functional elements represent individual transformations and operations contributing to overall performance, while physical elements include the parts, components, and subassemblies that implement these functions (Ulrich & Eppinger, 2012). In a modular product architecture, physical elements encapsulate one or more functional elements in their entirety, and the interactions and interfaces between the elements are well defined in the architecture, enabling (or prohibiting) the mixing and matching of elements (Schilling, 2000; Ulrich & Eppinger, 2012; Voss & Hsuan, 2009). These physical elements or modules and the standardization of interfaces allow for greater reusability and commonality (Voss & Hsuan, 2009).

Generally, modularity and architectures present organizations with an opportunity to simplify their products or services while maintaining a high degree of configurability to satisfy needs and preferences. This offers several known benefits, such as lower production costs, reduced time to market, easier introduction of new technologies, and improved quality (Bask et al., 2010; Harlou, 2006; Meyer & Lehnerd, 1997; Simpson, 2014).

3.3.3 Configuration

Configuration involves the creation of a customized product or service by selecting predefined building blocks or modules using predefined methods (Harlou, 2006; Pulkkinen et al., 2004). It is employed as a tool to manage variety within sales, projecting, ordering, and engineering processes. Haug et al. (2010) referred to a configurator as a knowledge-based expert system that "*allows users to specify products by selecting components and properties under the restriction of valid combinations*."

Configurators rely on an inference engine and a model that represents modules, interfaces, rules, and constraints (Soininen et al., 1998). They include descriptions of individual modules and rules in a product model for selecting, dimensioning, and combining these modules (Hvam et al., 2008; Voss & Hsuan, 2009).

Based on the underlying architecture, a product model represents a formalized representation of a company's knowledge of the structure of a product, including how the components and their interactions can meet customer needs (Forza & Salvador, 2002). Developing a product model requires the rationalization and formalization of existing knowledge within an organization.

The literature highlights several benefits of implementing mass customization through configurators, including reduced labor resources, decreased lead times, improved customer communication, and enhanced product quality. Implementing a configuration system also enables product cost calculations to be more accurate because the system updates and validates possible solutions, resulting in fewer errors (Myrodia et al., 2017).

3.3.4 Relation to Maintenance

Modularity research is manifold, covering and combining different disciplines, such as product design, production/manufacturing, organization, and the supply chain (Bask et al., 2010). Existing research is mostly focused on *product* modularity (Brax et al., 2017), and there has been limited exploration of modularity in the field of maintenance. The term *modular maintenance* has been applied in the German railway industry (Friedrich & Nikutta, 2008; Wiegand & Helmut, 2001), and Petersen et al. (2016) used modularization to group related maintenance tasks into modules by considering technician competence and logical execution sequences to maximize efficiency. Given the limited research on the topic, the broader term of service has been used.

The growing interest in service businesses and services has raised the question of whether the principles and theories developed for products could be extended to service systems, and if the application of modularity might yield similar benefits as those seen for products (Bask et al., 2010). Current theories in the field of service operations management consider service offerings to be process-based (Brax, 2013). While services and products share some characteristics, such as both being offerings provided by businesses to meet the needs and wants of customers, they differ in others. For instance, services are produced and consumed at the same time, meaning the service product can be the service process itself (Voss & Hsuan, 2009). Therefore, the concepts and principles of modularity developed in the context of physical products and manufacturing should be reconsidered.

Service architectures and modularization play a crucial role in transitioning services from ad hoc activities to standardized, customizable service offerings (Johnson et al., 2021). Bask et al. (2010) defined service process modularity as the "*usage of reusable process steps that can be combined ('mixed and matched') to accomplish flexibility and customization for different customers or situations in service implementation*."

Maintenance can be viewed as a process-based service, since its activities should be customized to the different needs of systems and customers. My research group conducted work on modularization and architectures in maintenance, beyond the scope of this thesis, which is discussed in Section 6.

3.4 Reflections on the Theoretical Basis for the Research Project

The theoretical basis has served as a foundation for the work of this thesis. The viewpoint adopted is that of systems theory, with asset maintenance as the subject matter and mass customization as the means for improvement.

Systems theory not only provides an understanding of the systems to be maintained but also of the interconnected systems within an organization, such as processes, people, information, and environment. Additionally, it facilitates understanding of maintenance preparation as a system that can be enhanced, involving people, resources, information, environment, and management.

There are many and diverse academic literature and industry interpretations of maintenance. The theories presented in this thesis serve as the basis for understanding the subject matter.

The viewpoint of MBSE, which emphasizes fostering a shared understanding of systems within an organization and establishing a single source of truth, is an essential inspiration for the work of this thesis. This viewpoint has been employed to improve maintenance preparation processes and the prepared maintenance activities through the application of configuration, modularization, and architectural thinking.

4

Results

The six papers resulting from this PhD project have been compiled into this paper-based thesis. The papers present the collective contribution of the research project and address the research questions. The following sections summarize the findings of each paper.

Papers A, B, and C consider different approaches for extracting relevant information from maintenance data to aid in various maintenance preparation tasks. They emphasize the synthesis and appropriate representation of data to facilitate decision-making processes. Paper A specifically focuses on utilizing data to deduce the relevant history, experience, and past performance of both individual items of equipment and overall systems. Paper B considers the identification and visualization of safety issues and subjects for opportunistic maintenance based on an organizations' maintenance data. Paper C explores how past best-performing maintenance solutions, identified through historical data, can be reused, and improved to support future maintenance. Collectively, Papers A, B, and C offer different perspectives on the following research question:

RQ1: *How can data on failures and maintenance activities be utilized for maintenance preparation?*

Paper C further examines the variability of maintenance activities recorded in historical data and analyses their commonalities. Papers D and E extend the investigation of commonalities in maintenance through modularization, focusing on formulating models for modular maintenance activities. Specifically, Paper D investigates the use of modularization concepts from the service domain to modularize maintenance based on existing services, while Paper E examines the formulation of modular maintenance architectures for maintenance instructions. These papers address the following research question:

RQ2: *How can historical data be utilized for the modularization of maintenance?*

Lastly, to assess the effectiveness of modularization and developed configurators in delivering potential benefits, Paper F investigates how to ensure that the evaluation of configuration projects is aligned with their development and implementation objectives. The findings of Paper F address the following research question:

RQ3: *How can development and performance assessments be aligned in configuration system development projects?*

4.1 List of Included Publications

Several publications have emerged from this PhD project that collectively cover the research presented in this thesis, as follows. The results of the publications are presented in Section 6.

Paper A

Didriksen, S., **Hansen, K. B.**, Sigsgaard, K. V., Mortensen, N. H., Agergaard, J. K., & Ge, J. (2022). Utilising failure history to improve maintenance planning. *Proceedings of NordDesign 2022 (Vol. DS 118)*. https://doi.org/10.35199/NORDDESIGN2022.42

Paper B

Hansen, K. B., Vandrup Sigsgaard, K., Agergaard, J. K., & Henrik Mortensen, N. (2021). Visualize maintenance data to identify safety issues and opportunistic maintenance possibilities. *2021 Annual Reliability and Maintainability Symposium (RAMS)*, *May 2021*. https://doi.org/10.1109/RAMS48097.2021.9605777

Paper C

Hansen, K. B., Sigsgaard, K. V., Mortensen, N. H., Agergaard, J. K., Ge, J., & Didriksen, S. (2022). Improve maintenance by reusing and refining previous maintenance cases. *2022 6th International Conference on System Reliability and Safety (ICSRS)*, 310–317. https://doi.org/10.1109/ICSRS56243.2022.10067286

Paper D

Hansen, K. B., Mueller, G. O., Mortensen, N. H., Sigsgaard, K. W., Agergaard, J. K., Ge, J., Didriksen, S., & Jespersen, C. B. An investigation into how modularization principles can be applied to maintenance and commissioning services. Submitted for publication to the journal *Concurrent Engineering: Research and Applications*.

Paper E

Sigsgaard, K. V., Agergaard, J. K., Mortensen, N. H., **Hansen, K. B.**, & Ge, J. (2023). Modular maintenance instructions architecture (MMIA). *Journal of Quality in Maintenance Engineering*, *29*(5), 50–67. https://doi.org/10.1108/JQME-08-2021-0063

Paper F:

Hansen, K. B., Ge, J., Haug, A., Hvam, L., Mortensen, N. H., Sigsgaard, K. W., Agergaard, J. K., Didriksen, S., & Jespersen, C. B. Applying performance measures before, during, and after configurator development. Submitted for publication to the journal *Computers in Industry*.

Contributions have been made to maintenance-specific journals and conferences, as well as to general engineering design and information technology journals and conferences. Detailed summaries of these papers are provided in the following sections.

4.2 Paper A

It is crucial for maintenance preparers to understand the history of failures of and previous maintenance work on the equipment they plan maintenance for. This information is vital for helping them choose the most effective maintenance approaches. This paper explores the usefulness of historical data in providing maintenance preparers with comprehensive insights into an asset's maintenance history. It should be noted that in this paper, maintenance preparation is referred to as maintenance planning.

Title: Utilising failure history to improve maintenance planning

Conference: NordDesign 2022 (Vol. DS 118)

Status: Published

Associated Research Question:

- RQ1: How can data on failures and maintenance activities be utilized for maintenance preparation?

4.2.1 Research Method

This study was conducted using a case-based approach. In the case company, the researchers observed that the maintenance records contained vast amounts of data concerning previous failures and maintenance work. However, the volume of data for individual pieces of equipment was often low. Consequently, maintenance planners faced the challenge of attempting to extract meaningful insights from historical equipment data when little or no previous failures or maintenance work had been recorded. Furthermore, the maintenance planners experienced difficulties in gaining and synthesizing meaningful insights from the data due to the fragmented manner in which they were stored in the CMMS.

This study aimed to derive valuable information from historical maintenance records, despite the inadequate data per piece of equipment, by leveraging similarities across equipment. Drawing on existing principles identified in the literature, a principle was proposed that links failure history data with a multi-classification model of the physical system. The case company provided access to 11 years of maintenance records. This data was then used to investigate how the proposed approach could enhance key corrective maintenance decisions, minimize routine-based failures, address complex but infrequently observed failures, and assist in identifying and preventing recurring failures.

4.2.2 Research Contributions

The proposed principle structures and models historical data to create two views of the data: the actual history and the association history of the equipment, as illustrated in Figure 4-1. The actual history represents all relevant historical information about failures and past maintenance work on a single piece of equipment, whereas the association history includes historical data from all pieces of similar equipment. Hence, if a particular piece of equipment has minimal or no history, it is possible to find and review the history of similar pieces of equipment that operate under the same conditions. This dual perspective enables maintenance planners to understand the history and behavior of equipment to make informed decisions about planned maintenance work. Furthermore, it enables them to employ successful past solutions when creating new ones.

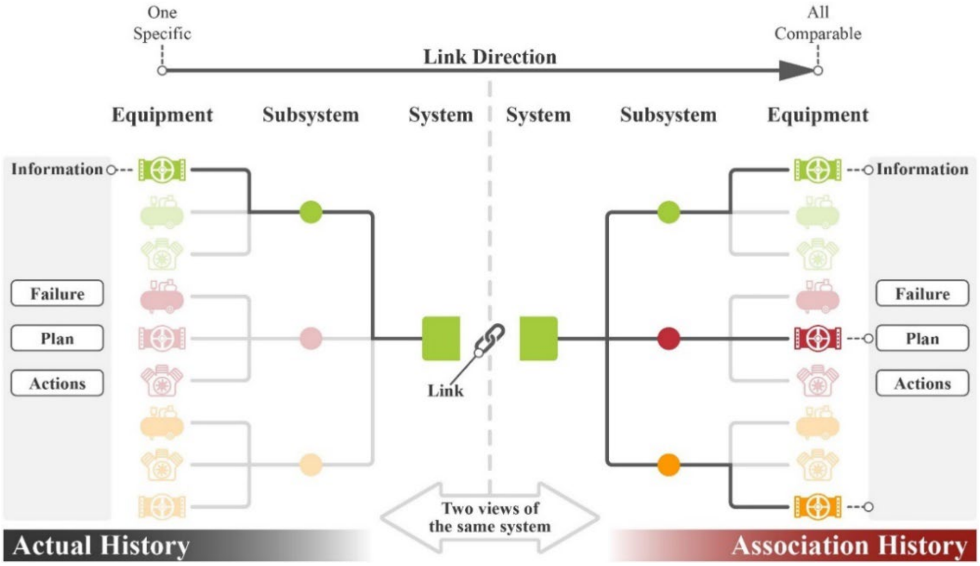


Figure 4-1. Proposed model for representing and linking failure history data (Didriksen et al., 2022)

The case study highlighted three key scenarios in which the proposed principle can be effective:

Routine-based maintenance work: The proposed principle can help identify past failures and maintenance work for a single piece of equipment by consolidating fragmented data into a single model. Maintenance can be planned according to this information, potentially by reusing an effective past solution.

Failures with low-frequency observations: In scenarios where a single piece of equipment has little or no history, the association history can be used to find exact matches with similar equipment and failures. This associated history can be used to understand the behavior of and effective solutions for similar equipment as inspiration for a maintenance plan with correct actions for equipment with minimal history.

Recurring failures requiring new solutions: The principle allows recurring failures to be identified by reviewing the actual history of a piece of equipment. By examining the association history, alternative maintenance plan designs can be identified, serving as inspiration for new solutions to address the recurring failures.

4.2.3 Reflections

This principle broadens the availability of failure history data, facilitating maintenance planning for a wider range of failures in complex systems, particularly failures that occur infrequently. By employing hierarchical structures and identifying similarities among equipment, valuable data that may have been overlooked due to fragmented data storage and low occurrence rates can now be effectively leveraged. However, it is important to note that this paper does not explore the implementation and consequences of the proposed model. Further investigation in this area could be conducted to validate the model.

4.3 Paper B

As outlined in Section 3.2.4, maintenance preparers must assess environmental factors and the associated risks of maintenance tasks before implementing appropriate solutions. However, identifying this information from the available company data presents a practical challenge. This is an apparent gap both in literature and industry as discussed in this paper. This paper investigates the synthesis, visualization, and use of data to address this issue.

Title: Visualize maintenance data to identify safety issues and opportunistic maintenance possibilities

Conference: 2021 Annual Reliability and Maintainability Symposium (RAMS)

Status: Published

Associated Research Question:

- RQ1: How can data on failures and maintenance activities be utilized for maintenance preparation?

4.3.1 Research Method

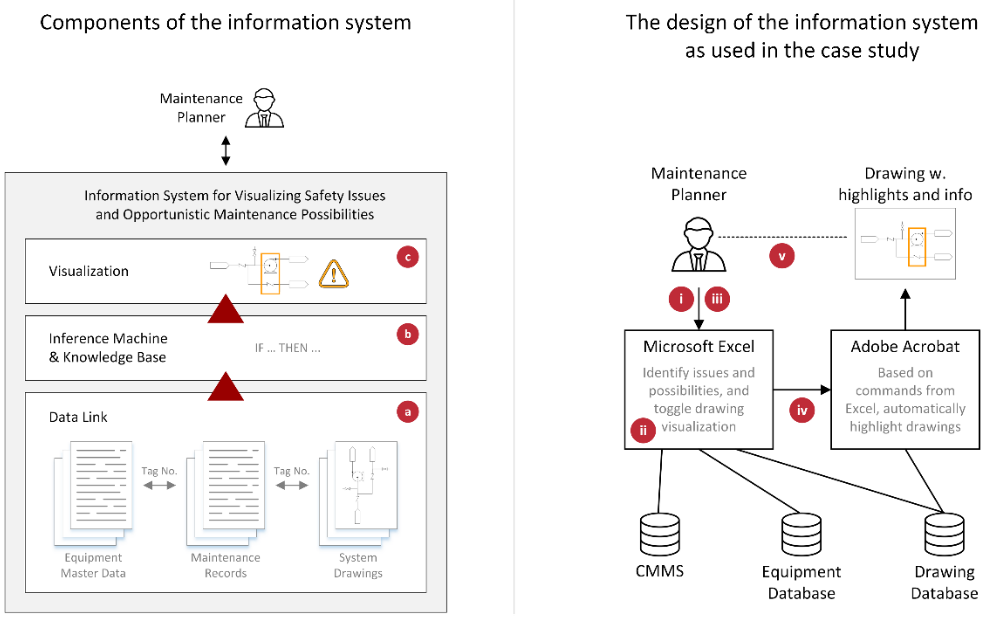
The motivation and need for this study emerged from a case study in which it became apparent that maintenance preparers had to review vast amounts of maintenance requests and work orders in a CMMS to identify safety issues and subjects for opportunistic maintenance. However, given that hundreds or thousands of requests and orders are active in the CMMS, it becomes challenging or even impossible to identify the dependencies of the maintenance. This could result in missed issues and potential opportunities—a finding that was further substantiated by reviewing the literature.

To address this issue, this paper proposes a data-driven approach for visualizing potential issues and opportunities in system drawings. Highlighting potential issues and opportunities in system drawings makes the information more accessible for maintenance preparers. The proposed method was applied and evaluated within the case company and subsequently evaluated for its practical applicability.

4.3.2 Research Contributions

Based on the theory of expert systems, which supports reasoning and problem-solving that would otherwise require substantial human effort and experience, an information system was proposed to allow for linking relevant data, inferring reasoning, and visualizing issues and potential opportunities, as illustrated in Figure 4-2. The relevant data were equipment master data, maintenance records describing previous failures and maintenance activities, and system drawings. The results of the case study application demonstrated benefits compared to the existing situation in terms of efficiency and effectiveness.

The study showed that the proper use of data, combined with its synthesis and visualization, facilitated quicker and simpler decision-making. Moreover, vast amounts of data could be filtered, and their relevance inferred, to enable maintenance preparers to make more informed decisions. This also enabled them to identify issues and opportunities that might have been overlooked or would have taken a considerable amount of time to identify using traditional methods.



Components of the information system

The design of the information system as used in the case study

Figure 4-2. The components of the proposed information system and the design of the system as used in the case study (Hansen et al., 2021).

4.3.3 Reflections

The proposed approach aims to contribute to the practical aspects of hazard identification and opportunistic maintenance. It considers the multiunit nature of systems and the multidisciplinary aspects of planning, in contrast to traditional methods. For instance, FMEA considers each system entity in isolation, whereas the proposed approach of this paper considers dependencies across entities, potentially extending the FMEA model.

This approach requires the interconnection of multiple sources of data, necessitating the existence and availability of appropriate data, the ability to link attributes such as common identifiers (e.g., equipment tag numbers), and suitable data quality in terms of consistent formatting and relative completeness. Further research could explore alternative methods of visualizing or presenting the information derived from an organization's maintenance data if these requirements cannot be met.

4.4 Paper C

Motivated by the insights from Papers A and B regarding the value of an organization's data, this study aimed to explore whether historical solutions could be reused in a more formalized and structured manner that also allows for their improvement.

Title: Improve maintenance by reusing and refining previous maintenance cases

Conference: 2022 6th International Conference on System Reliability and Safety (ICSRS)

Status: Published

Associated Research Questions:

- RQ1: How can data on failures and maintenance activities be utilized for maintenance preparation?
- RQ2: How can historical data be utilized for the modularization of maintenance?

4.4.1 Research Method

An observation at the case company revealed a significant amount of unnecessary variation of maintenance activities, including 23,000 different descriptions used for approximately 43,000 past activities. These variations in activity descriptions could lead to potential safety risks and increased rework due to technicians interpreting the activities differently. This finding revealed that maintenance solutions were often uniquely designed each time an individual failure occurred. To address this, the reuse of best-performing solutions from the vast amount of historical data were proposed. By leveraging the large number of past solutions, the aim was to improve the time-consuming maintenance preparation process and employ the experience gained from previous maintenance to improve future maintenance. The objective was to uncover and share valuable knowledge stored in underutilized historical data.

Upon investigating literature, it was discovered that existing approaches mainly focused on reusing individual activities rather than complete work packages comprising of multiple activities. Additionally, these approaches lacked a learning aspect, where previous activities could be improved upon based on their accuracy and effectiveness (i.e., accuracy in terms of whether the maintenance resolved the issue and how well it was resolved).

A three-step decision-making process was proposed to support maintenance preparers in finding, improving, and reapplying relevant previous solutions. A case company was used to assess and evaluate the proposed decision process.

4.4.2 Research Contributions

The proposal was for the selection of maintenance activities to be divided into two distinct decision-making processes to solve a failure: 1) screening various past solutions, such as repair and replacement, and 2) evaluating different courses of action for a chosen approach, such as dismounting, mounting, and testing. Essentially, these decision-making processes involve deciding on what to do and then determining how to do it. Separating these two processes can mitigate the inherent human difficulty of screening vast amounts of alternatives and enable complete work packages to be reused. Case-based reasoning was employed to compare and identify relevant previous maintenance cases from historical data for these two decision-making processes. Given that past solutions had been designed for cases that were similar but not identical to current failures, a refinement process step was included to allow for the tailoring of the solution to the current case and to improve it based on past performance. The most effective past maintenance could thus be reused and enhanced. The proposed decision-making process is shown in Figure 4-3.

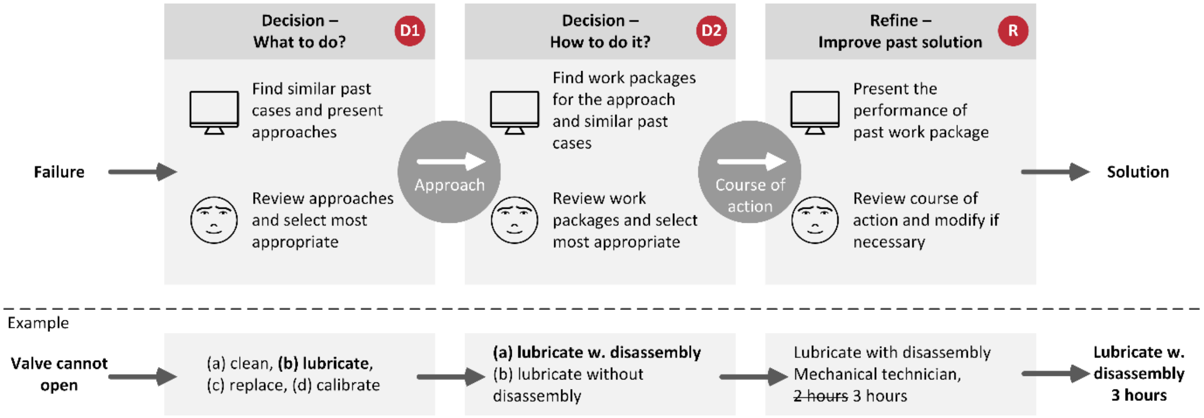


Figure 4-3. The proposed three-step decision-making process for preparing maintenance activities (Hansen et al., 2022).

The case study based on interviews with maintenance preparers revealed a faster and less time-consuming preparation process. The maintenance preparers showed confidence in the applicability and accuracy of the generated solutions. Furthermore, the process guided maintenance preparers in using correct terminology and descriptions. The potential to reuse historical data was also analyzed to determine whether maintenance records could be reused to effectively address new failures. Most of the data could be classified according to equipment type, the respective failure modes, and the approaches used to rectify the failures. Despite significant variability in the data, commonalities could be determined.

4.4.3 Reflections

In essence, the study aimed to minimize unnecessary variation in maintenance activities, improve the accuracy of solutions, and leverage the company’s historical data. However, this approach necessitates a substantial amount of data, which should be reusable and representable of the maintenance performed on the asset. This also involves the correctness and completeness of the dataset. The case study focused on the applicability and usefulness of the proposed decision-making process. Future research directions could include studying whether non-value-adding variations can be decreased, and whether the reused solutions are more accurate. This accuracy could be in terms of reliability, investigating whether improved solutions lead to more dependable operations.

The finding that the variability in the data can be described by certain commonalities forms the basis for the potential of modularization. Furthermore, this insight, together with the formalization and structuring of the decision-making process, provides the potential for configuration.

4.5 Paper D

This paper investigates the formalization of maintenance to address deficiencies in the quality, correctness, and completeness of data that might hinder direct reuse. It utilizes the concept of modularization to define the solution space of activities through modules and interfaces, thereby facilitating the comprehensive overview, governance, and management of these solutions.

Modularization is crucial for facilitating configuration, allowing for the reuse and substitution of modules. Moreover, the application of configuration systems enables the benefits associated with modularization, such as providing customized services to a diverse range of customers. This paper considers how maintenance can be modularized and how modularization can facilitate the configuration of maintenance.

Title: An investigation into how modularization principles can be applied to maintenance and commissioning services

Journal: Concurrent Engineering: Research and Applications

Status: Submitted for publication

Associated Research Question:

- RQ2: How can historical data be utilized for the modularization of maintenance?

4.5.1 Research Method

This study aimed to investigate the applicability of modularization to offshore maintenance and plant commissioning services and to explore the associated benefits through two case studies. Whereas previous research on service modularization has focused on the conceptual and theoretical aspects of benefits, this study seeks to provide empirical evidence of the feasibility of applying modularization to specific types of services and to assess whether benefits could be achieved. The aim was to gain a comprehensive understanding of service modularization and its implications in the context of service configuration while uncovering valuable insights into the successful application of service modularization in practice. To achieve this, the study approach involved examining the existing services of the two companies that participated in the case studies. Historical service design data were collected, analyzed, and used as inputs for modularization. In addition, insights and knowledge regarding the services to be modularized were gathered through interviews and workshops with experts from the respective companies.

An evaluation was conducted of the applicability of modularization for maintenance and commissioning services, the usefulness of the resulting modular service designs, and the potential associated benefits.

4.5.2 Research Contributions

This study analyzed and identified modules, decompositions, interfaces, and modular designs for architectures from reviewing literature on service modularization. Two case studies were conducted to validate the following aspects synthesized from the literature:

Results

- Service modules possess well-defined specific functions and consist of elements that can be reused, modified, and replaced to suit different contexts.
- Decomposition can be conducted by partitioning information, processes, and services into modules and elements at multiple levels.
- Standardized interfaces enable functions to be packaged and substitution of modules and elements without disrupting the entire service.
- Modular service architectures provide a framework for integrating and combining modules, thereby facilitating overall service delivery.

The existing services of the two case companies were modeled based on the aspects identified in the literature. For maintenance, the historical variation could be significantly reduced and represented by 37 action modules (i.e., repair and replacement) and 61 activity modules (i.e., dismount and mount). The resulting modular designs align with the design criteria and requirements outlined in the existing literature for service configurators. Additionally, the study evaluated the associated benefits of modularization. The following are the results, mainly concerning maintenance services:

Cost reduction and profitability: The case studies demonstrated the potential for cost reduction through the reuse and sharing of modules. Additionally, standardization could reduce historical variations and promote reusability.

Customization and variety of services: Modularization facilitated a high degree of customization and service variety for maintenance services. Service modules can be modified, combined, or substituted to address a broad scope of maintenance needs.

External collaboration and outsourcing: By decoupling functionality, collaboration with external partners and the outsourcing of specific modules or services can be achieved.

Increase in flexibility and responsiveness: The ability to adapt, fine-tune, and combine modules enables quick adaptation to diverse maintenance requirements.

Simplification of complex systems: The principles of modularity effectively simplify complex maintenance service systems and provide a clear and manageable structure.

This paper successfully demonstrates the applicability of service modularization in the maintenance and commissioning domains, highlights potential benefits, and highlights modularization’s role in facilitating service configuration.

4.5.3 Reflections

This paper contributes valuable insights for both researchers and practitioners, highlighting the potential of applying service modularization to enhance service design and delivery. It demonstrates the applicable designs of modular services supported by real-world applications. However, it is important to note that while the paper presents the potential benefits of service modularization, the actual post-implementation realization of these benefits requires empirical validation through further research. Additionally, future studies could focus on the implementation of modular service designs and investigate the implications and long-term effects of adopting modularization.

4.6 Paper E

This paper further investigates the modularization of maintenance, focusing on studying the maintenance instructions utilized in preventive maintenance. Maintenance instructions describe the maintenance tasks to be performed.

The primary objective of the research was to develop an architecture model that would not only provide an overview of the existing instructions and their applicability but also facilitate the identification, evaluation, and pruning of non-value-adding tasks, defined as redundant descriptions of the same tasks, overlapping objectives for different tasks, or simply tasks that need not be performed.

Title: Modular maintenance instructions architecture (MMIA)

Journal: Journal of Quality in Maintenance Engineering

Status: Published

Associated Research Question:

- RQ2: How can historical data be utilized for the modularization of maintenance?

4.6.1 Research Method

In the case company, the need for a method to evaluate the value addition of various maintenance instructions was observed. The instructions were written one-by-one in a free-text format, resulting in a large amount of variation, which made it difficult and time-consuming to ensure the effectiveness, consistency, and quality of the instructions.

A review of literature was conducted to explore existing approaches for addressing this issue and found that although standardization approaches exist, the identified studies have not considered value-addition of instructions.

A method is proposed to modularize maintenance instructions and reduce non-value-adding variation through analysis derived from product architecture theory. The aim of the method was to create an architecture that would provide an overview of and evaluate variations in maintenance instructions. A case study was conducted to evaluate and modularize maintenance instructions for safety-critical valves.

4.6.2 Research Contributions

The proposed method distinguishes between an as-is and a to-be architecture. The as-is architecture was utilized to describe and provide an overview of the existing variations in instructions, which in turn created the basis for a to-be architecture where non-value-adding variation is pruned.

The mapping process involved establishing the relationship between two dimensions: action and physical. This entailed mapping the individual tasks in the instructions to the equipment for which they would be used, which enabled overlaps of instruction coverage to be identified and consolidated. Figure 4-4 provides a simple example of the as-is mapping of instructions for maintaining bikes and illustrates the evaluation process, including the pruning of non-value-adding variance.

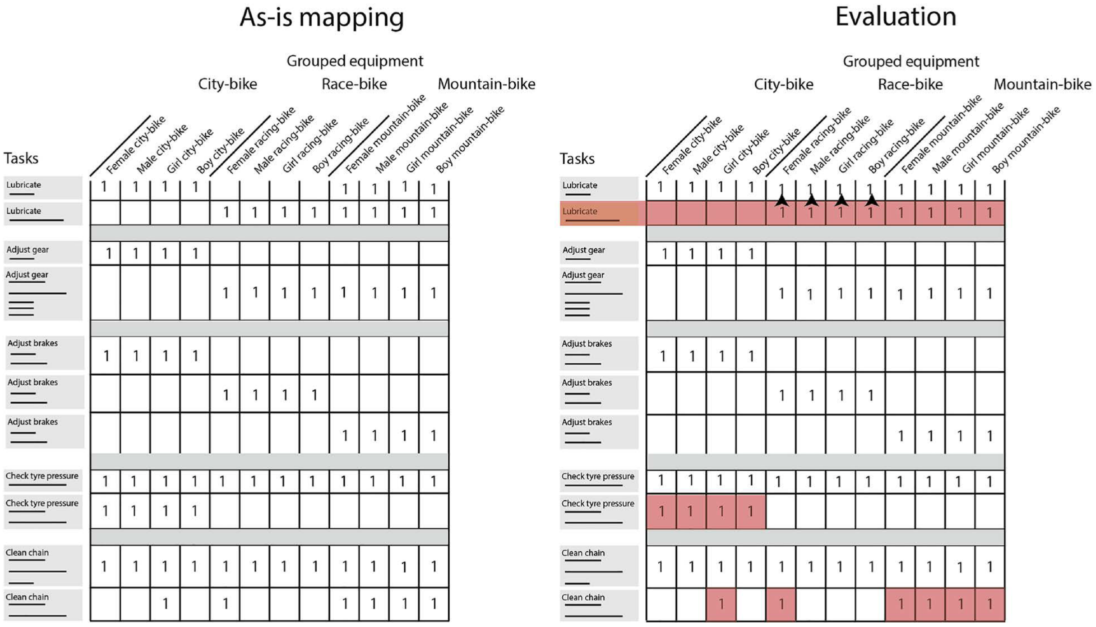


Figure 4-4. As-is mapping and evaluation using a simple bike maintenance example (Sigsgaard et al., 2023)

To assess the applicability of the method, a case study was conducted that involved analyzing the physical characteristics of the equipment, historical data on maintenance execution, and the maintenance instructions themselves. This analysis included mapping the as-is architecture, evaluating the value of each variation, and developing the to-be architecture. The findings of the case study indicated a significant reduction in the number of instruction tasks, from 224 to 20 variants. These 20 variants were found to cover 83% of the maintenance performed while also being simplified and improved in terms of quality.

4.6.3 Reflections

This study aimed to examine the sharing of instructions across different types of equipment by exploring commonalities among them while still providing the required variety of necessary instructions. Achieving this balance between commonality and variety is essential for effective maintenance. This study demonstrated the potential of streamlining maintenance instructions by minimizing non-value-adding variations and modularizing the remaining tasks, thereby achieving maintenance configurability. This approach is particularly suitable for multiunit systems in contrast to existing methods that focus on single-unit maintenance, making it more applicable to large production facilities. However, the implementation, realization, and effects of this approach were not investigated in this study. Further research is needed to explore the time and effort required to implement the proposed method, sustain the realized results, and understand the potential long-term benefits. It is important to note that this study represents a single perspective on maintenance modularization and architecture. Given the early stage of research in this field, additional studies are required to further explore and define these concepts.

4.7 Paper F

Performance measurements are crucial for evaluating the impact of a configurator on a company's business processes, specifically for assessing the effectiveness of modularization and its associated configurator in delivering potential benefits. It is essential for the evaluation process to align with the configurator's scope and development, encompassing its purpose and requirements.

This paper considers how to align the evaluation of configurator projects with their development and implementation objectives.

Title: Applying performance measures before, during, and after configurator development

Journal: Computers in Industry

Status: Submitted for publication

Associated Research Question:

- RQ3: How can development and performance assessments be aligned in configuration system development projects?

4.7.1 Research Method

The study started with a literature review, which revealed a gap in the existing literature regarding a structured approach to the performance assessment of configurators. Based on the findings of the literature review, a structured approach was developed to incorporate performance evaluation into configurator development projects. The purpose was to improve the realization of potential benefits and minimize the likelihood of project abandonment. To validate the framework, a longitudinal case study was conducted, to examine the application of the proposed approach to the development of a maintenance work order configurator at the case company. Maintenance work orders are used to specify the details and requirements of maintenance jobs, including the required tasks and resources, the parts and materials needed, and the estimated duration.

The study encompassed the stages of initial scoping, development, and post-development, providing comprehensive insights into the applicability and usefulness of the approach.

4.7.2 Research Contributions

The findings of the literature review highlighted several limitations in existing studies regarding performance assessment in configurator development. It was observed that many studies only examined a few performance aspects and did not provide a complete performance picture. Additionally, the selection of performance measures often lacked structure and method, potentially leading to weak connections between development objectives and evaluation outcomes. Furthermore, it was observed that the importance of considering performance evaluation in the early stages of configurator development is often overlooked, potentially leading to misalignment between data collection and performance needs and resulting in data availability limitations and the selection of proxy measures. Therefore, there is a need for a performance evaluation approach that aligns with the configurator development process from start to end.

To address these issues, this study proposes the integration of performance assessment into configurator development. Based on the literature, an approach has been developed for the selection and application of performance measures in configurator projects. This approach ensures that configurator development and performance assessment are aligned, facilitating accurate and comprehensive performance evaluations while ensuring data availability. This coordinated approach is presented in Figure 4-5.

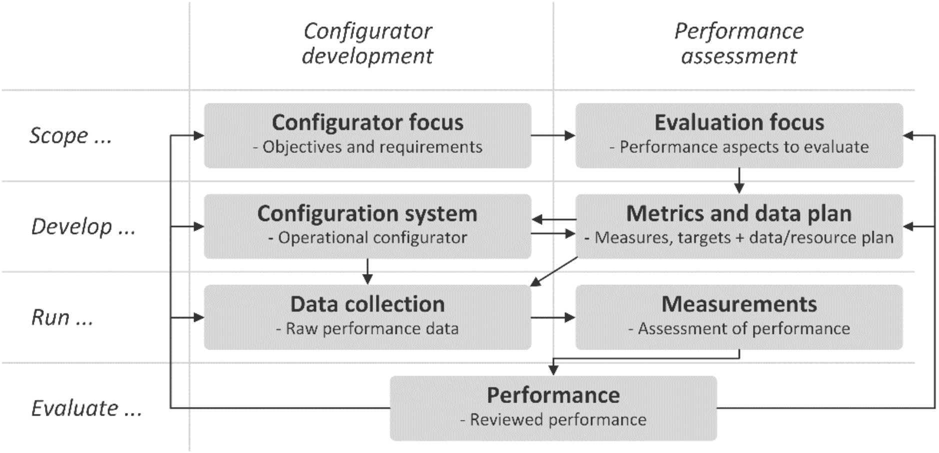


Figure 4-5. Coordinated approach to configurator development and performance assessment

The case study showed that the suggested approach was valuable during the development and implementation of a configurator. It emphasized the significant role of performance evaluation in configurator development projects and showed the positive prospects of using configurators for maintenance activities. The failure to prepare materials was less than 1% for configured work orders, compared to about 4% for non-configured work orders. The average time spent on work preparation using the configurator was measured and compared to the times reported by maintenance preparers, revealing a time reduction of 75–92% compared to the traditional method of creating work orders.

By incorporating performance measures into an early stage of the configurator development process, the case study illustrated that progress could be monitored, evaluated, and guided toward specified targets. This approach ensured a strong focus on performance measures, allowing the company to successfully steer the project.

Overall, the case study demonstrated the usefulness of the proposed approach in supporting the development process and ensuring the completeness and accuracy of the performance assessment.

4.7.3 Reflections

The application of configurators to the maintenance field is new, highlighting the importance of properly scoping the configurator, supporting its development through performance measurements, and accurately evaluating its impact relative to uncertain outcomes. The findings from the case study provided support for these considerations. To validate these findings further, additional case studies should be conducted in other fields.

Detailed information regarding each aspect of the performance assessment and evaluation was not provided in the paper. The study is primarily aimed to propose a comprehensive approach to performance assessment and evaluation. Further research could consider each aspect of the approach to achieve a greater understanding of successful performance evaluation in configurator development projects.

5
Conclusions

In this section, the conclusions on the thesis work are drawn by answering the research questions and discussing the combined contribution of the research project, including the academic and industrial impact. Furthermore, the limitations of the research project are discussed.

The aim of this research was to improve maintenance preparation by leveraging historical data. It approached maintenance preparation as a design activity and incorporated principles from mass customization for its enhancement. The study aimed to investigate the relevance of historical data for maintenance preparation, and to effectively structure and reuse the data based on modularization and architecture concepts. It also explored the alignment between the development of a configurator and the measurement of its performance. The overall goal was to benefit researchers and practitioners by advancing the understanding and utilization of historical data in maintenance preparation. Furthermore, to highlight the principles and requirements involved in configuring maintenance, providing insights for preparing a maintenance-performing company to achieve this.

5.1 Answering the Research Questions

This paper-based thesis synthesizes a collection of papers, their relationships, and their contributions. It comprises six papers that collectively address the research questions. Figure 5-1 depicts the individual contributions made by these papers in answering the research questions. The following section considers each research question to provide answers based on these contributions.

Publications		Research Questions		
		RQ1	RQ2	RQ3
		How can data on failures and maintenance activities be utilized for maintenance preparation?	How can historical data be utilized for the modularization of maintenance?	How can development and performance assessments be aligned in configuration system development projects?
Paper A	Utilising failure history to improve maintenance planning	●		
Paper B	Visualize Maintenance Data to Identify Safety Issues and Opportunistic Maintenance Possibilities	●		
Paper C	Improve Maintenance by Reusing and Refining Previous Maintenance Cases	●	●	
Paper D	An investigation into how modularization principles can be applied to maintenance and commissioning services		●	
Paper E	Modular maintenance instructions architecture (MMIA)		●	
Paper F	Applying Performance Measures Before, During, and After Configurator Development			●

Figure 5-1. Overview of the contributions of the papers to answering the research questions

RQ1: *How can data on failures and maintenance activities be utilized for maintenance preparation?*

This research question underpinned an investigation of the utilization of historical data through the three studies presented in Papers A, B, and C. These studies explored various use cases for leveraging historical data in maintenance preparation, including gaining comprehensive insights into an asset's maintenance history, identifying safety issues and opportunistic maintenance possibilities, and reusing previous maintenance solutions.

To provide comprehensive insights into an asset's maintenance history, Paper A provides a means to model and structure historical data. This allows relevant historical information on failures and past maintenance work for a single piece of equipment, as well as the historical information for all pieces of equipment that share similarities, to be consolidated. This approach supports maintenance planners in understanding an item of equipment's history and behavior, allowing them to make informed decisions about the maintenance work to be performed. In cases where there is minimal or no historical data for a particular piece of equipment, the model facilitates the retrieval and review of the history of similar equipment operating under similar conditions to be used for deciding on maintenance activities.

To identify safety issues and opportunistic maintenance possibilities, Paper B provides a data-driven approach for visualizing potential issues and opportunities in system drawings. This is achieved by linking maintenance records with equipment master data and system drawings, facilitating inferred reasoning based on the data to identify issues and opportunities, and then visualizing them on system drawings. This information enables maintenance preparers to make more informed decisions, and to identify issues and opportunities that may have been overlooked or would have taken a considerable amount of time to derive using traditional methods.

For reusing previous maintenance solutions, Paper C proposes a three-step decision-making process for leveraging historical data to find relevant previous solutions, reuse them for new failures, and enhance the solutions to improve the accuracy of new maintenance solutions. The study demonstrated that the vast amount of historical data describing previous maintenance activities, which may appear overwhelming to individual maintenance preparers, can support the reuse and enhancement of maintenance approaches based on their previous performance. By leveraging the collective experience stored in historical data, maintenance preparers can reuse and improve the most effective past maintenance solutions to address new failures.

In summary, these studies demonstrated that data on failures and maintenance activities can be utilized more effectively for maintenance preparation. Paper A provides insights into modeling and structuring data, Paper B presents a data-driven approach for identifying issues and opportunities, and Paper C demonstrates the reuse and improvement of previous maintenance solutions. By leveraging data effectively, maintenance preparers can derive valuable insights and maintenance preparation can be effectively improved.

RQ2: ***How can historical data be utilized for the modularization of maintenance?***

This research question is addressed through the collective findings of Papers C, D, and E, which provide insights into the utilization of historical data for modularizing maintenance.

Paper C emphasizes the need to analyze and assess the potential reuse of historical data for modularization. The data should exhibit commonalities to underpin the identification and classification of approaches for conducting maintenance. By analyzing previous solutions in the historical data, the best-performing approaches and courses of action can be identified and modularized. This necessitates reusable data that accurately represent the maintenance performed on specific assets.

Paper D investigates the modularization of maintenance using historical data and principles from service modularization. The study demonstrated that maintenance activities can be partitioned and decomposed into modules and elements at multiple levels. These service modules have well-defined functions and consist of reusable, modifiable, and replaceable elements, allowing for their adaptation to different contexts. The interfaces among these modules enable packaging of functions and substitution of modules and elements without disrupting the entire service. The modular service design aligns with the requirements for service configuration. The paper concludes that the modularization of maintenance offers several benefits, including cost reductions, increased customization and variety of services, opportunities for external collaboration and outsourcing, increased flexibility and responsiveness, and the simplification of complex systems.

While Paper D primarily focuses on corrective maintenance, Paper E extends the investigation of maintenance modularization by studying the maintenance instructions used in preventive maintenance. The study addressed the non-value-adding variation in historical instructions. Mapping the instructions data to an as-is architecture depicting individual tasks and the equipment for which they are used allows non-value-adding varieties, such as redundant task descriptions, overlapping objectives, or unnecessary tasks, to be identified. These tasks can be pruned, resulting in improved a to-be architecture for more effective maintenance that ensures the necessary variety of instructions while allowing instructions to be shared across different types of equipment.

In summary, these studies demonstrated the potential of utilizing historical data to modularize maintenance. Maintenance configurability can be achieved by analyzing data to understand previously conducted maintenance and identify commonalities. This involves modeling maintenance according to modularization principles and employing architectural mapping to eliminate non-value-adding variations. This use of historical data enhances maintenance effectiveness, facilitates knowledge sharing, and enables flexible adaptation to different contexts.

RQ3: ***How can development and performance assessments be aligned in configuration system development projects?***

To address this research question, Paper F explores the integration of performance assessment into the development processes of configurator projects. This paper identifies certain challenges, such as the lack of structure and methods for selecting performance measures, as well as the misalignment between data collection and performance assessment needs. In response, an approach is developed to ensure the alignment of performance assessment with configurator development. The proposed approach incorporates performance measures into configurator development from start to end. By introducing performance measures at an early stage, progress can be monitored, evaluated, and guided toward specified targets. This approach enables projects to be steered successfully, ensuring that configurator development remains on track.

The performance assessment of a configuration system should be integrated into and aligned with the development of the system. This coordination and integration can facilitate alignment between objectives and requirements for configurator development and their evaluation before, during, and after configurator development to support the development process and ensure complete and accurate performance assessment. Ultimately, developing a configurator that is not just successful but one that had been specifically designed to address the company’s challenges.

In summary, Paper F demonstrates an approach that aligns development and performance assessments in configuration system development projects. By integrating performance measures into the development process, progress can be monitored, evaluated, and steered toward achieving targets. This ensures that the configurator is designed to address the company’s challenges effectively, resulting in a successful and tailored solution.

5.2 Academic Contribution

In the introduction of this thesis, it was highlighted that the academic literature has identified several issues (see Section 1.2), including mistakes resulting from poor documentation and procedures, prevailing communication and information issues, a lack of systems to harness knowledge-related information, and the essential role of knowledge, experience, and communication in enhancing maintenance efficiency and effectiveness (Belkadi et al., 2019;

Jardine et al., 2006; Phogat & Gupta, 2017; Psarommatis et al., 2023; Sheikhalishahi et al., 2016; Villani et al., 2018).

This research addressed these issues by leveraging historical data and applying mass customization to maintenance preparation, which has so far received limited attention in the existing literature (Psarommatis et al., 2023). Additionally, the research emphasized real-world solutions, in contrast to the focus on mathematical analyses and techniques found in many maintenance papers (Fraser et al., 2015).

The ARC diagram presented in the introduction (see Section 1.7.1) illustrates the key areas of contribution: modularization and configurator performance assessment, as well as maintenance preparation and instructions.

Modularization and Configurator Performance Assessment

This PhD project demonstrated the applicability and value of product and service modularization principles to maintenance (see the answer to RQ2 in Section 5.1). Maintenance activities can be decomposed and modularized based on historical data. Since the quality of historical data is rarely optimal, a modularization process is crucial for leveraging experience and sharing knowledge. The modular design facilitates the sharing and reuse of activities across an organization, acting as a central source of knowledge for all employees. This approach contrasts with the document-centric approach, which often leads to highly variable activities and ineffective maintenance.

Additionally, this thesis presents a structured approach to configurator performance assessment for integrating performance measures into the development process, to monitor and evaluate progress and to steer development toward achieving targets (see the answer to RQ3 in Section 5.1).

Maintenance Preparation and Instructions

This PhD research demonstrated that data-driven approaches for leveraging historical data can enhance the maintenance preparation process by making information accessible through structured data modeling tailored to specific decision-making. Additionally, it showed that existing activities and instructions can be improved through modularization, and that the decision-making process can be structured and facilitated by configuration systems.

In summary, this thesis makes academic contributions by addressing the key issues identified in the literature. It applies modularization and configurator principles to maintenance preparation through real-world applications, demonstrating that data-driven approaches can improve maintenance preparation.

5.3 Industrial Impact

The factors that underpin effective maintenance were outlined in an industrial survey conducted by McKinsey & Company (2014b, 2014a), as presented in the thesis's introduction (see Section 1.1). These factors emphasize the significance of clear, visual, and easily understandable maintenance information, the elimination of low-value or value-destroying activities, and the optimization of planning and execution. Furthermore, the survey emphasized the importance of learning from past failures and maintenance practices to drive appropriate changes.

This thesis addresses all these factors, and each paper included in the thesis focuses on optimizing the planning, preparation and execution of maintenance activities.

To provide clear, visual, and easily understandable information, Papers A, B, and C propose methods to help maintenance preparers identify relevant historical data, thus facilitating effective decision-making. Papers D and E propose approaches for modularizing maintenance activities to achieve clear and easily understandable maintenance programs. In addition, Paper E addresses the elimination of low-value or value-destroying activities through modularization and architectural mapping, specifically targeting non-value-adding activities.

The findings revealed that the historical variation of corrective maintenance could be significantly reduced and represented by 37 action modules (i.e., repair, replace) and 61 activity modules (i.e., dismount, mount). For preventive maintenance, the instructions could be significantly reduced from 224 to 20 variants. These 20 variants covered 83% of the maintenance performed and were simplified and their quality improved. These well-defined modules provide clear, visual, and easily understandable information, facilitating the comprehensive overview, governance, and management of maintenance solutions.

Papers A and C present methods for extracting valuable insights from past failures and maintenance activities by structuring and modeling historical data and through reusing and refining past activities for solving new failures. This facilitates an understanding of the history and behavior of equipment and enables maintenance preparers to utilize past successful solutions to create new ones. The result is a faster and less time-consuming preparation process with improved applicability and more accurate solutions.

To evaluate the impact of the configuration, Paper F integrates performance assessment into configurator development. By implementing a configurator for maintenance work orders, the error rate decreased from above 4% to below 1%, and a time reduction of 75–92% was achieved compared to the traditional approach.

By addressing these factors and implementing the methods, concepts, and frameworks presented in this thesis, effective maintenance can be achieved that addresses the challenges of high costs and decreasing productivity in the offshore industry. The findings of this thesis support more cost-effective and safety-focused maintenance.

5.4 Research Limitations

The work and results presented in this thesis were conducted as part of a 3.5-year PhD project that involved close collaboration with a case company. These aspects, along with the chosen research approaches and methodologies, have led to certain research limitations and challenges.

5.4.1 Single Case Company

The research project's use of primarily a single case company constrains its generalizability. To achieve greater applicability and transferability of the findings, it would be essential to study the proposed methods, concepts, and frameworks in different contexts and companies. Unfortunately, due to the project's time constraints, it was not possible to conduct such evaluations.

5.4.2 Bias

The employed problem-based approach and the research methods of action research and case studies may have introduced bias. Furthermore, close collaboration with the primary case company could have led us to focus on this company's specific challenges. Additionally, unavoidable subjectivity due to the ambition and desire to succeed in both industry and academia may have introduced further bias.

To address potential bias, several measures were employed. First, all the papers were coauthored by several people, including members of the research group, people outside the group within DTU, and researchers from other universities. Furthermore, participation in conferences and seminars were made to specifically share and discuss the approaches, methods, progress, and findings of this research. These interactions with field experts and other scholars helped evaluate the research and provided a broader perspective. In addition, discussions have been held with companies across different industries such as power grids, offshore wind, and marine ships. These discussions involved operators, OEMs, engineers, contracting companies, and management system developers. Furthermore, engaging with industry networks and other young professionals has provided valuable insights and perspectives.

These measures were taken to mitigate bias and ensure more rigorous research. It should be noted that close collaboration with the primary case company has also led to a deep understanding of the company's operations, thereby establishing a stronger foundation for addressing its challenges and interpreting the findings.

5.4.3 Long-Term Effects

The limited time scope of the PhD project has also limited the scope of the findings, particularly regarding the long-term effects of the developed methods, models, frameworks, etc. However, the effects may take time to manifest, and sustaining long-term effects would necessitate additional work, such as learning and de-learning processes (Blessing & Chakrabarti, 2009). Further investigations are required to explore and validate the long-term effects.

6

Further Research Suggestions

Given the limits and constraints of the PhD project, not all aspects of the research have been covered. The following section highlights suggestions for further research directions.

6.1 Generalizability

The findings of this research project primarily stemmed from research conducted in a single company, with the exception of Paper D, which included an additional company. The generalizability of the findings has been considered, but to improve generalizability, other companies and industries could be studied (e.g., other companies within the offshore industry, such as offshore wind and energy islands). Future research could also consider other asset-intensive industries, such as the rail, road, or power grid maintenance industries. Exploring these different contexts would enhance the generalizability and applicability of the findings.

6.2 Sustaining Long-Term Effects

The immediate effects of the research conducted during this PhD project have been studied, but the investigation of its long-term effects was constrained by time limitations. Consequently, further research is necessary to explore these long-term effects.

Additionally, sustained improvement depends on the functionality and applicability of the developed support (Blessing & Chakrabarti, 2009), as well as on factors such as user engagement, proper utilization, effective application, maintenance, etc. This may require training, additional analysis and resources, and organizational changes. Consequently, these areas could be explored in future studies in relation to the findings of this project.

6.3 Balancing Risk, Reliability, Cost, and Sustainability

Maintenance involves balancing risk, reliability, cost, sustainability, and other company-specific factors. This task is particularly challenging due to the complexity of multiunit systems that require maintenance. Maintenance preparation focuses on planning activities to achieve the desired outcomes. Although this research did not directly focus on these outcomes, it established the foundation for their consideration by formulating a solution space for activities. Further research could investigate the decision-making process involved in maintenance preparation, particularly in relation to balancing these outcomes and achieving optimal maintenance. One suggestion is to employ simulation and scenario analysis to project and assess the effects and impacts of various decision alternatives.

6.4 Facilitate Industry 4.0 Technological Advancements

The research underpinning this thesis addressed the formalization of a solution space for maintenance activities using historical data, specifically focusing on modularization, architecture, and the selection and combination of appropriate activities (i.e., configuration).

The next generation of smart manufacturing systems is expected to rely on increased automation of maintenance activities and decisions (Psarommatis et al., 2023). Furthermore, recent maintenance research has primarily focused on condition-based monitoring, predictive and prescriptive maintenance, and aspects such as failure detection, diagnostics, and prognostics (Kumar & Galar, 2018). However, the effective definition and preparation of maintenance activities have not been addressed within these research fields.

By formulating and structuring a solution space for maintenance activities and describing their applicability, the findings of this PhD project provides a fundamental basis for these future advances. To facilitate the automation of decision-making processes and align them with recent research trends, the findings can be further explored.

6.5 Incorporate Sustainability into Maintenance Decisions

Maintenance decisions have typically been driven by economic and technical considerations, with insufficient regard for environmental and social dimensions, despite the significant impact of maintenance activities and their consequences on sustainability (Saihi et al., 2023). This neglect can result in various environmental problems, such as increased greenhouse gas emissions, higher energy consumption, and inefficient utilization of materials and resources.

Researchers are increasingly recognizing the need for a paradigm shift in how maintenance is perceived, moving beyond its role in retaining systems' functionalities to considering its broader impact on all dimensions of sustainability (Saihi et al., 2023). This paradigm shift calls for the incorporation of environmental and social factors into maintenance planning and decision-making models to facilitate the integration of sustainability considerations into maintenance practices, as well as the development of practical and implementable models (Saihi et al., 2023).

Further research could explore these possibilities based on the findings of this study. Specifically, in offshore operations, where comprehensive data on emissions are rigorously collected to assess environmental impact, there is an opportunity to link this data with maintenance records. Such an approach would support an evaluation of the environmental consequences of maintenance decisions and facilitate informed decision-making regarding the impact of future maintenance activities.

6.6 Investigate Applicability to the Permit-to-Work Process

The effective management of health and safety is crucial for ensuring safe operations and establishing a solid foundation for an organization's sustainable development (Pika et al., 2021). A permit-to-work system is a vital tool for effectively managing health and safety and controlling work hazards, including maintenance activities. A permit-to-work document is a formal written document that covers detailed planning, risk assessment, the development of a hazard control plan, the designation of necessary personnel, and the establishment of step-by-step procedures to ensure that work is conducted safely (Mroszczyk, 2013).

Recent findings from a case study highlighted issues related to conformance and performance in the permit-to-work process (Pika et al., 2021). Another study examining 770 cases of major accidents in the chemical process industry revealed that 9% of these incidents could have been caused by an ineffective permit-to-work process (Bakar et al., 2017). This rate has not improved during the past two decades (Yan et al., 2017). One of the primary contributing factors to these incidents is communication, including incomplete or incorrect information on the work to be performed, inappropriate equipment specifications, and procedures and instructions (Yan et al., 2017).

Considering these challenges, Jahangiri et al. (2016) suggested, based on a case study, that future research should focus on simplifying and automating the permit-to-work process to minimize human error and faulty decision-making and facilitate communication.

Future research could leverage the findings of this PhD thesis by applying informed decision-making based on historical data, introducing modularization for alternatives, and aiding decision-making by configuring the permit-to-work process. As in maintenance, large volumes of data are recorded, and permits are manually created and issued (Pika et al., 2021). Future research could consider incorporating configurators to streamline and improve the process.

7

Supplementary Results

In addition to the publications selected to address the research questions in this thesis, there were eleven additional coauthored publications. This section offers an overview of these publications, all of which present data-driven approaches for tackling various maintenance challenges.

Through active involvement in and contributions to these studies, I have gained diverse perspectives and insights into maintenance. These experiences have extended my understanding of its nature, challenges, potential approaches for its improvement, and state-of-the-art advances. Concise summaries of the studies and their outcomes are presented in this section.

Clustering of Maintenance Activities

The studies discussed hereafter focused on understanding maintenance activities and exploring ways to group and cluster them. The objective was to optimize efficiency, share resources, and minimize the impact of maintenance operations on production.

A framework was introduced to identify similarities among maintenance jobs by applying standardization principles derived from modularization theory (Agergaard et al., 2021). This framework aims to facilitate the grouping of activities by addressing maintenance variations with the goal of reducing production shutdowns and allowing resources to be shared. A case study that employed this framework demonstrated a potential time saving of 7–9% through such grouping of activities.

A method for evaluating the true variation of past and present maintenance actions through standardization and modularization has been developed (Agergaard et al., 2022a). A case study revealed that the application of this method achieved a substantial reduction in historical variations in maintenance action descriptions across 112,537 operations. The majority of these actions could be effectively represented by only 165 distinct, standardized action words.

An approach has been proposed to decompose and analyze maintenance through physical, action, and process dimensions to clarify and minimize the impact of maintenance processes on production (Agergaard et al., 2022b). A case study demonstrated that this approach had the potential to facilitate faster identification of improvement opportunities (i.e., through grouping and clustering). Moreover, it revealed a greater number of opportunities compared to conventional approaches.

An investigation of the impact of clustering in the early stages of maintenance decision-making was conducted (Agergaard et al., 2023). The case study findings demonstrated that applying clustering early in the maintenance process can lead to significant reductions in planned work hours. Specifically, during the identification phase, planned work hours can be reduced by 4.6%. In the planning/preparation phase, a reduction of 2.7% can be achieved, while in the scheduling phase, clustering can result in a reduction of 2.4%.

Grouping of Equipment

Studies have also been conducted to investigate the grouping of equipment based on their similarities and to explore ways to leverage these groupings.

A systematic framework for grouping of different equipment that can be maintained together has been proposed (Soleymani et al., 2020). This framework aims to facilitate the development of preventive maintenance plans for groups of equipment rather than for individual pieces of equipment. The results of a case study demonstrated a potential 24% decrease in the number of maintenance plans, leading to a more manageable level of variation and lower costs associated with managing and controlling these plans.

A systematic evaluation framework for assessing the performance of periodic maintenance has been introduced (Ge et al., 2023). This framework effectively categorizes and evaluates numerous components within various systems, enabling the identification of potential performance issues across component groups. A case study demonstrated significant potential for improvement, including a reduction of up to 23% in periodic maintenance hours.

Improving Maintenance Scheduling

For the process step of scheduling maintenance activities for execution, studies have also been conducted.

A method has been introduced to accurately estimate the duration of maintenance activities (Khalid et al., 2021). This method leverages machine-learning algorithms that utilize historical data to predict the required hours, enabling the creation of more effective schedules. A case study conducted to evaluate the method demonstrated significant improvements in estimations compared to conventional approaches.

A design support tool utilizing mathematical optimization has been proposed to achieve optimum maintenance scheduling (Khalid et al., 2020). This tool considers a vast scope of complex scheduling constraints. A case study demonstrated that this tool could balance a company’s workload to match its available capacity, and even distribute work to reduce the number of people required to carry it out.

Improving Maintenance Management

Management of maintenance has also been the focus of studies, particularly employing architectural thinking to determine strategies and initiatives for improving the maintenance process.

A maintenance architecture model based on equipment grouping and maintenance approaches has been developed to support strategic decision-making (Sigsgaard et al., 2022). The model aims to enhance maintenance management by facilitating an understanding of the dependencies between equipment, maintenance actions, and processes. The case studies highlighted the potential for implementing customized maintenance strategies.

Initiatives to improve the maintenance process have been suggested to address sequential issues (Sigsgaard, Agergaard, Mortensen, et al., 2020). A case study demonstrated the potential of applying the suggested initiatives, leading to an estimated 12% reduction in maintenance costs.

Use of Historical Data for New Development

A method has been proposed to structure and contextualize data to aid in the evaluation of the impact of early decisions on the development of production facilities (Sigsgaard, Agergaard, Bertram, et al., 2020). The case study findings confirmed the method’s applicability and usefulness, demonstrating that leveraging historical data can mitigate some of the uncertainties associated with the development of new production facilities.

8

Final Remarks

This thesis marks the culmination of several years of work, which have involved quite a journey. In my PhD application, I wrote, *"I find it very motivating and meaningful to be at the forefront of both research and industry."* Throughout this project, I have aimed to leverage state-of-the-art research to advance industry operations. Essentially, being able to drive change and make an industrial impact has been extremely meaningful for me.

In my application, I also wrote, *"I believe the PhD project is future-oriented and provides an opportunity for me to contribute with pioneering research, but also to learn and develop."* Looking back, I now recognize that I may have been a bit overly confident regarding this project. Pioneering and groundbreaking research are rare, and this project is neither. Nevertheless, I believe that I have made valuable contributions that can benefit both industry and other researchers. Moreover, there are some promising perspectives for further leveraging and building on the findings of this research.

During the initial stages of my PhD project, I read Schwartz's (2008, 2015) academic essays on the importance of stupidity and indifference in research. This led me to recognize the value of being comfortable about embracing ignorance, allowing myself to be "stupid," and actively engaging in uncertain areas. The core of scientific discovery is studying the unknown—finding answers that nobody else has found. Essentially, when I started this research, I did not know the answers to my research questions, but neither did anyone else. Having the freedom and time to explore and conduct research with a mindset of "productive stupidity" has been personally and professionally rewarding.

Before starting this work, I had received no teaching or training in asset maintenance and had limited associated experience and knowledge. My expertise was in product development and industrial engineering, which I believed could be leveraged to make valuable contributions to maintenance. My ambition was to utilize historical data and implement concepts such as modularization and configuration to enhance the overall maintenance process.

In approaching this ambition, I also embraced a point made by Schwartz (2015) regarding the need to be non-attached to a specific hypothesis and indifferent to being proven right. The human desire to be right can hinder the search for truth. Therefore, I made a conscious effort to acknowledge my personal hopes, desires, and ambitions without allowing them to interfere with the research process. I understood that the desire to be “smart” or right should not impede the pursuit of more accurate and impactful results.

Pursuing a PhD has certainly helped me learn and develop professionally and personally. Throughout my time as a PhD student, I have significantly improved my skills as an analyst, communicator, presenter, facilitator, and colleague. I have learned to remain calm and composed in stressful, complex, and demanding situations. Moreover, I have become capable of juggling many stakeholders and their diverse needs, while simultaneously focusing on activities that generate value to satisfy their expectations while advancing my own work.

I now understand the significance of maintaining consistent momentum to sustain progress. In this regard, the 2020–2022 COVID-19 pandemic had an impact on the PhD project. Just as I was about to engage in the collaborative aspects of my work with the main case company, Denmark introduced lockdowns, disrupting my plans. It took a considerable amount of additional work and effort to eventually reestablish the necessary relationships and collaboration, which happened online more than six months later. During this time, I became skilled in precise and clear communication, since conducting collaborative research with a case company online presented unique and unexpected challenges.

Thank you for taking the time to read this thesis.

I hope you found it engaging and enjoyable.

P.S. If you are interested in learning how the research underpinning this thesis has been perceived by the industry, please follow this YouTube link: https://youtu.be/y4pLThY7fYQ

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Appendix A - Appended Publications

A.1 Paper A

Title: Utilising failure history to improve maintenance planning

Authors:

- Simon Didriksen (DTU)
- Kasper Barslund Hansen (DTU)
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In the literature, improving decision support by utilisation of failure history maintenance data is considered to hold a great potential for enhancing the maintenance planning process, as decisions are based on experience and available information. Five principles were identified to structure maintenance failure history data to support decisions in the maintenance planning process, when having high frequency observations of failures. However, the possibility of utilizing the full extent of the available failure history data for all occurring failures and the usefulness of failure history data for decision support in low-frequency observations of failures have not been addressed in the literature. Proposals often tend to present data structures that rely on high frequency observations of failures on individual equipment with a limited possibility of failure history comparison across the entire system. This paper proposes a principle for linking failure history to a multi-classification model of existing physical systems for supporting key decisions in corrective maintenance when having low-frequency observations of failures. The proposal is a fundamental linkage principle indicated to precede those described in the current literature. It also expands the principles identified from the literature by enabling a comparison of failure history data across the entire system to support decisions when having both high- and low frequency observations of failures. Through a case study, the principle proved useful for supporting key decisions in routine-based maintenance work, complex failures with low frequency observations, and identifying recurrent failures that may require new maintenance plan designs. Its potential benefits were the acceleration of knowledge gathering, improved consistency and quality of maintenance plan designs, comparison of all failures across the entire system when having low frequency observations, and indication and prevention of recurrent failures. However, further studies must be conducted to assess the extent of the identified benefits and the effect of the proposed principle.

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Utilising failure history to improve maintenance planning

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Abstract

In the literature, improving decision support by utilisation of failure history maintenance data is considered to hold a great potential for enhancing the maintenance planning process, as decisions are based on experience and available information. Five principles were identified to structure maintenance failure history data to support decisions in the maintenance planning process, when having high frequency observations of failures. However, the possibility of utilising the full extent of the available failure history data for all occurring failures and the usefulness of failure history data for decision support in low-frequency observations of failures have not been addressed in the literature. Proposals often tend to present data structures that rely on high-frequency observations of failures on individual equipment with a limited possibility of failure history comparison across the entire system. This paper proposes a principle for linking failure history to a multi-classification model of existing physical systems for supporting key decisions in corrective maintenance when having low-frequency observations of failures. The proposal is a fundamental linkage principle indicated to precede those described in the current literature. It also expands the principles identified from the literature by enabling a comparison of failure history data across the entire system to support decisions when having both high- and low frequency observations of failures. Through a case study, the principle proved useful for supporting key decisions in routine-based maintenance work, complex failures with low frequency observations, and identifying recurrent failures that may require new maintenance plan designs. Its potential benefits were the acceleration of knowledge gathering, improved consistency and quality of maintenance plan designs, comparison of all failures across the entire system when having low frequency observations, and indication and prevention of recurrent failures. However, further studies must be conducted to assess the extent of the identified benefits and the effect of the proposed principle.

Keywords: Decision-making, information retrieval, knowledge sharing, optimisation, data driven design

1 Introduction

When a failure in a system occurs, an appropriate maintenance plan must be designed for the system to function again. In industrial maintenance, this plan is defined through the maintenance planning process, which is one of the five steps of the maintenance management process described by Sigsgaard, Agergaard, Mortensen, et al. (2020B). Maintenance planners must ensure that the proper decisions are made for selecting the right maintenance actions with the correct estimates and more (Duffuaa & Raouf, 2015). This requires experience and expert knowledge within the field and an understanding of the failure. When a new maintenance plan is created, its design is mainly based on the available data and the experience of the maintenance planner. Maintenance planners can access the available data through the company's computerised maintenance management system (CMMS) and use them to guide their decisions. However, the maintenance planner might not be able to locate and translate the relevant data into meaningful knowledge to support the decision-making for a particular problem, as the CMMS links the data to the maintenance work process, which complicates finding the relevant information with a suitable approximation for a specific problem. Collecting the data is time demanding (Hodkiewicz & Ho, 2016), which forces decisions to be based on tacit knowledge rather than on existing information. Applying historical data to support the decision-making process has been shown to hold a great optimisation potential as much valuable knowledge and decisions are layered within the data (Bokrantz et al., 2017; Sigsgaard, Agergaard, Bertram, et al., 2020). Previous studies on decision support based on failure history exist; however, support for decision-making is lacking when the equipment has a low frequency of failures. Large volumes of valuable data are available for physical long-life systems (Hodkiewicz & Ho, 2016), while the equipment in the system can have a low frequency of observations. In this case, historical data can only truly be utilised for decision support if the full volume of data is available and comparable across the entire system for assessment of individual failures. Furthermore, data must be linked, structured, and contextualised to understand them (Stark, 2016; Teixeira et al., 2021).

This paper proposes a principle for linking failure history to a multi-classification model that consists of multiple classes representing similar elements in different hierarchical levels of an existing physical system. Applying this principle can provide a design-thinking approach for using historical maintenance data as decision support in maintenance planning. The proposal expands the study by Sigsgaard, Agergaard, Bertram, et al. (2020A) on improving decision-making in early development by contextualising data through a hierarchical decomposition of existing physical systems. The study presented in this paper focuses on:

1. How can decisions be supported when the frequency of observations is low?
2. How can failure history be linked to a multi-classification model of existing systems?

These questions were used to explore how the proposed principle can support key decisions in corrective maintenance, improving on routine-based failures, complex failures with low frequency observations, and identifying and preventing recurrent failures. The paper is structured as follows: First, the research method is presented, followed by the Background and Motivation section, which discusses the use of failure history as decision support in maintenance. Next, the proposed principle is presented, followed by a case study presenting the application of the approach and scenarios of the key decisions that can be supported. Lastly, a discussion and conclusion are presented.

2 Research method

The background and motivation of this paper were focused on maintenance and built around the existing body of literature for the use of failure history as decision support in maintenance. The proposal in this paper is based on the principle of Sigsgaard, Agergaard, Bertram, et al. (2020A) on how to structure and contextualise historical data by linking them to a hierarchical decomposition of systems. This paper is mainly built around a case study. The case study approach was chosen to provide a better understanding of the utilisation of failure history as decision support in the maintenance planning process. This approach is chosen as theory and research are in the forming stages, which is where case studies can bring value in the formation (Voss et al., 2002).

The case study presented was based on approximately 11 years' worth of failure history maintenance data acquired for the period 2010–2021 from the CMMS of a major offshore oil and gas production company. This case covers approximately 50 installations distributed over 16 offshore oil and gas fields. The historical maintenance data applied for this case study included all failure notification data, maintenance work order plan data, and general location and equipment data for all 50 offshore installations over the stated period. In this period, the volumes of notified failures and maintenance work order plans were 99.336 and 93.836, respectively. The data were extracted using three standardised extraction codes from the CMMS that the company use to store all maintenance related data, where the volume from the three extractions was more than 1.5 million rows of data.

3 Background and motivation

This section presents five failure history decision support principles for improving decision support based on maintenance failure history data, focusing on the linkage of the data. These principles are identified as the most relevant proposal for utilising failure history as decision support in maintenance planning and they form the background and motivation of this study. Principle 1 is on comprehensive information framework creation, principle 2 is on the evaluation of maintenance policies, principle 3 is on cause-and-effect mapping, principle 4 is on data structuring for condition-based maintenance decision support, and principle 5 is on risk assessment visualisation for maintenance planning.

3.1 Principle 1: Comprehensive information framework creation

Hao et al. (2010) proposed a comprehensive decision support framework for corrective-, preventive-, and condition-based maintenance that includes failure history data, real-time project management, and condition monitoring system. The framework organises the content of the physical system as CMMSs do, but it allows for accessing varied information in a multi-faceted view, with both prescriptive and descriptive information for all levels of a system. However, the data linkage only enables decision support for high-frequency observations. The data structure is not presented to enable comparison between similar types of equipment and failures, but it contains prescriptive knowledge and rules that may enable alternative types of support.

3.2 Principle 2: Evaluation principle for maintenance policies

Morant et al. (2016) presented a decision support data modelling principle for maintenance by analysing the current maintenance to help determine better actions for improving future maintenance policies. The study focused on failure frequency from a holistic perspective by reviewing the effect on the corrective maintenance performance based on changes in maintenance policies. The model shows great potential for the analysis of maintenance plans for the overall system, but as the failure history is linked to the highest level of the system, the failure history could not be reviewed for the individual equipment.

3.3 Principle 3: Cause-and-effect mapping

Fischer et al. (1996) and Galley (2004) both presented accumulative malfunction and experience database models consisting of cause-and-effect diagrams that enhance the amount of experience in which the employee can rely on. The causes of the malfunctions can be located and solved faster, and time can be saved for finding the right information to solve the failures. However, both proposals do not provide a principle for linking the data, and the core principle is only supported by having high-frequency observations of failures.

3.4 Principle 4: Data structuring for condition-based maintenance

Teixeira et al. (2021) proposed a principle for structuring and standardising failure history data and combining them with preventive maintenance event and equipment monitoring data to analyse equipment failures to support decisions for condition-based maintenance implementations. The proposed data structure is a hierarchical composition of a production line, where the failure history data are linked to the low-level equipment in the machines of the line. The study focused on data analysis and machine learning methods, and shows a potential for providing detailed information for the failure history of individual equipment. However, this paper does not present a principle for linking the equipment to the totality of the system and between different production lines to compare failure similarities across the system.

3.5 Principle 5: Risk assessment visualisation for maintenance planning

Sarshar and Haugen (2018) presented a risk-assessment decision support concept for the maintenance planning process in the offshore petroleum industry. The concept was developed to establish and manage maintenance plans while identifying hazards in relation to the maintenance actions. This is accomplished through location visualisation, external condition data, and failure history data. It provides context to planned activities, in contrast to enterprise resource planning systems, and it can be used to review all activities in one or multiple maintenance plans. However, the study focused on the application and use of the concept, rather than on the structuring of the underlying data. Whether the proposal provides a linkage of the data that can enable comparison of similar failures and equipment across the entire system is not indicated, compromising the overview that can be provided in the case of low-frequency observations.

The five principles can provide varied valuable information for high-frequency observations of failures. However, in the case of low-frequency observations of failures, the principles cannot utilise the full range of available failure history data for decision support because they lack a clear classification and data linkage that enable comparison of similar failures or equipment across the system. Either the classification and linkage were not presented in previous studies or they lack the ability to enable cross comparison in the system.

4 Principle for linking failure history to a multi-classification model

In the literature, no studies were identified to utilise the full volume of available failure history data for failures with low-frequency observations. To expand on the reviewed studies and achieve a full utilisation of failure history data for support of the key decision in maintenance planning, a principle for linking failure history to a multi-classification model is proposed in Figure 1. It is based on the principle of linking data to the hierarchical decomposition of existing physical systems presented by Sigsgaard, Agergaard, Bertram, et al. (2020A), which originates from the Theory of Technical Systems (Hubka & Eder, 1988). Furthermore, the proposal is based on the principle of assessing a piece of data and comparing it with all other similar pieces of data, and the structure of the physical system is reflected in the data structure to bring it into context (Stark, 2016). The principle presented in Figure 1 is composed of a one-to-many comparison, where the model contains two views of the same system, which means that the two sides consist of identical data sets and hierarchical structures of the system. Each side of the model contains a hierarchical structure, where the data are linked between the failure history, equipment, subsystem, and system. The link and link direction enable the comparison of specific equipment with all similar equipment in different subsystems of the same system. As presented in the figure, a system may contain a multitude of different subsystems and equipment, but with the right classification and structure, comparable equipment can be identified by applying a bottom-up search followed by a top-down search through the same system.

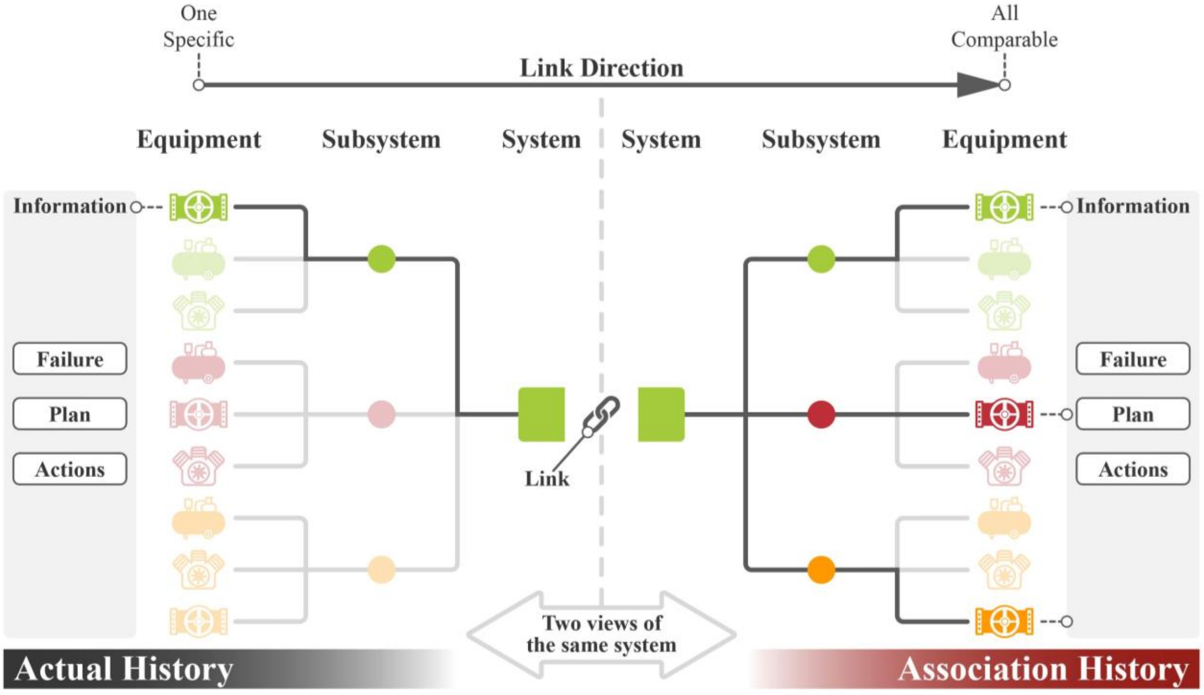


Figure 1. Principle for linking failure history data to a multi-classification model. The failure history is made available for a specific equipment and for all comparable equipment in the system by linking two views of the same system.

By starting from one specific equipment at the lowest level of the hierarchy with a bottom-up approach and then applying a top-down approach from the highest level of the hierarchy in the same system, comparable equipment can be located at the lowest level of the hierarchy on the basis of a single equipment. The related information of all the located equipment can then be accessed by structuring and contextualising the historical data, where information for failures, plans, and actions are linked to each equipment. To explore a specific failure of an equipment in a system, all the relevant historical failure information for that specific equipment would be accessible through the left side of the model, identified as the actual history in Figure 1. The link then combines the equipment to the rest of the system and makes all available data for equipment and related failures in the system accessible through the right side of the model, identified as the association history in Figure 1. Thereby, the failure at multiple levels of the hierarchy and across the entire system can be compared. This enables maintenance planners to start further ahead in the maintenance plan design process, apply previous and successful designs for new designs, and avoid creating a new design that might be identical to an already existing design for an equipment with multiple recurrent failures. Furthermore, it enables the utilisation of all available failure history data as decision support for failures with low-frequency observations.

The proposed principle enables the maintenance planner to specify how precise the match should be between the actual history and the comparable association history to review relevant data at multiple levels across the system. The proposal is a fundamental maintenance data linkage principle that precedes what currently exists in the identified literature for maintenance decision support systems and can provide flexible data to be used as decision support and evaluation for new designs of maintenance plans. The principle expands on the principles presented in the literature by enabling a comparison of equipment failure history across the entire system for supporting key decisions regarding both high- and low-frequency observations. However, it requires a right classification of the system and a sufficient quality level of the data for the proposal to enable decision support through association history.

5 Case study

The data acquired for the case study were utilised in accordance with the proposed principle through the business intelligence software Power Bi. The case study is divided into three sections: the first section presents the realised data structure based on the proposed principle, the second section presents a dashboard application realised from the data structure, and the third section presents scenarios for three key decisions in corrective maintenance planning that the proposed principle can support.

5.1 Data structure realised from the proposed principle

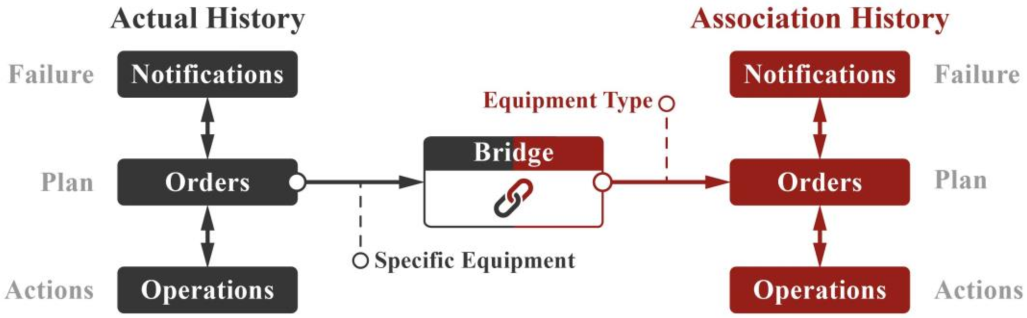
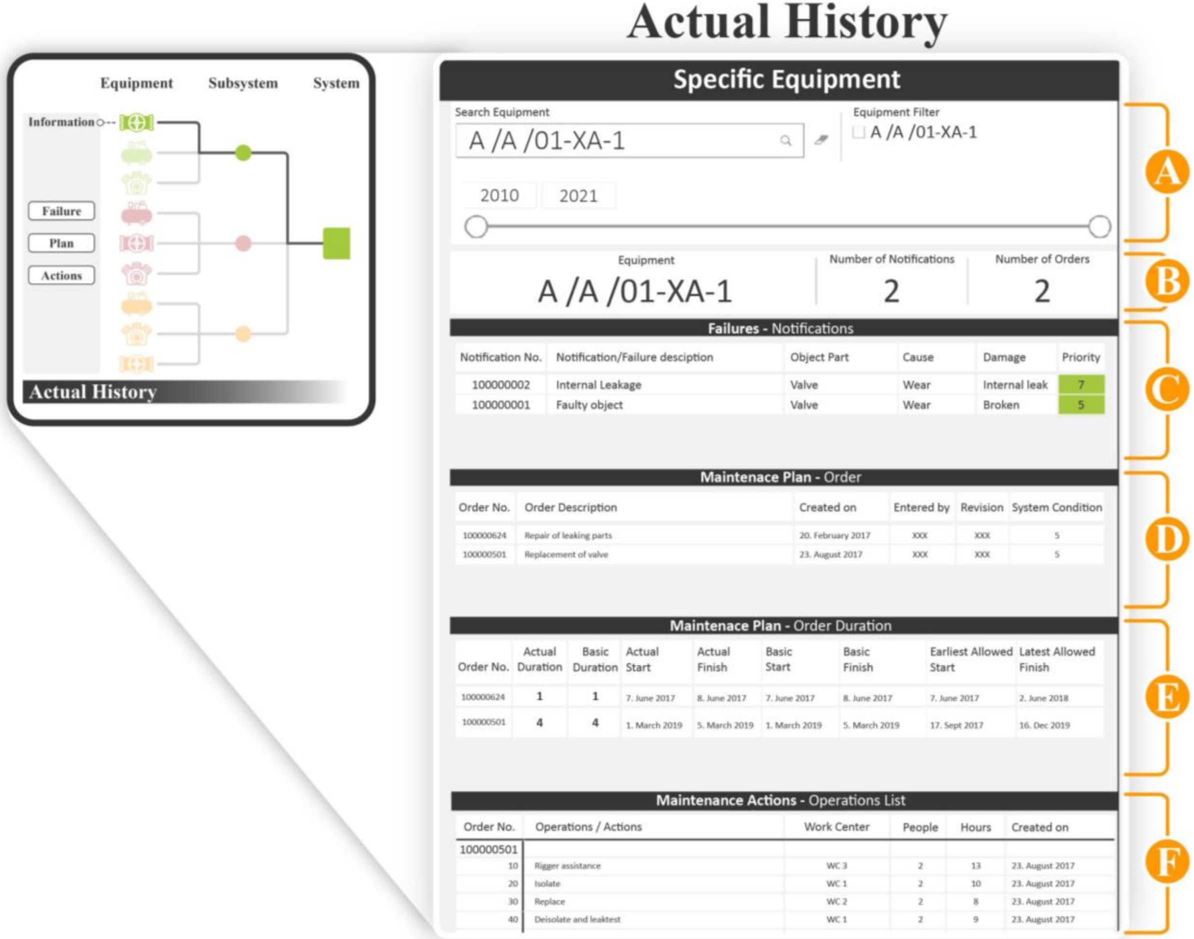


Figure 2. The data structure realised from the proposed principle. The two sides contain the same datasets, the bridge links the sides by matching specific equipment with the equipment type, and the link direction enables searching all levels of the system hierarchy.

The data from the case company consist of three separate datasets. The notification dataset contains all historical data for notified failures. The order dataset contains all historical data for the maintenance plans. Lastly, the operations dataset contains all historical data for how the maintenance plans were designed with actions that should mend the notified failures. The data structure presented in Figure 2 was created on the basis of the proposed model in Figure 1, where the three datasets are duplicated, so the actual history side consist of the same data as the association history side. The three datasets in each side are double-directionally linked to each other based on the order number present in all the datasets. The order dataset contains equipment and equipment type data that were extracted and used to generate the bridge data table in the middle. The equipment data in the order dataset of the actual history side is one-directionally linked to the equipment data in the bridge table. The equipment data in the bridge are matched to the equipment type data, which are then linked to the equipment type data in the order dataset of the association history side. One equipment can only match one equipment type, while one equipment type can match multiple equipment. The one-directional linkage through the bridge enables the data structure to provide data for multiple equipment belonging to a single equipment type based on the search of one specific equipment.

5.2 Dashboard application realised from the data structure

The presented data structure can be utilised for creating the failure history dashboard, which is divided into Figures 3 and 4. Figure 3 presents the dashboard area realised by the actual history side of the proposed principle and data structure.



Search Equipment: A /A /01-XA-1

Equipment Filter: ☐ A /A /01-XA-1

2010 2021

Equipment	Number of Notifications	Number of Orders
A /A /01-XA-1	2	2

Failures - Notifications

Notification No.	Notification/Failure desciption	Object Part	Cause	Damage	Priority
100000002	Internal Leakage	Valve	Wear	Internal leak	7
100000001	Faulty object	Valve	Wear	Broken	5

Maintenace Plan - Order

Order No.	Order Description	Created on	Entered by	Revision	System Condition
100000624	Repair of leaking parts	20. February 2017	XXX	XXX	5
100000501	Replacement of valve	23. August 2017	XXX	XXX	5

Maintenace Plan - Order Duration

Order No.	Actual Duration	Basic Duration	Actual Start	Actual Finish	Basic Start	Basic Finish	Earliest Allowed Start	Latest Allowed Finish
100000624	1	1	7. June 2017	8. June 2017	7. June 2017	8. June 2017	7. June 2017	2. June 2018
100000501	4	4	1. March 2019	5. March 2019	1. March 2019	5. March 2019	17. Sept 2017	16. Dec 2019

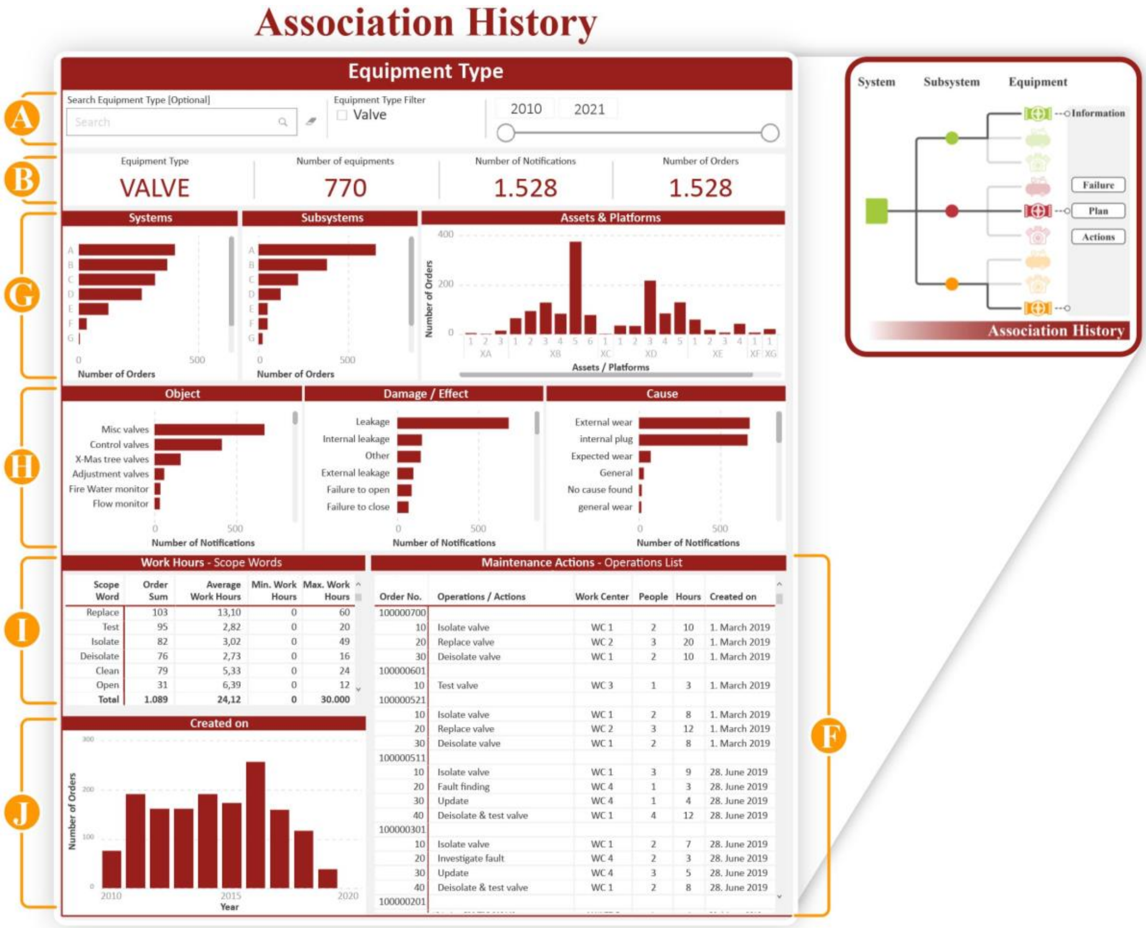
Maintenance Actions - Operations List

Order No.	Operations / Actions	Work Center	People	Hours	Created on
100000501					
10	Rigger assistance	WC 3	2	13	23. August 2017
20	Isolate	WC 1	2	10	23. August 2017
30	Replace	WC 2	2	8	23. August 2017
40	Deisolate and leaktest	WC 1	2	9	23. August 2017

Figure 3. The actual history area of the dashboard showing failure history data for a specific equipment. A) Equipment search field and time filter. B) Failure and plan frequency. C) Failure data. D) Maintenance plan data. E) Maintenance plan timestamps. F) Maintenance plan operation list with planned actions.

The areas marked with letters in Figure 3 indicate all available failure history data for individual equipment. A) shows where the maintenance planner can search for specific equipment to access all available data and furthermore filter the time frame. B) shows the observation frequency of the notified failures and maintenance plans for the specific equipment. C) is a table containing data related to the notified failures of the specific equipment. D) presents a table with all the maintenance plans. E) presents a table containing the relevant timestamps for the maintenance plans. In F), the operation lists, which contain the planned actions with all the estimated resources and materials for maintenance plans, are shown.

Figure 4 presents the dashboard area realised by the association history side of the proposed principle and data structure. This provides the maintenance planner with all associated maintenance data across the system for the same equipment type as the one that has been searched for. The areas marked A, B, and F in Figure 4 provide the same type of information as that in Figure 3, but for all associated equipment across the entire system.



Scope Word	Order Sum	Average Work Hours	Min. Work Hours	Max. Work Hours
Replace	103	13,10	0	60
Test	95	2,82	0	20
Isolate	82	3,02	0	49
Deisolate	76	2,73	0	16
Clean	79	5,33	0	24
Open	31	6,39	0	12
Total	**1.089**	**24,12**	**0**	**30.000**

Order No.	Operations / Actions	Work Center	People	Hours	Created on
100000700					
10	Isolate valve	WC 1	2	10	1. March 2019
20	Replace valve	WC 2	3	20	1. March 2019
30	Deisolate valve	WC 1	2	10	1. March 2019
100000601					
10	Test valve	WC 3	1	3	1. March 2019
100000521					
10	Isolate valve	WC 1	2	8	1. March 2019
20	Replace valve	WC 2	3	12	1. March 2019
30	Deisolate valve	WC 1	2	8	1. March 2019
100000511					
10	Isolate valve	WC 1	3	9	28. June 2019
20	Fault finding	WC 4	1	3	28. June 2019
30	Update	WC 4	1	4	28. June 2019
40	Deisolate & test valve	WC 1	4	12	28. June 2019
100000301					
10	Isolate valve	WC 1	2	7	28. June 2019
20	Investigate fault	WC 4	2	3	28. June 2019
30	Update	WC 4	3	5	28. June 2019
40	Deisolate & test valve	WC 1	2	8	28. June 2019
100000201					

Figure 4. The dashboard area realised by the association side of the proposed principle. All available data across the entire system are accessible for the equipment type linked to the searched specific equipment.

In Figure 4, G) provides an overview of the frequency of maintenance plans in the different systems, subsystems, assets, and platforms for the equipment type. H) provides the frequency of notified failures related to different objects, damages, and causes for the equipment type. I) provides the possibility to filter for specific scope words related to the type of maintenance plans. By using scope words, the type of maintenance that is mostly designed for the specific equipment type can be identified. J) is an overview for the frequency of maintenance plans created at different times. One or multiple tables and graphs in the dashboard can be clicked to filter the data and find an exact match for the failure at hand, such as filtering for a specific cause or/and maintenance action.

5.3 Key decision scenarios supported by the proposed principle

Three scenarios are presented to reveal how the proposed principle can support key decisions in maintenance planning. The first scenario presents routine-based maintenance work with high-frequency observations, the second scenario presents decision support for complex failures with low-frequency observations, and the third scenario presents decision support for recurrent failures that may require a different maintenance plan design. The three scenarios reflect failures and maintenance plans that have been identified to occur in the offshore installations of the case company. The principle was in this case applied for selecting whether to replace or repair a valve given various failures and historical data. Valves were selected for the scenarios, as it is central flow control equipment in offshore oil and gas production installations. They are equipment with increased fragility, as they consist of movable parts that results in high-frequency observations for some failures and low-frequency observations for other failures.

5.3.1 *Scenario 1: Routine-based maintenance work*

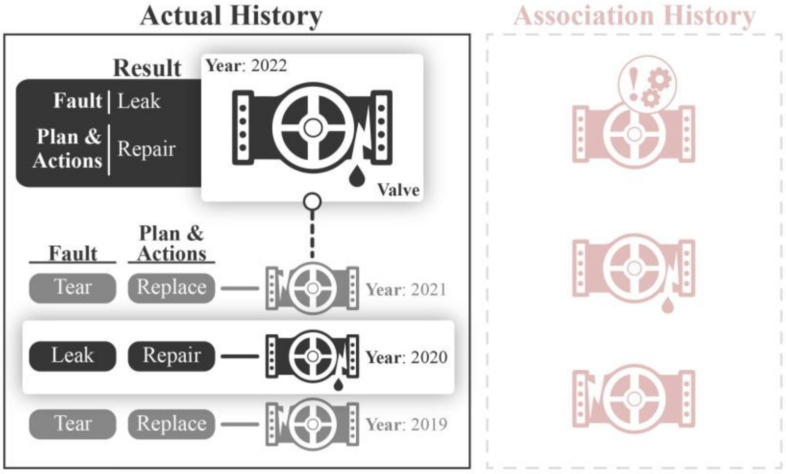


Figure 5. Routine-based maintenance work scenario for both high-frequency observations. The actual failure history can be reviewed to see how maintenance plans for the same fault were designed in the past.

The scenario in Figure 5 presents a valve with a leakage failure that needs maintenance. By applying the proposed principle, the maintenance planner is provided with the actual history of the valve, which shows high-frequency observations of failures. By reviewing the actual history, the exact same failure of the valve 2 years prior can be identified. The maintenance planner can reuse the maintenance plan design from the previous identical fault, which was repair. By doing so, it enables the maintenance planner to not start from scratch and it accelerate the knowledge gathering. Furthermore, it supports the maintenance planner in selecting the best solution that has been effective in the past. This is useful for developing a high-quality maintenance plan design and maintaining consistency in handling routine-based failures.

5.3.2 *Scenario 2: Complex failures with low-frequency observations*

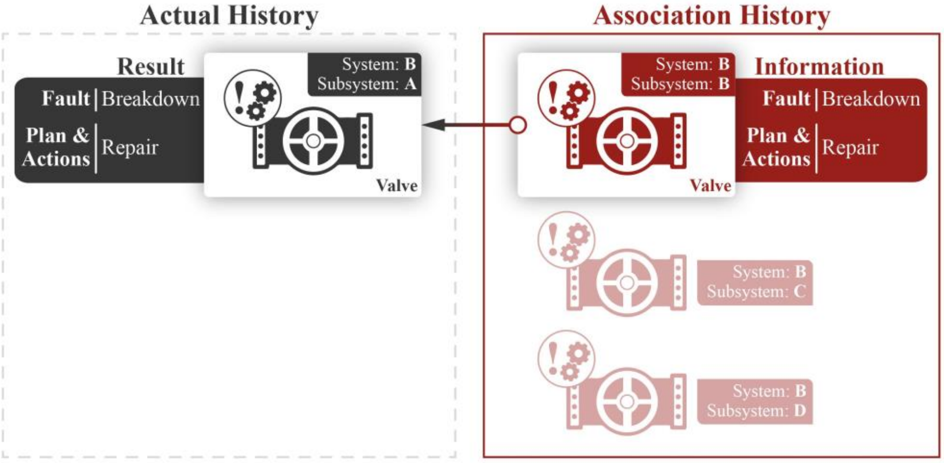


Figure 6. Scenario of a complex failure with low-frequency observations in the actual history of a specific piece of equipment. The association history can be used to find exact matches of similar equipment and failures and as an inspiration to create an adequate maintenance plan with correct actions.

The scenario in Figure 6 presents a complex breakdown failure of a valve in subsystem B, which needs a maintenance plan. As it is a case with low-frequency observations, the maintenance planner can apply the proposed principle and use the association history to search across the system and locate similar historical failures for similar valves. The maintenance planner locates three similar valves with the same failure as the one at hand in three different subsystems. The maintenance planner can use the maintenance plan designs from the association history as an inspiration for the new maintenance plan. In this case, return of experience through historical data can provide guidance and inspiration for failures, where no data are available in the actual history of the specific equipment.

5.3.3 Scenario 3: Recurrent failures requiring new solutions

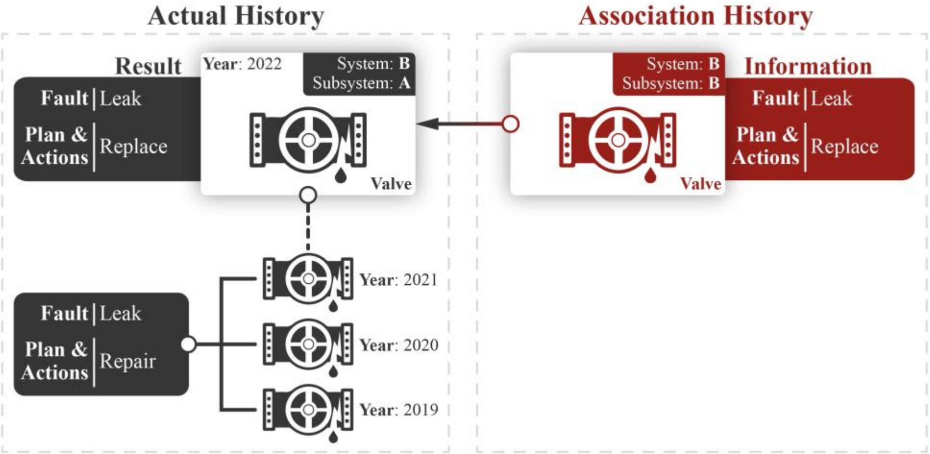


Figure 7. Scenario of a recurrent failure that may require new solutions to end the repetition. By reviewing the actual history, recurrent failures can be identified. By examining the association history, alternative maintenance plan designs can be identified and used as inspirations for new solutions to a recurrent failure.

The scenario in Figure 7 presents a valve in subsystem A with a leakage failure that needs maintenance. By applying the proposed principle, the maintenance planner can, through high-frequency observations, identify that the failure has occurred three times before at continuous intervals and that the maintenance plan for each failure was to repair it. By accessing the actual history, the maintenance planner can identify that the failure is recurrent, which may be due to continuous application of incorrect maintenance plan designs. By examining the association history, whether similar valves with the same failure across the system have a recurrence of the failure can be known. In the scenario, a similar failure occurred in a valve in subsystem B with no recurrent failures, and the maintenance plan was to replace the valve. Thus, the maintenance planner can use the proposed principle to identify recurrent failures and as an inspiration for new solutions to prevent a continuous occurrence of a failure.

6 Discussion

6.1 Implications for research

Five principles have been identified to propose the utilisation of data that can provide valuable failure history information for the maintenance planner to apply as decision support when having high-frequency observations of failures in a system. Different elements from the identified principles were applied in the development of the proposed principle. These elements were data organising and hierarchical structuring of physical systems, application of failure cause and effect frequency observations, and application of failure history data for maintenance plan designs. However, the proposals in the literature lack the ability to utilise the full volume of the available failure history for failures with low-frequency observations and for comparison of failures across the entire system. Either the proposed data structures are not capable of providing this possibility or it is not indicated in the studies. The proposed principle in this paper allows for the use of the full volume of failure history data for each occurring failure by linking failure history to a multi-classification model. Applying this principle expands the accessibility of failure history data to support maintenance planning for a larger variety of failures in complex systems, which extends the current research by enabling new application areas for failures with low-frequency observations.

6.2 Implications for practitioners

The case study scenarios present potential benefits for the maintenance planner by the application of the proposed principle. These benefits include acceleration of knowledge gathering, improved quality and consistency of maintenance plans, comparison across the system in cases of low-frequency observations, and prevention of recurrent failures. Utilising the full volume of the available failure history data in the maintenance planning process for past failures can potentially provide an adequate level of information that the maintenance planner can rely on as a basis for the decision-making for future maintenance plan designs.

6.3 Limitations and further research

The usability of the full volume of failure history data can be limited by having low-quality data and an incorrect classification of the system. As Janssen et al. (2017) and Hussin et al. (2010) reported, obtaining quality data is an important factor in ensuring the quality of the decisions derived from the data. The data made accessible to maintenance planners through the proposed principle are based on previous designed maintenance plans. Therefore, these data will be relevant to future maintenance plan designs, as the same type of data input is required. Whether additional types of data should be included can only be evaluated by testing the proposal in collaboration with maintenance planners in future studies. Some study limitations and problems were uncovered regarding the access to and identification of the relevant data points and the quality of the data. The principle is only applicable for old systems, as a large volume of historical data is required. The single-case study formed the basis, which limited the study to provide only an indication for potential. To assess the extent of the identified potential benefits, further studies on the effect of the principle must be conducted. Furthermore, studies on the generalisation of the principle to other industries and the implementation of the principle in generic systems such as configuration systems could be beneficial extensions of the research.

7 Conclusion

A principle for linking failure history to a multi-classification model of existing physical systems is presented in this paper. Indications of potential for the principle to support key decision in maintenance planning for low-frequency observations were found by enhancement of the comparability of failure history across the entire system. The case study reveals that data structures and decision support applications can be developed on the basis of the principle to support the key decision for routine-based maintenance work, complex failures with low-frequency observation, and identification and prevention of recurrent failures. The principle is not indicated to be unique, but the fundamental linkage principle is identified to precede what currently exists in maintenance literature for the utilisation of failure history data. It is a steppingstone to enhance the use of historical data and design-thinking approaches in maintenance planning.

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A.2 Paper B

Title:

Visualize maintenance data to identify safety issues and opportunistic maintenance possibilities

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2021 Annual Reliability and Maintainability Symposium (RAMS)

Abstract:

In this paper, a proposed visualization method for identifying safety issues and opportunistic maintenance possibilities is presented. The focus is on the practicability of opportunistic maintenance and hazard identification, which is lacking in both literature and industry (i.e. case company). The proposed method uses visualization and system drawings for communicating the potential issues and opportunities to maintenance planners. The visualization is data-driven and uses common maintenance data for highlighting potential safety issues and opportunistic maintenance possibilities on system drawings. The applicability of the method was tested at a case company and the results confirm that benefits can be achieved by using the proposed method. Through the use of the method, issues and opportunities were identified which would not have been discovered or would have taken a considerable amount of time to derive using the existing maintenance planning procedure.

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Visualize Maintenance Data to Identify Safety Issues and Opportunistic Maintenance Possibilities

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Key Words: hazard identification, maintenance data, opportunistic maintenance, visualization

SUMMARY & CONCLUSIONS

In this paper, a proposed visualization method for identifying safety issues and opportunistic maintenance possibilities is presented. The focus is on the practicability of opportunistic maintenance and hazard identification, which is lacking in both literature and industry (i.e. case company). The proposed method uses visualization and system drawings for communicating the potential issues and opportunities to maintenance planners. The visualization is data-driven and uses common maintenance data for highlighting potential safety issues and opportunistic maintenance possibilities on system drawings. The applicability of the method was tested at a case company and the results confirm that benefits can be achieved by using the proposed method. Through the use of the method, issues and opportunities were identified which would not have been discovered or would have taken a considerable amount of time to derive using the existing maintenance planning procedure.

1 INTRODUCTION

For achieving efficient, effective, and safe maintenance execution, thorough maintenance planning is crucial. Maintenance planning is concerned with determining the work scope of maintenance actions, considering safety aspects of work and failures, and reducing delays in production [1,2]. In regards to safety aspects, it is crucial to identify issues related to system safety. Large industrial systems are characterized by consisting of many pieces and types of equipment and by having many inter-dependencies between these. This system complexity makes it difficult for maintenance planners to determine true criticality and risks of maintenance work and the mitigating actions that must be taken. Also, due to the inter-dependencies of industrial systems, a failure or a maintenance action is not isolated to a single piece of equipment but needs to be considered together with other failures or actions affecting the system. For instance, hot work should not be planned in proximity to a flammable liquid leakage, as well as two concurrent non-safety critical failures might result in a safety threat when happening simultaneously. In addition to finding safety issues, maintenance planners also need to consider the grouping of maintenance work, both preventive and corrective, to minimize set-up costs and maintenance costs, and to maximize production availability. This concept is known as opportunistic maintenance and correlates with the thinking in Lean maintenance planning of “doing more with less” [3–5]. An opportunistic maintenance possibility could be to, during a shutdown of a system for maintenance, perform all scheduled maintenance for the system to avoid another shutdown. Another possibility could be to, when erecting a scaffold or isolating an area, extend it to cover work located conveniently close together instead of doing it separately. Hence, if resources are already on-site or systems have already been isolated, utilize the opportunity to conduct other maintenance.

This paper presents a method for visualizing maintenance requests and work orders, which could pose potential safety issues or be subject to opportunistic maintenance, given some criteria, on system diagrams. The visualization is data-driven and realized by comparing maintenance records data from the computerized maintenance management systems (CMMS) with extracts of data from system diagrams and equipment-specific data. Based on predetermined states or matches in the data, safety issues and opportunistic maintenance possibilities are highlighted on the system drawings. This provides a clear visualization of the current system condition and of improvements that maintenance planners could make. The objective is to identify issues and opportunities that might otherwise have been overlooked or would have taken a considerable amount of time to derive.

This paper is structured as follows: first, the motivation for preparing the paper is discussed. Then follows a presentation of the proposed visualization method. A case study evaluating the method is then presented and lastly, a discussion is presented.

2 MOTIVATION

In multi-unit systems such as most industrial systems, interactions and dependencies exist between components. These interactions and dependencies can be classified as [3,6]:

- Economic dependencies implying maintenance performed on several components at the same time costs less than the sum of performing it separately.

- Structural dependencies referring to the integral nature of systems, so that a failed component also results in required treatment for other parts of the system.
- Stochastic dependencies implying that the state of a component can influence the state of others. Failure dependence is a case of stochastic dependencies.

The consideration of these dependencies is essential in the planning of maintenance. The identification of the dependencies leads to discoveries of safety issues and opportunistic maintenance possibilities. Through observations in industry, the authors have seen that it can be difficult for maintenance planners to identify the dependencies in their daily work. The work of a planner is to prepare the information and resources needed to complete a maintenance task safely based on a received request and available information. The work includes task descriptions, responsibility selection, material ordering, time estimations, and cost estimations. Also, the planner needs to consider the environment of the item on which maintenance is to be performed by identifying and analyzing risks posed to the workers, equipment, and environment, and determine ways to mitigate and protect them [1,2]. Maintenance planners, as observed by the authors, browse through maintenance requests and work orders stored in the CMMS, looking for issues and opportunities. As hundreds or thousands of requests and work orders exist at any point in time, it can be difficult or even an impossible task to identify the dependencies of the maintenance items active in the CMMS. This results in limited discoveries of issues and opportunities.

This finding can be supported by the maintenance literature. A limited amount of research strives to make opportunistic maintenance practical and help the decision-maker (i.e. maintenance planner) optimize maintenance activities [7]. Levrat et. al [8] have studied optimal production stoppages for conducting maintenance activities and Derigent et. al [9] have studied the proximity of components potentially subject to opportunistic maintenance. Generally, the application of opportunistic maintenance in the industry is limited [7]. Nevertheless, research in opportunistic maintenance is increasing [7]. Broadly, the focus in research has been on terming the concept and the approach of opportunistic maintenance, and on developing maintenance policies based on it [7].

The stochastic dependence of failures is common in industrial systems and have been extensively studied [6,10,11]. The rationale is that a failure can induce a failure of other components or influence the performance of other components [12]. The failure dependence can result in production losses and risks to the safety of personnel, assets, and environment [11]. Several studies consider stochastic failure dependence between components with the objective of developing mathematical models for optimizing maintenance policies [13], including opportunistic maintenance policies [11]. In a recent literature review by de Jonge & Scarf [13], the practical applicability of these models are deemed challenging due to the amounts of condition data required to fit the models to practical situations.

Maintenance is the solution for preventing and rectifying failures, but conducting maintenance may also introduce safety hazards, e.g. risk of physical harm [14]. Therefore, maintenance-related safety hazards should also be identified and managed. For instance, at the Swedish railway, analysis has shown that 80% of accidents and incidents are caused by executing maintenance work [15]. Insights from the analysis showed that accidents and incidents could have been prevented by better communication and transfer of risk information.

The proposed method of this paper provides maintenance planners with information about issues and opportunities through visualizing dependencies of relevance. Thereby, striving to make opportunistic maintenance practical and safety issues caused by failure and maintenance work evident.

3 RESEARCH APPROACH

The research approach of this study is based on design science research in information systems [16]. The research approach comprises of six process-steps:

i. The identification of a problem. The problem of this study has been presented in the introduction and motivation sections of this paper. The problem was found in both industry and maintenance literature.
ii. The definition of objectives of a proposed solution. For solving the defined problem, a visualization method has been proposed and the objectives have been presented.
iii. The design and development of an artifact. The method is realized in an information system (i.e. artifact). The research contribution is embedded in the design of the artifact.
iv. A demonstration of value through applying the artifact to solve a problem. For this, a case company is used.
v. An evaluation of the efficiencies and effectiveness gained or lost by applying the artifact.
vi. Communication of the results, e.g. through scholarly publications. This is the purpose of this paper.

For the remainder of this paper, the process-steps iii-v will be in focus.

The study has been conducted in collaboration with a case company. The case company is presented in the case study section of the paper. The primary data used in this study were collected through semi-structured interviews with managers and employees at the case company. Secondary data were collected from document databases and the company's CMMS, and used in conjunction with the primary data. The interviews and literature were used to identify the problem and to determine the objective. The design and development of the artifact were based on the authors' knowledge of theory that can be brought to bear in a solution. After the design, the artifact was adjusted based on feedback and discussions with interviewees during the demonstration process-step. The artifact was then evaluated through further interviews.

4 THE VISUALIZATION METHOD

The proposed method is visualizing the important aspects for the maintenance planner to identify issues and opportunities by performing reasoning on relevant maintenance data. The planner can then take action based on the information. The relevant information should be presented clearly and concisely to facilitate the planner's interpretation. For this, illustrating the information is proposed in the method. The common English phrase "A picture is worth more than a thousand words" can be stated here. The meaning of the phrase in this context is that complex information can be more easily conveyed through an illustration than a mere description. Nevertheless, text descriptions should also be shown to the planner for clarification purposes.

The proposed visualization method is realized through an information system that is based on the theory of expert systems [17]. Expert systems perform reasoning on a representation of human knowledge and solve problems or give advice. Expert systems can solve tasks that would otherwise require substantial human effort and experience. The knowledge of an expert system and the reasoning can be well-documented, thereby enabling a high degree of control and governing of the problem-solving.

The information system consists of three components, which are illustrated in Figure 1; (a) a data link synthesizing the information needed, (b) an inference machine performing reasoning, and (c) a visualization component to communicate the results to the maintenance planner.

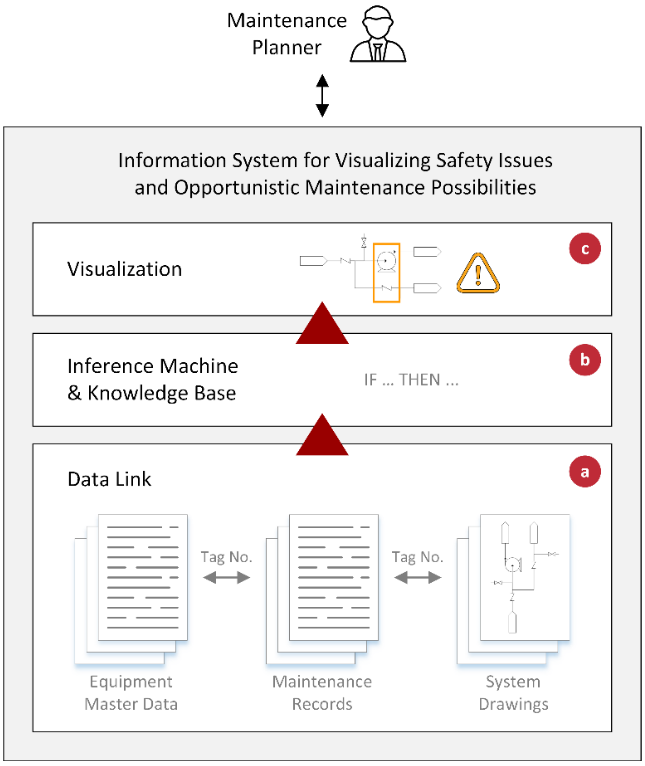

Figure 1 - Components of the information system

The first component, the data link (a) component, is creating a relation between relevant data pools;

- maintenance records describing current failures, and already planned and scheduled maintenance,
- equipment master data describing the specifications and characteristics of the equipment (e.g. type, dimensions, weight, age, performance),
- and system drawings describing the structural dependencies of the system.

Separately, the data pools provide different perspectives and information to the maintenance planner. By creating a relationship, the information is synthesized and contextualized and can provide a greater understanding [18].

A prerequisite for linking the data is to store the data digitally and make it available in data pools. This can be achieved by storing the data in tables on a server or locally. The data relation is created by matching columns in the tables where the columns' contents are similar and values identical. The relation between the data pools in the proposed information system should be created by matching columns identifying the maintenance item, such as the equipment tag number. Hence, by relating the maintenance records and the master data through the equipment tag number, it enables looking up the specifications of a failed piece of equipment. Moreover, by extending the relationship to the system drawings, the placement of the equipment in the system(s) can also be looked up. Thereby, information about the state of maintenance items, their specifications, and system locations can be derived from the data relationship.

The second component, the inference machine (b), performs the reasoning using documented knowledge of the planners. The inference machine interprets the data and identifies the safety issues and opportunistic maintenance possibilities using a knowledge base. The knowledge base is a container for the explicit knowledge of the maintenance planners. Planners supply their knowledge about the issues and possibilities and it gets stored in the knowledge base as rules. The rules are constraints for the reasoning of the inference machine. The knowledge base should contain the joined knowledge of the planners and should be documented collectively to achieve agreement. The knowledge documentation task is only required once but should be frequently revised and updated with changes if needed. The rules can be represented in relation tables, conditional statements, or others [17]. The rules should describe the circumstances of opportunistic maintenance possibilities and the situations in which safety issues occur. The data can then be interpreted to identify issues and opportunities. For example, a rule could be: if the distance between two maintenance jobs is less than 2 meters then opportunistic maintenance could be possible else not. The inference machine uses this rule to browse the data looking for cases where the rule is true. If found, the system highlights the cases on the system drawings. Therefore, by documenting the knowledge of the planners and using an inference machine, it is possible to automatically derive the issues and opportunities from the data.

The third component, the visualization component (c), is the explanatory component and should illustrate the findings of the inference machine clearly and effectively for the maintenance planner to quickly understand the issues and possibilities currently present in the system. For this purpose, system drawings such as Process Flow Diagrams (PFD) or Piping and Instrumentation Diagrams (P&IDs) [19] are used as the communication medium. From interview insights, it was discovered that system drawings are used to manually identify relationships and is the primary source used to identify issues and opportunities in the current process. By highlighting the issues and opportunities on the drawings, the planners can quickly interpret them and take action. The highlighting requires intelligent system drawings where highlighting is possible. Accompanying the highlighted system drawings, details about the information found by the inference machine should also be supplied. The details specify the arguments and can be verified by the planner. This provides clarity and understanding for the planner. If the planner finds the arguments wrong, the knowledge base should be adjusted.

In the combination as an information system, the three components can relate the relevant data, perform reasoning on it to find issues and opportunities, and clearly present the results to the planner.

5 CASE STUDY

The visualization method has been demonstrated and evaluated through a case study at a major multinational oil and gas company. The case study was conducted at a maintenance department at a regional support unit for offshore oil and gas production in the Danish part of the North Sea. There are approximately 1500 people employed at the regional support unit. In the maintenance department, there are eight maintenance planners employed. The planners have different experiences, competencies, and responsibilities. Generally, senior planners have an aerial view of the maintenance operations while other planners deal with one trade only (e.g. mechanical or electrical equipment). Additionally, some of the planners are only focused on corrective maintenance while others are also attentive to preventive maintenance. On average, there are approximately 4000 requests and work orders outstanding, open, and scheduled in the CMMS at any particular time. Due to the one-sided view of some planners and the difficulty in identifying issues and opportunities due to the magnitude of requests and work orders, issues and opportunities have been overlooked in the past. Furthermore, the task time of planners is also varying considerably. Hence, there is a need for improving the current situation. Two use cases were identified for the method in the case company. The first, to visualize all issues and possibilities on one or several diagrams. The second, to choose a specific piece of tagged equipment and highlight issues and possibilities on the diagram(s) related to this piece of equipment. The latter use case was chosen for the case study.

In the development of the information system (i.e. the artifact), standard software available in the company was used. The design of the information system can be seen in Figure 2. For the data link and inference machine components, Microsoft Excel is used and stored locally in a document. The maintenance records from the CMMS, the master data from the equipment database, and the contents of the system drawings were imported through the Excel tool, Power Query, and the data relationships were created in the Excel tool, Power Pivot. Due to the available equipment data of the case company being incomplete and non-standardized, rule creation and management would become complex. Therefore, the contents of the knowledge base were simple. In the solution, the inference machine identified all requests and work orders on the relevant system drawings and presented the accompanying equipment master data. Thereby, the planner could review the presented data and apply their knowledge accordingly.

The visualization component was realized in Adobe Acrobat. The system drawings used by the case company were stored as PDF (i.e. Portable Document Format) documents and featured switchable color layers for highlighting items. Adobe Acrobat can toggle the visibility of the color layers and take commands from Excel through Excel VBA and JavaScript. Thereby, a system drawing with highlights can be produced.

The process of using the information system to identify issues and opportunities is as follows (*Figure 2):*

i. The planner inputs the equipment tag number of a maintenance item in the Microsoft Excel document.
ii. The inference machine (i.e. Excel) identifies the drawing(s) in which the maintenance item is present and identifies the outstanding, open, and scheduled requests and work orders on the(se) drawing(s). Now, all potential requests and work orders have been identified and they are presented to the planner.
iii. The planner reviews the presented requests and work orders, and the accompanying data from the CMMS, equipment database, and drawing database. The planner selects parts of or all of the request and the work orders to be highlighted on system drawings.
iv. The Microsoft Excel document sends a command to Adobe Acrobat to highlight the selections and produce highlighted drawing(s). Adobe Acrobat produced the requested drawings.
v. The planner can evaluate if safety issues or opportunistic maintenance possibilities are present.

Due to the lack of an extensive knowledge base and guidance therefrom, the process is iterative and the planner repeats steps iii-v until a sufficient confidence level has been achieved. An example of a highlighted drawing can be seen in Figure 3 The drawing will be accompanied with data about the highlighted maintenance items.

Generally, when evaluating the information system, planners' expressed that the task of identifying issues and opportunities is quicker and easier by the use of the system. The data has become comprehensible and is presented in a communication medium familiar to planners. The planners had difficulty in evaluating if certain issues or possibilities would have been overlooked if the information system were not used. However, a past example of an overlooked opportunistic maintenance possibility was brought up during the interviews:

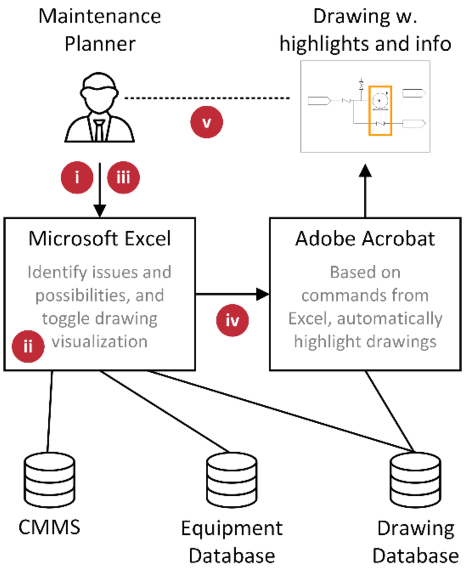

Figure 3 - The design of the information system used in the case study (i.e. the artifact)

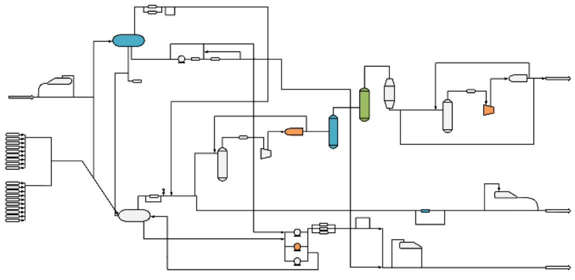

Figure 2 - An example of a highlighted system drawing. Due to confidentiality, the example is fictitious.

two valves had failed on the same pipeline with half a day in between the failures. Both valves had to be functional for the pipeline to be in operation. Maintenance planning began after both failures had been reported but actions were planned separately. This lead to a delay of a day between the first valve being repaired until the other valve was repaired even though both valves could have been repaired when the first valve was repaired. The extended shutdown of the pipeline resulted in a significant economic loss. The economic loss was greater than the expected investment of the proposed information system presented in this paper. The planners expressed that this opportunity would have been discovered using the system.In terms of safety issues, the planners also identified some which might otherwise have been overlooked during planning if the system was not used. A planner mentioned that work occasionally gets planned next to failures where the combination becomes safety-critical if performed. This planning error has however never had direct safety consequences yet due to being caught later in the process. Using the system, these planning errors have been caught and thereby decreased the risk of accidents. Through the use of the method, planning was expressed to be more reactive and dynamic as beneficial changes to existing plans can be more easily identified when new failures emerge or scheduled maintenance gets released. The method also enables multi-component and multi-disciplinary planning of the maintenance.

6 *DISCUSSION*

The information system proposed in Section 4 has been applied to a case study presented in the previous section. The case study demonstrated that the information system offers benefits compared to the existing situation in the case company both in terms of efficiency, effectiveness, and safe operations. The generalizability of the proposed system can be argued. The case company is acting in the highly regulated and standardized offshore oil and gas production industry. This implies that other companies in the same industry are similar in terms of organization structure, processes, procedures, etc. This suggests that other potential applications are present. However, generalizability should be further studied. Other industry sectors might also encounter some of the challenges discussed in this paper. The case study showed that existing data available in the case company could be utilized for identifying issues and opportunities. In further studies, the task of documenting knowledge could be investigated, potentially through analysis of historical information, Another further study could be the implementation of the information system. Afterward, the actual benefits could also be investigated, e.g. comparing the number of accidents before and after implementation. Companies should beware that full application in practice will only be possible if the discussed data pools and intelligent system drawings are available, standardized, and organized properly. The aim of the study to contribute to the practicability of opportunistic maintenance and hazard identification has been reached. The proposed method can be seen as an extension of the FMECA (Failure mode, effects, and criticality analysis) method. FMEA and FMECA are usually single-unit-centric and considers the impact of failures for each system entity respectively. This is partly due to the impracticality and extensive amount of work required to define the impact of combinations across system entities. The proposed method considers the impact of concurrent maintenance jointly and provides a visualization aid for interpretation.

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A.3 Paper C

Title:

Improve maintenance by reusing and refining previous maintenance cases

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Abstract:

A three-step decision process using case-based reasoning to support maintenance preparation is proposed. By reviewing historical maintenance records based on case similarity, the best previous maintenance solutions can be reused for current and future equipment failures. A decision process is proposed to reuse solutions, including an improvement step to increase the maintenance accuracy of the solutions. The proposed process mitigates the difficulty of reusing previous successful maintenance solutions. The study follows a prescriptive approach. A case company was used to assess and evaluate the proposed process regarding its feasibility in an industrial context. Contrary to the current known approaches presented in research, the proposed decision process enables the reuse of complete work packages rather than single activities, the evaluation of previous solutions based on accuracy, and accounting for low-quality data otherwise seen as a barrier to the reuse of activities. The application at the case company shows a faster decision process with greater employee confidence in the applicability and accuracy of the prepared maintenance work. The proposed method also supports new employee training and ensures continuous improvement in maintenance, based on the evaluation of the success of previously prepared maintenance.

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Improve Maintenance by Reusing and Refining Previous Maintenance Cases

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***Abstract*—A three-step decision process using case-based reasoning to support maintenance preparation is proposed. By reviewing historical maintenance records based on case similarity, the best previous maintenance solutions can be reused for current and future equipment failures. A decision process is proposed to reuse solutions, including an improvement step to increase the maintenance accuracy of the solutions. The proposed process mitigates the difficulty of reusing previous successful maintenance solutions. The study follows a prescriptive approach. A case company was used to assess and evaluate the proposed process regarding its feasibility in an industrial context. Contrary to the current known approaches presented in research, the proposed decision process enables the reuse of complete work packages rather than single activities, the evaluation of previous solutions based on accuracy, and accounting for low-quality data otherwise seen as a barrier to the reuse of activities. The application at the case company shows a faster decision process with greater employee confidence in the applicability and accuracy of the prepared maintenance work. The proposed method also supports new employee training and ensures continuous improvement in maintenance, based on the evaluation of the success of previously prepared maintenance.**

Keywords—maintenance preparation, maintenance decision support, continuous improvement, maintenance management

I. INTRODUCTION

In industrial systems, equipment deteriorates over time due to stress, load, usage, and age. This deterioration can eventually lead to failures. Failures are unwanted, and maintenance has been introduced as an efficient way to ensure satisfactory system reliability [1], [2]. Maintenance is concerned with conducting activities to either rectify or prevent failures. The activity types could be cleaning, lubrication, adjustments, calibration, repair, refurbishments, replacements, etc. [3]. In general, these maintenance activities are repetitive and common across different equipment types; for example, both valves and pumps can be repaired. The difference is in the parts being maintained and in the activities performed; for example, securing the area might be required if working with gas, and subsequent testing should be carried out if there is a risk of leaks. In addition, the variation in maintenance activities for a piece of equipment is limited; for example, a valve can have varying degrees of repair, replacement, and refurbishments during its lifetime [4]. As maintenance activities are performed in response to equipment failure or as prevention, the failure mode is central to the selection of maintenance activities. Failures are also limited in the ways or modes in which they might occur. For example, in the petroleum, petrochemical, and natural gas industries, 22 general failure modes have been defined for mechanical equipment [5, p. 188]. Although the types of activities and failure modes are limited, the actual number of variations in activities in the industry is very high. The examination of the case company's computerized maintenance management system (CMMS) showed about 23,000 different wordings for about 43,000 activities. This large number is the effect of maintenance work preparers not looking into previous activities when preparing new ones. Instead, they prepare everything from scratch; thus, the descriptions of the activities and the activities vary. By not reusing previous activities, the process is time-consuming and a missed opportunity for learning, that is, using the experience from previous maintenance to improve future maintenance. Variations in activity wording can also lead to unsafe behavior and rework as the technicians' activity interpretations differ. To resolve this issue, several approaches have been introduced. Methods such as failure mode and effect analyses (FMEAs) can be used to select maintenance actions, but they are not activity-specific [6, pp. 235–260]. For this reason, service manuals have more detailed descriptions of activities but are either not extensive or too comprehensive to find relevant content [7]. Other approaches use maintenance records found in companies' CMMS to prepare for new maintenance [8], [9]. These approaches compare previous maintenance cases for solutions to reuse and are able to reuse activities based on case relevance. The approaches can find and reuse single activities but are not suited for the reuse of entire work packages (i.e., several activities, competencies, durations, materials, etc.). Complete work packages are the output of maintenance preparation [10]. The current approaches in the literature also lack a learning aspect, in which previous activities are improved upon based on the accuracy of the previous maintenance. Accuracy refers to whether the maintenance solves the issue and how well it was solved. To tackle these issues, the present study focuses on reusing and improving previous work packages. The focus is on providing value through the sharing of knowledge stored in maintenance records. For knowledge sharing to be valuable to individuals and organizations, the knowledge must be received, accepted, and applied by those who need it [11]. Thus, the central research focus is on how maintenance preparers find previous relevant solutions, easily evaluate them, and reapply an accurate solution for a specific failure. For this, a three-step decision process using case-based reasoning for maintenance case comparison is presented in this paper. The presented decision process is inspired by human choice behavior to facilitate a more comprehensive selection of work packages compared to single activities.

The paper is structured as follows: First, the research approach is presented. Then, observations in the industry regarding maintenance preparation are made, leading to a review of relevant research literature. The proposed method is then presented, followed by the application of the method at a case company. Finally, a discussion and conclusion are included.

II. RESEARCH APPROACH

This study followed a prescriptive approach, and a case company was used to evaluate the proposed process in an industrial context. An interest in the subject was developed through observations in the industry, and a need to support the maintenance preparation process was observed. This was the motivation for further investigation. The academic literature was examined for the state of the art and to clarify the research direction of the study. The literature search focused on decision support for maintenance preparation and the value brought to practitioners. The proposed method was derived from findings in the literature and maintenance industry standards. Inspiration from human choice research was also used to mitigate the decision difficulty in the method. A case company was used to investigate the applicability of the proposed method. The case company was chosen because it operates many large offshore plants that require an immense amount of maintenance. The company provided access to 8 years (2011–2019) of maintenance records for the maintenance case comparison. Eight work preparers were also available for testing. The method was evaluated and compared to existing research and the benefits for practitioners.

III. OBSERVATIONS IN INDUSTRY

Through industrial insights and engagement with the case company and other maintenance-performing companies, the authors observed a need to improve maintenance preparation. The common practice is to prepare maintenance with limited reuse of solutions from previously prepared and executed activities, although there are high similarities between previous and present solutions. In addition, the performance of previous activities is not accounted for in the present solutions. Therefore, there is a limited return on experience. As preparers have different experiences and training, manually prepared maintenance for the same failure situations can differ substantially. This leads to highly varied maintenance activities in terms of wording, content, and completeness. This is non-value-adding, as the variation is unwanted due to quality and misinterpretation concerns. The scheduling and execution of maintenance activities depend on high-quality maintenance preparation. If the output of the preparation step is poor, the quality of the scheduling and execution steps deteriorates, or they take longer. Moreover, misinterpretations can lead to unsafe behavior, rework, and delays. Therefore, when several process steps succeed, maintenance preparation has a great impact on overall maintenance performance.

IV. LITERATURE REVIEW

To further investigate the need to improve maintenance preparation as identified in industry, relevant literature was examined. Research on decision support for maintenance preparation was explored to evaluate existing methods and approaches. In particular, research on documenting maintenance knowledge and reusing previous maintenance solutions was reviewed.

A. Service Manuals

In certain industries, it is common to document maintenance knowledge in comprehensive instructions and procedures in service manuals. For example, for a commercial two-stroke marine engine, the service manual for technicians can be more than 2,000 pages, and the manual describes the most commonly known procedures needed for maintenance. In addition to being an extensive task to document, the amount of information is overwhelming for technicians, especially the less-experienced technicians, and has resulted in mistakes being made [7]. This example supports a difficult balance between providing comprehensive and accurate information, while also being concise and clear and being able to provide it in a timely manner [12, p. 68]. In easing this balance, research has been conducted not only to provide easier and faster ways to locate relevant documentation in service manuals and other maintenance documentation [13]–[17] but also to deliver user-tailored and task-specific information (i.e., step-by-step description of maintenance procedures) [18], [19]. Generally, the focus is on easing the search for relevant information in the comprehensive documentation of procedures. The use of service manuals and the approach for easing the information search lack customization for specific maintenance situations.

B. Support for Maintenance Preparation

In other industries, it is common to employ maintenance preparers instead of documenting maintenance knowledge in service manuals. Maintenance preparers use their knowledge and experience to decide on reasonable work for different maintenance failures and prepare the maintenance information needed to complete a maintenance activity safely [10]. Several studies have presented results for decision support. Reference [20] presented an integrated decision support system to diagnose faults and generate efficient maintenance and production schedules. To generate maintenance in this system, a look-up table is used that includes the description of activities needed to fix a certain failure and information about the sequence of the activities and the time required. Similarly, [21] presented a sequential failure troubleshooting system that proposes different possible failure states to the user. If the user agrees that the failure state is occurring, the documented procedures for correcting the failure are shown. If the failure is not corrected, the process continues or starts anew.

C. Documentation and Knowledge Acquisition

In the tools presented by [20] and [21], every failure situation and the resulting procedures must be documented. In terms of documentation, [22] argued that one of the most important aspects of maintenance decision support is expert knowledge acquisition, that is, the transfer and transformation of expert knowledge to an expert system. Reference [22] also suggested that maintenance experts may know more than they may be able to express or define, such as documenting procedures for different failures. Instead of documenting the explicit knowledge of maintenance preparers and experts, another approach is to look at their previous actions, decisions, and behaviors. Reusing previous maintenance solutions has been proposed. Historical data of previous maintenance contain the output of the preparers' maintenance decisions and the accuracy of the decisions (i.e., quality control, evaluation, close-outs, etc.). By reusing data from previous maintenance activities, the tacit knowledge of maintenance preparers can be used and refined.

D. Reusing Previous Maintenance Solutions

The process of using previous experiences to solve new failures is related to case-based reasoning. In industrial maintenance, case-based reasoning has proven useful for managing experience [23]–[26]. The concept suggests that failures reoccur, and so do maintenance activities [8]. If a specific maintenance failure arises several times, it is beneficial to reuse the best previous solution to solve the failure. The objective is to detect, capitalize on, and preserve previous maintenance experience [27]. The relationship between the maintenance failure and the corresponding solution can be deemed case knowledge, which is knowledge applicable to a specific situation within a particular domain [28]. Thus, documenting all possible equipment failures and the resulting maintenance solutions is not required, as knowledge exists in the maintenance records. However, an approach is required for browsing through cases to determine the commonality between a current failure and previous cases. Several approaches have been presented in maintenance research.

E. Approaches for Reusing Maintenance Solutions

Reference [8] presented an approach for reusing previous solutions to solve new maintenance failures by describing failures and solutions with a list of standard variables, thus enabling a comparison between cases. Using previous experience, [9] presented the design of a recommender for building maintenance that can recommend an action required in response to a failure in the heating, ventilation, etc. The underlying assumption is that similar failure descriptions correspond to similar actions. The recommender uses information about previous failures and solutions to recommend actions for current failures based on computed similarity. The focus is on single-activity reuse, whereas maintenance is often a combination of activities [10]. The research by [8] and [9] assumed that there are good solutions present in the CMMS, and they are ready to be found and reused.

F. Data Quality Considerations

Reference [9] found that the data quality of CMMSs was low (i.e., missing or incomplete information), and thus, the recommender had varying results. To account for this issue, [29] introduced association rules to uncover relationships in the data. However, the data quality might be low, and the data may be non-reusable. In general, companies struggle with the usability of CMMSs [30], and usability can be a challenge if the manual input of information is extensive [31], [32]. CMMSs are commonly and extensively used today [29]. A large amount of data exists in the systems because more data are being collected (i.e., sensors) and logged, and due to the long-time use [30]. With extended use, many solutions are documented in the system, and more than one solution for a failure might exist. More than one solution for a failure is a latent aspect in the existing research literature, where the focus is on finding one solution, not the best solution among many solutions. Existing research has achieved results for filtering previous maintenance activities to find relevant solutions to a current failure but not for validating and evaluating the performance of the relevant solutions to find the best solution for a specific failure. Existing research has not accounted for the accuracy of the maintenance, whether the maintenance solves the issue, and how well it was solved [8], [9].

To conclude, the current known approaches presented in the literature are (1) reusing single activities and not completing work packages, (2) not evaluating the found solutions based on accuracy, and (3) not accounting for low data quality as a barrier to the reuse of solutions. These three aspects are the focus of this study. This paper presents a framework for including the accuracy aspect in the selection and reuse of previous activities as well as refinement of the selected activities.

V. MAINTENANCE PREPARATION AS A THREE-STEP DECISION PROCESS SUPPORTED BY CASE-BASED REASONING

As observed in literature and industry, decisions must often be made with incomplete information or based solely on an individual's experience and knowledge. Generally, in decision-making, the decision maker may not consciously recognize the need for information, which is a barrier influencing information-seeking [33]. During a decision process, decision-makers often process only a limited amount of information about available decision alternatives (i.e., maintenance solutions) during the initial screening stage [34]. Then, they focus on evaluating in greater depth a small number of alternatives that survived the screening, and they select an alternative from these options. Decision-makers naturally tend to follow this two-stage process of screening and evaluation when choosing their preferred alternative to ease and simplify their decision process [34]. The two-stage process was used as the basis for developing the proposed framework. To mitigate the perceived decision difficulty and to support the maintenance preparation process, we propose splitting the selection of maintenance activities into two distinct decisions: The first decision involves screening different approach alternatives (i.e., repair, replace, etc.) that are relevant to solving a maintenance failure, and the second decision is about evaluating the different courses of action (i.e., dismount, mount, test, etc.) for a selected approach. For both decisions, case-based reasoning is used to find relevant alternatives based on case similarities. To find a solution to a maintenance failure, maintenance preparers answer two questions: (1) what to do and (2) how to do it. The first question is about the maintenance approach, whereas the second question is about the course of action. The maintenance approach is linked to the overall objective of the maintenance, for example, to clean (approach) and cleaned (objective), whereas the course of action is the work package to achieve it, for example, an employee with cleaning supplies for 1 hour and soaking and scrubbing. By making two distinct decisions about the approach and the course of action, more than one activity can be reused without decision difficulty. After the decisions are made and a solution is selected, a refinement step should be included, as the selected solution

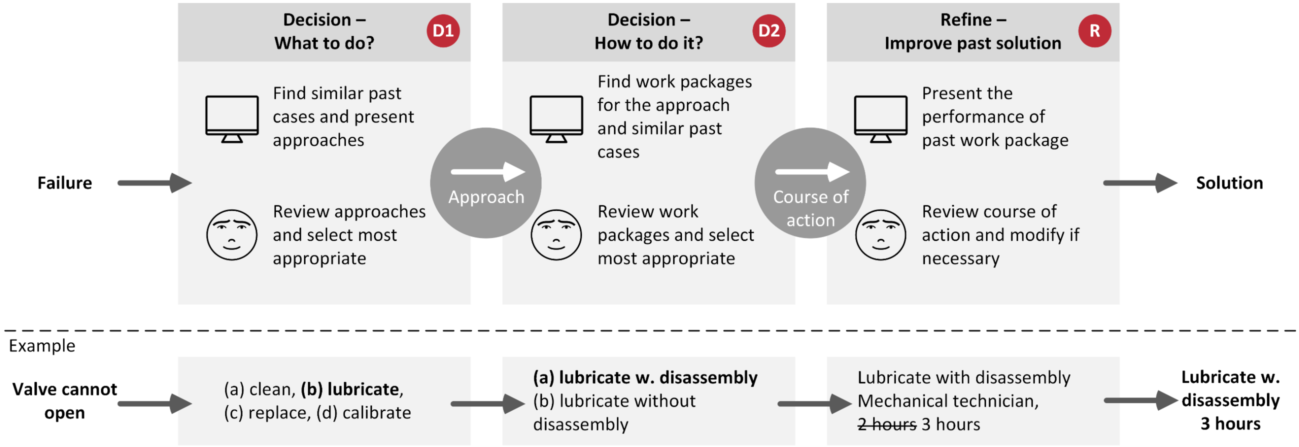


Fig. 1. The three-step decision process for supporting the preparation of maintenance activities.

was designed for a similar but not identical case. In addition, the data quality might be low, and the degree to which the solution solved the maintenance objective might differ from the prepared objective. Therefore, to improve on previous solutions, the selected solution is adjusted to the current case and refined by examining previous performances. The two decision steps and the refinement step are presented in Fig. 1. The accuracy of previous maintenance can be evaluated based on the difference between the estimated maintenance duration and the actual duration, the use of resources and materials, and the activities not performed according to the preparation [10]. The introduction of a refining step to improve the accuracy is an extension of previous research that mainly focused on reuse. In addition, the decision process is suited for the reuse and improvement of entire work packages as a combination of several activities.

VI. APPLICATION

A three-step decision process and case-based reasoning are proposed to reuse previous solutions for an improved and customized solution. To justify the proposed method, it was applied in a case company. The Danish affiliate of a large multinational company with more than 100,000 employees and affiliates around the world was used as the case company. It operates offshore oil and gas production in the Danish part of the North Sea. The company is responsible for developing, operating, maintaining, and decommissioning the assets required for production. At the time of the study, the company operated and maintained 50 offshore installations. The company sought to improve its maintenance preparation department. In the company, the work preparers work in “silos” and do not align their terminology, approaches, descriptions, etc. Therefore, maintenance variation is quite high, which is undesired due to maintenance accuracy concerns. In addition, the company has experienced data quality issues. The case company is interested in supporting decision-making in maintenance preparation to overcome these issues. In the following section, the setup at the company is presented, and then the use of the proposed decision process is described.

A. The Proposed Decision Process at the Case Company

To support the three-step maintenance process, a comparison algorithm and a knowledge base are needed to compare cases and show the relevant previous maintenance. The algorithm performs the comparison and uses the knowledge base as a repository for all previous maintenance cases. It contains information about the failures, solutions, and results for each case. In the case company, the elements of the maintenance cases were collected at different points in the maintenance process, as shown in Fig. 2. The maintenance failures were collected from failure descriptions created by the technicians, the solutions were prepared in work packages, and the results were collected after the maintenance was executed and evaluated. In terms of data, the case company uses work orders to document and store information about maintenance cases. The work orders describe the failure mode to be resolved, the approach, and the activities, including competencies, resources, and materials. The evaluation of the maintenance after execution is also logged in the work orders. An example of the available data in the case company is shown in Fig. 3. The data can describe the approach for failures, courses of action, and accuracy. The data are a combination of standardized data available in dropdowns/lists and non-standardized data stemming from free-text fields. The non-standardized data describe essential information about the maintenance cases, such as descriptions of the approach. Thus, a direct comparison of the descriptions will not show similarity, as the wording and terminology might differ. Between 2017 and 2019, there were approximately 23,000 distinct descriptions for about 43,000 activities. Thus, an algorithm or standardization of all data is needed if they are to be compared. The approach used for comparison is the systematic modularization of maintenance actions described by [35].

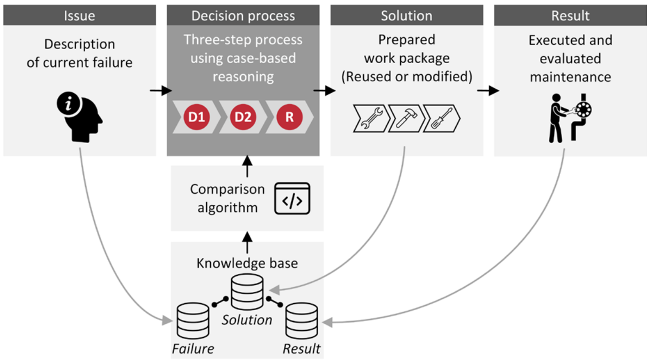
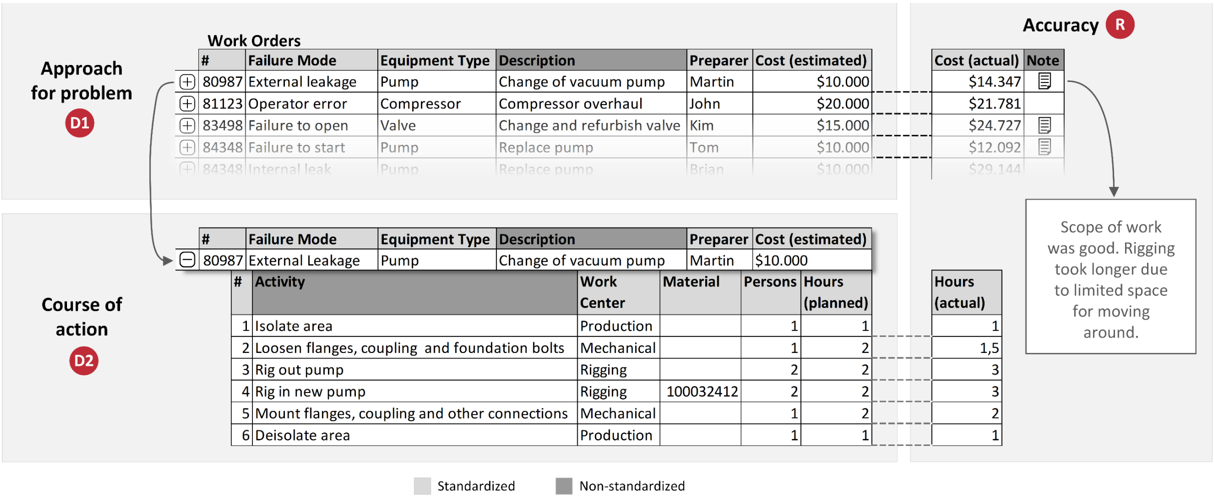


Fig. 2. The three-step decision process and the knowledge base containing case information relative to the maintenance process.



Work Orders

	#	Failure Mode	Equipment Type	Description	Preparer	Cost (estimated)	Cost (actual)	Note
⊞	80987	External leakage	Pump	Change of vacuum pump	Martin	$10.000	$14.347	🗎
⊞	81123	Operator error	Compressor	Compressor overhaul	John	$20.000	$21.781	
⊞	83498	Failure to open	Valve	Change and refurbish valve	Kim	$15.000	$24.727	🗎
⊞	84348	Failure to start	Pump	Replace pump	Tom	$10.000	$12.092	🗎
⊞	84348	Internal leak	Pump	Replace pump	Brian	$10.000	$29.144	

Scope of work was good. Rigging took longer due to limited space for moving around.

	#	Failure Mode	Equipment Type	Description	Preparer	Cost (estimated)
⊟	80987	External Leakage	Pump	Change of vacuum pump	Martin	$10.000

#	Activity	Work Center	Material	Persons	Hours (planned)	Hours (actual)
1	Isolate area	Production		1	1	1
2	Loosen flanges, coupling and foundation bolts	Mechanical		1	2	1,5
3	Rig out pump	Rigging		2	2	3
4	Rig in new pump	Rigging	100032412	2	2	3
5	Mount flanges, coupling and other connections	Mechanical		1	2	2
6	Deisolate area	Production		1	1	1

Fig. 3. An example of the data available at the case company that represent the approaches, courses of action, and accuracy of the maintenance.

B. *Usability of the Case Company's Data*

The case company provided maintenance records dating from January 2011 to March 2019. The potential of the proposed method is based on the usability of the data. The method cannot be used without a solid data foundation, and the maintenance history should be applicable to solving new failures. Therefore, for the majority of the equipment, a wide range of failures should have occurred and should have reusable solutions. In total, within the scope of the data provided, 59,522 failures were recorded. Fig. 4 shows the number of failures across the equipment types operated by the case company. A total of 426 failures across 18 equipment types were excluded due to the low amount of data for use in the proposed method.

For the test case, the pump type of equipment was chosen. There were 4481 pump failures in the data. Fig. 5 shows the recorded pump failures across the failure modes. The data were filtered for insufficient data (i.e., missing failure mode and the failure modes "Other" and "Unknown"). As shown in Fig. 5, the failures can be distributed into failure modes, and most failure modes include many previous failures. Continuing with the test case, the failure mode "Failure to start on demand" was selected. Fig. 6 shows the approaches for correcting the "Failure to start on demand" failure mode on pumps. The approaches were identified according to the method described by [35]. A choice of several approaches (e.g., selecting replace and test) is possible. Looking further into the data for the test case, there are various previous solutions for replacing a pump. There is a variation in the number of activities, ranging from 3 to 10, and the work crew also differs. The planned work for replacing a pump ranges from 10 to 40 hours. Two people are required for all solutions. The previous solution that best fits the current situation can then be found. Looking at the accuracy of the previous solutions for replacing a pump, the planned hours for performing the work have both been overestimated and underestimated. Most of the solutions have an estimation error of fewer than 2 hours. One solution had a note stating, "Approach OK," indicating that the solution corrected the failure. Other solutions included notes describing the actual work conducted (e.g., "Dismantling of existing pump installation. Preparation and installation of the new pump.

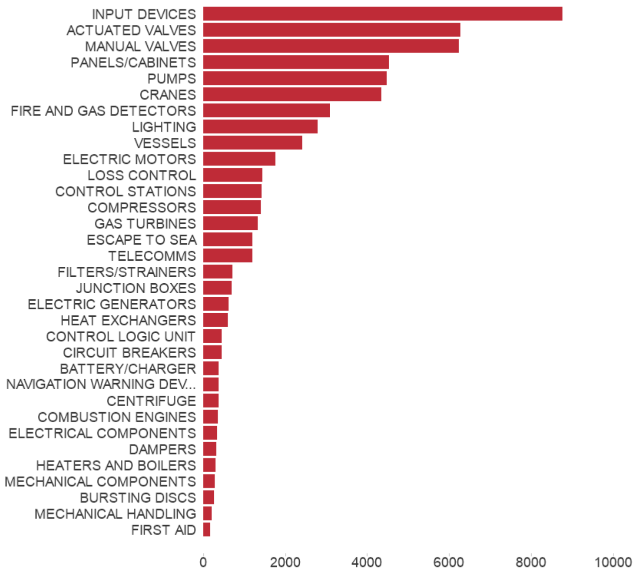


Fig. 4. The distribution of failures with recorded solutions across equipment types at the case company.

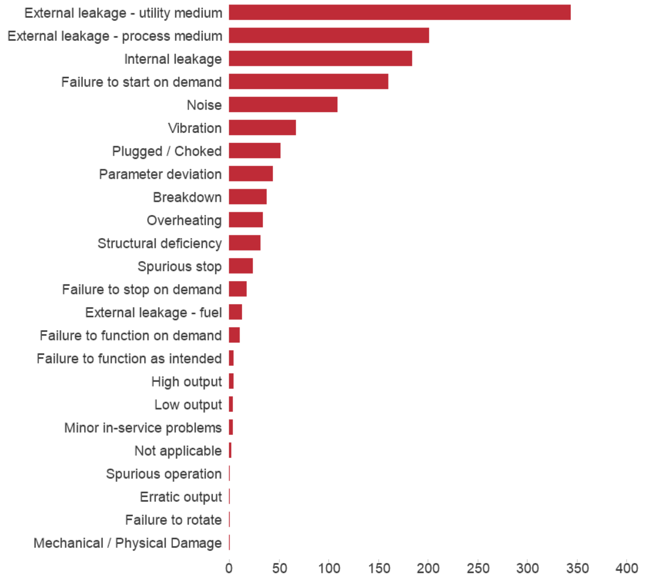


Fig. 5. The distribution of pump failures across failure modes at the case company.

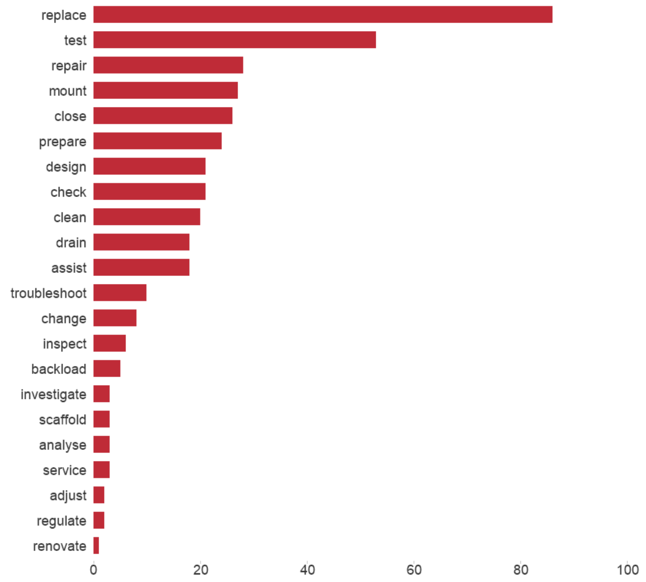


Fig. 6. Approaches for correcting the "Failure to start on demand" failure mode on pumps.

Test run and clean up"). This can be compared with the planned work to refine the solution. Another note said, "A new hose has been installed at the pump. It just had to be 'fitted' a bit, so be aware of that at the other places." This information can be used to refine future solutions.

The data foundation and data tendencies seen in the test case were also observed across other equipment types. As shown in Fig. 4, some equipment types have a low amount of data. Therefore, filtering per failure mode can be omitted. The rationale is that the work required does not change based on the failure mode. However, the hours required, the number of people, and other factors might change. Fig. 7 shows the general approaches to repairing combustion engines. Although there were only 129 failures, there is still history to use for reusing and refining previous solutions for future use. In general, across equipment types, for the majority of failures, data f previous solutions can be used to solve new problems. Frequent failures provide the best opportunity for the method, and with frequent failures, this method also delivers the greatest impact.

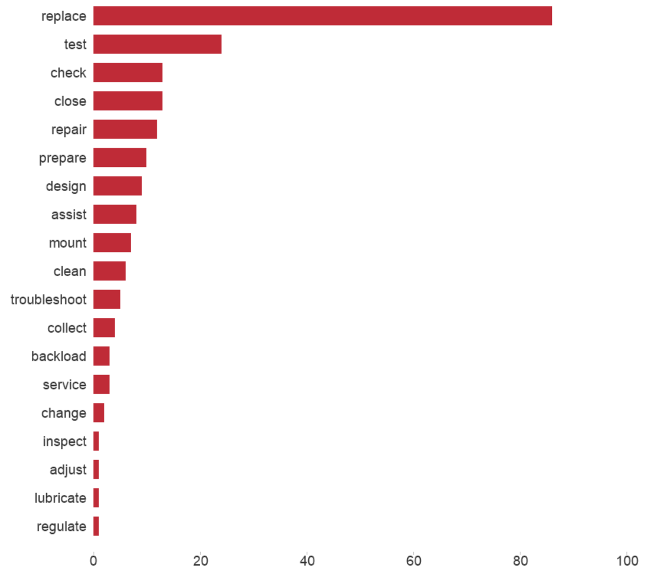


Fig. 7. General approaches for rectifying failures of combustion engines.

C. Use of the Proposed Three-step Decision Process by Maintenance Preparers

The proposed three-step decision process was used by a group of eight work preparers at the case company. The work preparers followed the decision process, as illustrated in Fig. 8. First, the work preparer describes the failure situation using the specific equipment and failure mode. Then, the relevant approaches from the previous solutions are found through computed case similarity and presented to the work preparer. The work preparer then makes the first decision about what to do to correct the failure. Then, relevant courses of action are found for the selected approach. The work preparer then makes the second decision and chooses the most suitable work package. The factors available for the decision are the number of activities, duration, cost, and seniority of the preparer of the previous solutions. Thus, the work preparer can compare solutions and choose the best one. There will be dominant solutions (i.e., better on all factors); otherwise, the work preparers use their own experience to select the best solution. The next step in the process is the refinement step to improve solution accuracy. For the evaluation of previous accuracy, the cost of maintenance, estimation of hours, and notes are used. The work preparers modify as they see fit. The result is a reused and improved solution. In general, the work preparers stated that the structured decision process was faster. It was less time-consuming reusing solutions than designing and preparing from scratch. They also stated that they had greater confidence in the selected solution in terms of applicability (i.e., able to solve the failure) and accuracy (i.e., how well it is solved). The group of work preparers consisted of permanent employees and short-term consultants. The consultants had difficulty narrowing in on the company's terminology and maintenance descriptions. The three-step decision process guided the consultants to use the right terminology and descriptions. This also applies to junior and newly employed maintenance preparers. The three-step decision process acts as a training tool in which employees can observe senior preparers' solutions and choose/modify their work accordingly. For experienced work preparers, the method supports them in delivering more accurate solutions. In addition, if low-quality data are present, the data quality can be corrected.

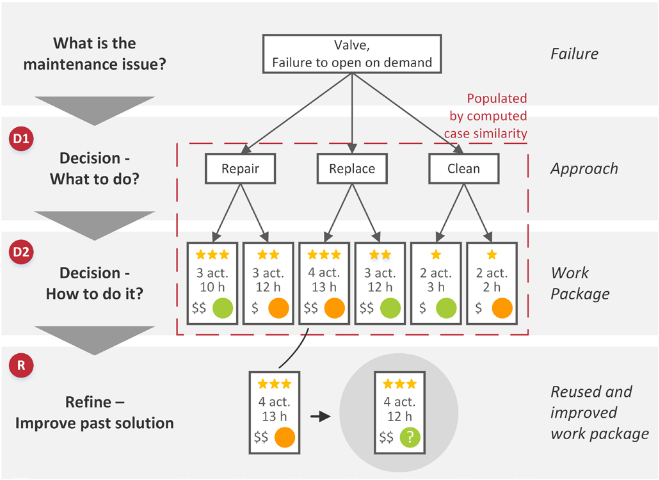


Fig. 8. A simplistic illustration of the three-step decision process used at the case company.

VII. DISCUSSION

This paper proposes a method for the systematic presentation of relevant and actionable information for work preparers. The method benefits from the available information about alternatives and utilizes the characteristics of the data instead of transforming them. The method relies on work preparers to make correct and improved decisions by supporting the decision process. The knowledge base used for the support is continuously updated and improved based on the work preparers' selections. The method does not need rigorous updates of manuals or knowledge bases, as it develops continuously based on experts' behavior. Therefore, continuous improvement is inherent in this method. In addition, unlike some approaches in the literature, the proposed method does not require documentation efforts to bring value. This leads to faster initial implementation. Moreover, existing research does not distinguish between a maintenance approach and a course of action [8], [9], [29]. This is essential for supporting the decision process of work preparers. By using the method, the group of work preparers at the case company became more consistent and more aligned in describing and selecting maintenance activities. Over time, use of the proposed method will decrease non-value-adding variation by making work preparers select the most accurate and best solution alternative.

A. Limitations and Future Research

One of the main assumptions of this method is the reusability of solutions. The dataset used for comparison must be representative of the maintenance conducted on a system. Thus, the most common failures and solutions should have occurred at least once, and they should have been documented. Another assumption is the correctness of the solutions in the dataset; otherwise, work preparers must have the competencies to modify the solution to be correct based on the documented accuracy evaluation. These aspects could be the subject of future studies. Another aspect is unintended use. By using this method, work preparers could risk continuous reuse of low-quality solutions if they are not corrected or evaluated. A feedback loop is essential for selecting the right solutions and improving these solutions. A subject for future studies could be the evaluation of solutions before they are presented to the work preparer. The dataset of previous maintenance cases could be analyzed, and low-quality solutions pre-filtered by senior subject experts. Representing the solutions with standard values could also be the next step in terms of easing the evaluation and selection. Another possibility for future work is to investigate the use of the method, such as which types of solutions are selected for certain types of failures. This could be used to review the actual maintenance carried out compared to tools such as FMEA aimed at ensuring reliability and safety. The discrepancies between behavior and procedures would be interesting to investigate. The inclusion of a governing component in the method to guide or constrain a user's behavior by the standards and company procedures could also be further researched.

VIII. CONCLUSION

This paper presents a three-step decision process for reusing and refining previous maintenance cases for use in current and future failures. The case-based reasoning approach and a structured decision process to mitigate decision difficulty made it possible to find applicable previous maintenance cases and to review their accuracy for reuse. The inclusion of a refinement step in the decision process ensures the improvement of the previous solution based on documented accuracy. In the current body of literature, approaches for single-activity reuse have been found, but not for complete maintenance solutions. Moreover, no approaches for evaluating previous solutions based on accuracy and improving the solution based on how well the maintenance failure was solved previously were found. The decision process in this paper was applied at a case company, and the results show greater employee confidence in the applicability and accuracy of the prepared maintenance work, along with faster preparation. New employee training can also be supported by the use of this decision process. Evaluating the success of previously prepared maintenance ensures continuous improvement. The conclusions are based on use at a single case company and are an indicator of the potential. Future studies should be conducted to investigate the longitudinal effects of the proposed three-step decision process and to thoroughly understand the benefits, potential drawbacks, and prospective research opportunities.

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A.4 Paper D

Title:

An investigation into how modularization principles can be applied to maintenance and commissioning services

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Abstract:

Emerging customer demands for personalized services have led to an increased interest in the application of modular product principles in service systems, termed as 'service modularization'. Despite its potential benefits in cost reduction, enhanced customization, concurrent engineering and faster service development, the domain remains relatively unexplored, with limited empirical studies on the application in service contexts. This research aims to investigate the application of service modularization in maintenance and commissioning services, focusing on whether such services can be modularized, and the resulting benefits. The objective is to facilitate service configuration systems, extending modularization to achieve customization and personalization. A case study approach was adopted, focusing on two cases from industries that have not yet been the focus of service modularity studies. The case studies demonstrated that maintenance and commissioning services can be decomposed into well-defined modules, which can be reused, modified, or replaced in different contexts. These modules are integrated via standardized interfaces, forming an overall service architecture. Service modularization, as demonstrated in maintenance and commissioning services, holds significant potential to improve service design and delivery. The modular approach facilitates cost reduction, customization, and variety in services, enables external collaboration and outsourcing, increases flexibility and responsiveness, and simplifies complex service systems. Despite the potential benefits, further empirical validation is required, advocating further research on long-term effects and application in diverse service domains. This study underscores the potential of service modularization to enhance service design and delivery.

An investigation into how modularization principles can be applied to maintenance and commissioning services

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Abstract

Emerging customer demands for personalized services have led to an increased interest in the application of modular product principles in service systems, termed as 'service modularization'. Despite its potential benefits in cost reduction, enhanced customization, concurrent engineering and faster service development, the domain remains relatively unexplored, with limited empirical studies on the application in service contexts. This research aims to investigate the application of service modularization in maintenance and commissioning services, focusing on whether such services can be modularized, and the resulting benefits. The objective is to facilitate service configuration systems, extending modularization to achieve customization and personalization. A case study approach was adopted, focusing on two cases from industries that have not yet been the focus of service modularity studies. The case studies demonstrated that maintenance and commissioning services can be decomposed into well-defined modules, which can be reused, modified, or replaced in different contexts. These modules are integrated via standardized interfaces, forming an overall service architecture. Service modularization, as demonstrated in maintenance and commissioning services, holds significant potential to improve service design and delivery. The modular approach facilitates cost reduction, customization, and variety in services, enables external collaboration and outsourcing, increases flexibility and responsiveness, and simplifies complex service systems. Despite the potential benefits, further empirical validation is required, advocating further research on long-term effects and application in diverse service domains. This study underscores the potential of service modularization to enhance service design and delivery.

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1 Introduction

Numerous companies have adopted mass customization strategies to satisfy growing demand for personalized products. These strategies aim to balance the flexibility and personalization of bespoke products with the cost efficiency associated with mass production. Modular product architectures play a crucial role in realizing mass customization by decomposing products into modules and managing their interactions (Jiao et al., 2007). Modules can be mass-produced and combined to meet specific customer needs. In the service domain, customers seek services tailored to their specific needs. This growing interest in customized services has prompted the question of whether modular product principles and theories can be applied to service systems and if the application of service modularity can yield similar benefits to those observed for products (Bask et al., 2010).

Modular services, as first proposed around the turn of the century (Baldwin and Clark, 1997; Sundbo, 2002), has gained some momentum in research (Bask et al., 2010; Dörbecker and Böhmann, 2013), and companies have begun to use modular service strategies in their service designs (Cheng and Shiu, 2016). Nevertheless, the research area remains relatively unexplored, common nomenclature is yet to be established, and literature on the subject is limited (Bask et al., 2010; Brax et al., 2017; de Mattos et al., 2021; Iman, 2016; Pekkarinen and Ulkuniemi, 2008).

Service modularization has been associated with several benefits, such as cost reduction, faster development and implementation of new services, complexity reductions, customization, personalization, and support of structured innovations (Brax et al., 2017; Dörbecker and Böhmann, 2015). Here, customization and personalization are among the key benefits expected from modularity (Bask et al., 2011; Brax et al., 2017; de Blok et al., 2010a; Moon et al., 2010; Silvestro and Lustrato, 2015). However, much of the existing research on services has addressed the benefits on a conceptual and theoretical level, rather than provided qualitative data on the application of modularity in a service context (Dörbecker and Böhmann, 2013). Modularity and configuration enable concurrent engineering to be an approach to coordinate development activities across multiple domains and departments (Prasad, 1996, 1997; Stjepandić et al., 2015). The concurrent development of different modules is facilitated by the decoupling of modules and freezing of interfaces, leading to significant time savings through the parallel development of modules (Prasad, 1999; Stjepandić et al., 2015).

This study aims to investigate the application of service modularization in maintenance and commissioning services through two cases from industries that have not yet been the focus of service modularity studies. The goal is to facilitate service configuration systems, extending modularization to achieve customization and personalization. Configuration refers to expert systems that are used to configure customized services for different customers while also preventing unfeasible configurations by using service modules with predefined interfaces and configuration rules incorporated into the knowledge bases of those systems (Mueller et al., 2022; Myrodia et al., 2017; Zhang, 2014).

Researchers have argued that a modular service knowledge structure is necessary for successful configuration (Aldanondo and Vareilles, 2008; Hellström et al., 2016; Liu and Xu, 2009).

This leads to the following research question: *How can existing modularization concepts, such as modules, interfaces, decomposition, and architectures, be applied in the configuration of maintenance and commissioning services?*

By addressing this question and enhancing understanding of modular service design and its application in service configuration, this study seeks to uncover insights that can guide the successful application of service modularization. Specifically, the aim is to determine whether maintenance and commissioning services can be modularized, whether customization and personalization benefits can be achieved, and if there are additional benefits to be gained. By exploring modularization in these less-studied areas, this study aims to contribute to the existing body of knowledge and provide applicable insights for researchers and practitioners alike.

The remainder of the paper is structured as follows. First, the research method is presented. A brief overview of the potential benefits of service modularization follows. Next, the concepts of modularization are investigated. The application of modularization in maintenance and commissioning services is demonstrated in two case studies. Subsequently, an evaluation of the case studies in relation to the potential benefits is presented. Lastly, the paper concludes with a discussion and conclusions.

2 Research Method

The field of service modularity research is relatively young, and there is still no uniform perspective and paradigm of service modularity (Iman, 2016). In areas where research and theory are in their formative stages, case studies are a valuable approach (Benbasat et al., 1987; Voss et al., 2002). Therefore, a case research approach was chosen for this study. A challenge in service modularity is the heterogeneity of the industries and the contexts in which the concepts can be applied (Brax et al., 2017). Healthcare, logistics, finance, electronic commerce, automotive, information and communications technology, and sea cruises are examples of industries that have been researched. The design of complex services depends heavily on contextual conditions and cannot be investigated separately from such services' environments, a situation that Yin (2011) considered to be most appropriate for case research implementation. This study focuses on two cases from industries that have not yet been the focus of service modularity studies, namely offshore maintenance and plant commissioning. The intent is to examine their existing services in the context of service modularization. Table 1 provides the main characteristics of the existing services of the two case companies, and more detailed information can be found in the case studies in Section 6.

Table 1. Characteristics of the case companies and the services they offer

Characteristic	Case company A	Case company B
Sector	Offshore oil and gas production	Processing technology for the chemical, pharmaceutical, and food industries
Employees	1500	1000
Type of service	Maintenance	Plant commissioning
Typical service duration	1 hour to 2 weeks	2 months to 1 year
Approx. number of entities in one service offering	10–20	100–200
Approx. number of service deliveries per year	8000	4

2.1 Data collection and analysis

Service planning documentation (project plans, milestone diagrams) and enterprise resource planning systems were utilized to collect historical service design data. The collected data were analyzed and used as input for discussions during workshops pertaining to the application of service modularization. Knowledge and expertise regarding the services subject to modularization were gathered from company experts during the workshops. Furthermore, semi-structured expert interviews were conducted in both case companies to evaluate the usefulness of the modular service designs that had been created. The data collection process for this study is presented in Table 2. In addition, the design of the new modular service architectures has been compared to historical service designs.

Table 2. Data collection in the case studies

Data collection method	Personal observations during meetings and workshops		Semi-structured expert interviews	
Case company	Case company A	Case company B	Case company A	Case company B
Attendees	2 maintenance engineers	1 commissioning manager 3 commissioning engineers 1 project manager 1 installation manager 1 site execution manager	2 maintenance leads 3 maintenance engineers 2 maintenance preparers	1 head of project execution 1 digitalization manager 1 commissioning manager 1 project planner 2 project managers 1 installation manager 1 site execution manager
Duration	7 meetings/ workshops (30–120 min each)	16 meetings/ workshops (30–90 min each)	10 interviews (30–90 min each)	5 interviews (60–90 min each)

3 Brief overview of the potential benefits of service modularization

Claims have been made regarding the positive impact of modularity in services and service delivery processes, yet rigorous research of this area has been found to be limited (Brax et al., 2017). Researchers often discuss the general benefits and risks of modularity, but they do have not specifically addressed its application to services (Dörbecker and Böhmann, 2013). For this study, the research and literature review conducted by Dörbecker and Böhmann (2013, 2015) on the relevant benefits and effects of service modularity have been adapted and summarized in Table 3. The benefits related to service innovation and new service development have been omitted, since they are outside the scope of this study, which focuses on modularizing existing services. In Table 3 Dörbecker and Böhmann's (2013, 2015) findings have been structured around the benefits and the means by which they can be achieved through service modularity. Most of the identified benefits and effects are on a conceptual and theoretical level (e.g., directly derived from product modularization) and stem from different industries and for different applications, such as services in elderly care, B2B, logistics, and ICT. It is unclear whether these benefits are generalizable or exhaustive and whether there are other benefits. This study explores the benefits identified in the literature through the application of modularization for maintenance services and commissioning services. Additionally, the research explores whether the inherent benefits will be sustained when service modularization is employed with the primary objective of integrating a modular service design into configuration systems. In general, service modularization enables configuration (i.e., reuse and substitution of modules), while the application of configuration systems facilitates the realization of certain benefits (i.e., offering customized services to a multitude of customers).

Table 3. The benefits of service modularity adapted from the research and literature review by Dörbecker and Böhmann (2013, 2015)

Benefits	Clarification	Means
Cost reduction and profitability	- Standardization: Modularity helps standardize service production, leading to better customer value and profitability (Pekkarinen and Ulkuniemi, 2008). - Reducing effort: Modularity can reduce effort in service development and delivery (Böttcher and Klingner, 2011). - Utilization: Services can be used for multiple clients or client groups (de Blok et al., 2010b).	- Reducing service variations: A large number of service variations can be effectively reduced (de Blok et al., 2010b). - Reusing modules: Modules can be reused within and across different services, leading to economies of scale (Dörbecker and Böhmann, 2015).
Customization and variety of services	- Offering differentiated service packages (de Blok et al., 2010b) - Modules can be combined to satisfy different customers (Lin and Pekkarinen, 2011). - Customization for customers and markets: Modularity allows for greater ability to customize for different market segments and customers (Pekkarinen and Ulkuniemi, 2008). - Reusing and combining standardized services: Standardized services can be reused and combined to fulfill diverse needs (Pekkarinen and Ulkuniemi, 2008). - Broadening the scope of services: Services' scope can be broadened, providing more solutions (Rahikka et al., 2011). - Balancing standardization and customization: Service providers can benefit from standardization without losing the ability to customize (Rahikka et al., 2011).	- Flexible services: Services can be combined for customers in many ways from one or several distinct components (de Blok et al., 2010b). - Sharing across clients: Services can be used for multiple clients or client groups (de Blok et al., 2010b). - Reintegrating existing modules: Services have the ability to reintegrate existing modules to satisfy the customer (Lin et al., 2010). - Easy reuse and composition: Modular services can be easily reused in different contexts and composed to satisfy new requirements (Kazemi et al., 2011). - Reconfiguring customer-specific needs: Modules can be reconfigured to meet customer-specific requirements (Dörbecker and Böhmann, 2015).
External collaboration and outsourcing	- Integrating or replacing partners, business services, and software modules: Modules can be integrated and replaced using a variety of sourcing options (Bask et al., 2010).	- Functionality packaging: Service modules enable functionality packaging (Bask et al., 2011). - Flexibility within module elements: Elements within modules can be altered without affecting overall interfaces (Bask et al., 2010).
Increase in flexibility and responsiveness	- Quick and customized product/service offerings become possible (Ho et al., 2009). - Flexibility in the service offering creates value for the customer (Rahikka et al., 2011).	- Adaptation and fine-tuning: Adaptation and fine-tuning of components allow for adjustments in content, time span, moment and place of delivery, required aiding devices, materials, etc. (de Blok et al., 2010b). - Simplifying maintenance: Modularity in services prevents changes from propagating to other services, thereby simplifying the maintenance of service systems (Kazemi et al., 2011).
Simplification of complex system	- Complexity reduction: Modularity reduces complexity in service and process design through simplification and rationalization (Böttcher and Klingner, 2011; Langlois, 2002). - Improved transparency of services (Böttcher and Klingner, 2011)	- Partitioning: Modules only contain part of the resources and processes of a service (Dörbecker and Böhmann, 2015).

4 Process and service configurators

The application of configuration systems in various industries has resulted in numerous advantages, including improved variant generation, heightened efficiency, reduced resource consumption, reduced lead times, and optimized products (Ardissono et al., 2003; Hvam et al., 2008, 2013; Kristjansdottir, Shafiee, Hvam, Bonev, et al., 2018; Kristjansdottir, Shafiee, Hvam, Forza, et al., 2018). These systems also facilitate both knowledge preservation and consolidation within organizations, promote better understanding of the implications of non-standard customization, and improve product and process quality through accurate specifications (Ardissono et al., 2003; Haug et al., 2019; Hvam et al., 2013; Johnsen and Hvam, 2019; Kristjansdottir, Shafiee, Hvam, Bonev, et al., 2018; Kristjansdottir, Shafiee, Hvam, Forza, et al., 2018). Configuration, like service modularization, originates from the product domain. A key difference between product and service configuration is the analysis and modeling of the knowledge base, which allows for the adaptation of the configuration task to specific service characteristics (Mueller et al., 2022).

Service can be viewed as a process (Carlborg and Kindström, 2014; Guillon et al., 2021). A process can be defined as a partially ordered set of activities, ordering constraints, and information exchanges between activities that create value by transforming an input into a more valuable output (Cao et al., 2006; Ciuksys and Caplinskas, 2007). This definition fits with the services provided by the case companies examined in this study. Numerous studies have investigated various aspects of service and process configuration. Hellström et al. (2016) identified the following three primary design criteria for a service configurator: (1) addressing a specific problem, (2) considering uncertainty and the co-creative nature of services, and (3) basing the service configurator on a modular service architecture. Besides Hellström et al. (2016), other researchers have highlighted the importance of modular service design and structure as a requirement for successful configuration (Aldanondo and Vareilles, 2008; Hellström et al., 2016; Liu and Xu, 2009). Service configuration generally requires three types of information: the context (including market state, customer profiles, company state, and stakeholder requirements), the technical solution (or the service itself), and the delivery process (Guillon et al., 2021). The intangibility of services necessitates incorporating the requirement to include the service delivery process in the configuration problem (Edvardsson et al., 2005; Guillon et al., 2021; Lovelock and Gummesson, 2004).

Based on an analysis of the service or process domain, a feature model can be developed that describes the variability and commonalities within a family of services or processes (Ciuksys and Caplinskas, 2007). This model creates the knowledge base for a configuration tool and should consist of a set of operations, required resources for the service delivery, and various constraints, such as the execution order of the included activities and stakeholder- and environment-related constraints (Aldanondo and Vareilles, 2008; Ciuksys and Caplinskas, 2007; Tiihonen et al., 2014). The primary distinction of this from product configuration problems lies in the need to model the stakeholders, environment, and service delivery process in the configurator's knowledge base (Tiihonen et al., 2014). However, this presents challenges due to the vast number of complex variabilities, particularly for large-size models (Asadi et al., 2014).

Moreover, services often involve many soft or human interfaces, necessitating the incorporation of flexible or soft constraints in the knowledge base. This aspect has further complicated the creation of fixed modules, compared to products (Bask et al., 2010), and may contradict the relative rigidity of modular architectures (Henderson and Clark, 1990).

5 Investigation of service modularization

The field of service modularization encompasses many terms and definitions, and there is still no uniform perspective or paradigm for service modularity (Iman, 2016). In this section, an attempt is made to navigate and cover the most widely agreed-upon aspects, which can also be examined in the case studies.

Service modularity is derived from architectural thinking in the product and process research domains (Brax et al., 2017; de Mattos et al., 2021; Voss and Hsuan, 2009). It can be described as activities (or a set of activities) that are part of interactions among a service system's components (Carlborg and Kindström, 2014; Iman, 2016). Modularity is concerned with decomposing a system into independent modules as standalone logical units with defined interfaces between them (Jiao et al., 2003). The concept of service architectures involves defining system boundaries and the modular structure of a system, including the decomposition of modules, interfaces, and resources (de Mattos et al., 2021; Tuunanen et al., 2012). In the current body of service literature, the concepts of modularity and architectures are intertwined, and most service architecture definitions are inherently modular (de Mattos et al., 2021; Tuunanen et al., 2012; Voss and Hsuan, 2009).

Voss and Hsuan (2009) used concepts from systems engineering and proposed a framework for service architectures whereby "*the functionalities of the service system are decomposed into individual functional elements to provide the overall services delivered by the system*." The authors conceptualized the service system as a network of nodes (i.e., modules or components) and linkages (i.e., interfaces) by taking a systemic view of service design. This enabled the overall system function to be broken down into service modules carrying individual functions and the interfaces among them.

Peters and Leimeister (2013) developed an approach for modularizing formerly integral services that consisted of five phases. Their method included an analysis of the current service and its decomposition, module creation, interface specification, and testing. However, no details were presented regarding the actual definition of modules and interfaces and their connection to service architectures. Similar to Peters and Leimeister (2013), Geum et al. (2012) proposed a matrix-based approach for identifying and defining modules based on the decomposition of an existing service. By using module drivers and the House of Quality approach, they clustered service elements into module candidates. Despite their detailed description of the identification of a service's modules, their approach lacked a definition for a service architecture that would incorporate those modules. Similarly, Eissens-van der Laan et al. (2016) proposed a three-step approach for decomposing services into individual functionalities and modules. Böttcher and Klingner (2011) defined a modular service as the compositional structure of service modules. In addition to proposing a graph-based composition, they also considered the interdependencies between modules. Here, the procedural characteristics of services are described by temporal interdependencies, while logical interdependencies enable the configuration of a service offering.

Service modularity is viewed as a strategy for designing (or redesigning) services based on a combination of standardized and clearly defined service modules that allow for the configuration and customization of services (de Mattos et al., 2021). The level of standardization of modular services will differ according to the modularization strategies they adopt (Sundbo, 2002; Tuunanen and Cassab, 2011).

This study investigates the analysis and identification of service modules, decompositions, interfaces, and the modular service design of architectures. By examining these aspects, the aim is to provide a comprehensive understanding of service modularization and its implications for the design and implementation of service systems in the context of service configuration. These findings are used and evaluated in the case studies of modularizing maintenance services and commissioning services.

5.1 Service modules

In general, a service module offers a well-defined specific function within a system and has precisely defined standardized interfaces with other modules (Böttcher and Klingner, 2011; Iman, 2016). The service module consists of one or more components that offer service characteristics (Bask et al., 2010). These components or form elements may be processes, people skills, or materials that must be integrated appropriately to result in a designed service (Goldstein et al., 2002). In a recent review, de Mattos et al. (2021) clearly distinguished between service elements/components and service modules. A service element/component, the smallest unit into which a service can be divided, includes processes, operations, people, objects, and/or resources. These elements are grouped based on their characteristics or functionality to form service modules. Whereas a service module consists of a collection of elements or components that can be offered to a client, delivering perceived value by performing a service function, service modules, as summarized in the research by Tuunanen et al. (2012), contain elements of common functions, and new variants can be developed by making major revisions or modifications to their functionality or interface. These modules can be reused as is or with minor revisions in various contexts beyond the original one.

Additionally, a module within a service system can be replaced with another without causing disruption or changes to the service.

5.2 Decomposition

Decomposing the entire service system into modules and interfaces, which in turn deliver the system's functionality, is the core concept behind service modularisation (Simon, 1991). No universally applicable type of decomposition has been found in the literature (Eissens-van der Laan et al., 2016). Voss and Hsuan (2009) proposed four levels of decomposition of service offerings, namely industry, service company, service bundle, and service component, while Moon et al. (2009) decomposed the service system into service families, platforms, modules, and components. According to Tuunanen et al. (2012), decomposition, as summarized from a literature review, refers to the partitioning of information, processes, and services into modules (components, elements, units, nodes). These modules are independent of each other, perform a certain function, and have interfaces for integration.

5.3 Interfaces

An important aspect of any modular system concerns the standardized, stable interfaces between the system's modules, prescribing how multiple elements in a modular system mutually interact and connect (Salvador, 2007; Tuunanen et al., 2012). By describing the behavior of the service system and its modules, the service modules can be mixed and matched to fulfill specific customer requirements (Tuunanen et al., 2012). Decomposition and interfaces enable substitution without disrupting the service offered (Tuunanen et al., 2012), and variants can thus be introduced using a variety of sourcing options (Bask et al., 2011). In the following, the interfaces for a service system are synthesized from existing service modularity publications and summarised in Table 4. Services share many characteristics with processes, including their sequential character (Bask et al., 2010). Therefore, a temporal interface needs to be defined (Böttcher and Klingner, 2011) to capture relations such as *Module A needs to be performed before Module B*. Furthermore, interfaces that specify the flow of information between modules need to be defined, including both soft or human and hard or technical aspects (Bask et al., 2010), resulting in an interface for information or materials. Another important characteristic of services is the co-creation of value between the service provider and external parties, such as the customers or suppliers of the service (Rexfelt et al., 2011; Vargo and Lusch, 2004). The resulting external interface, which describes the flow of information and the resources between the parties involved in the successful delivery of a service module, is therefore essential for the definition of a service system (Carlborg and Kindström, 2014; Pekkarinen and Ulkuniemi, 2008). In particular, the resources required to execute the service modules are of interest to describe the external interface. Depending on the level of involvement of the customer and other parties, such as suppliers, the necessary resource structure may differ (Carlborg and Kindström, 2014). Furthermore, de Blok et al. (2014)

defined internal, closed-customer flow interfaces (e.g., *if Module A is selected to be part of the service offering, Module B needs to be chosen as well*). Böttcher and Klingner (2011) defined a logical interface, capturing similar relations between modules.

Table 4. Interfaces in modular service design

Interface	Definition
Temporal interface	Describes the sequential character of the service
Information or material interface	Describes inputs and outputs between service modules
External interface	Describes the responsibilities of external parties and their impact on the service modules
Logical interface	Describes the impact of module or variant selection on other service modules

5.4 Service architectures

Many researchers, employing various theories and approaches from different fields, have developed frameworks and tools to investigate service architectures (Hyötyläinen and Möller, 2007; Pekkarinen and Ulkuniemi, 2008; Tuunanen et al., 2012; Voss and Hsuan, 2009). In general terms, a modular service architecture facilitates the customization of service offerings and promotes the sharing of service modules between different offerings. Service architectures transcend the modularization of an individual service, allowing for the utilization and reuse of service modules across multiple service offerings (Bohmann et al., 2003; de Mattos et al., 2021; Pekkarinen and Ulkuniemi, 2008). Within this context, architecture refers to the arrangement or structure of functions and their embodiment (Jiao et al., 2007). Thus, service architectures embody the service design, providing a framework for integrating and combining various modules (Bohmann et al., 2003). Service architectures depict the modular structure of the service, including the composition of the modules and their relationships, service interfaces, and boundaries as well as the standards, technologies, and shared or outsourced resources involved (Tuunanen et al., 2012).

6 The application of service modularization in two case studies

In this section, two case studies are presented that aim to highlight the challenges and design choices associated with applying modular service design within maintenance services and commissioning services with the aim of service configuration. The application of service modularization in this operational context is be evaluated, comparing it to the benefits of service modularization outlined in Section 3.

6.1 Case company A – the maintenance company

Case company A is an operator of offshore oil and gas production platforms in the North Sea. The company operates 50 offshore platforms and is responsible for their development, operation, maintenance, and decommissioning. This study focuses on the maintenance of the platforms, which is crucial to ensure productive facilities and the safety of workers and the environment (European Standard, 2017).

The majority of maintenance is provided as an internal service with an onshore department responsible for preparing and planning the maintenance service. This department consists of both permanent and temporary employees, with the latter hired as needed. The varying levels of experience and training among these employees can affect the efficiency and effectiveness of maintenance planning. To address this, the company has ambitions to introduce an approach for structuring and standardizing maintenance services. This will involve formalizing the expert knowledge of permanent senior employees and developing tools for customizing and configuring services for different maintenance contexts. The goal is to improve the quality of maintenance services through both service modularization and configuration, enabling the effective operational implementation of maintenance strategies.

6.1.1 Service modules in the maintenance company

Maintenance refers to the range of actions taken throughout the lifecycle of an item with the intention of preserving or restoring its ability to perform its intended function (European Standard, 2017). Such actions may include cleaning, lubrication, adjustments, calibration, repair, refurbishments, or replacements. Aligned with the discussion in the literature, service modules in the context of maintenance are formed around these actions. Each module incorporates the activities required to perform a given action as well as the necessary service elements to carry out these activities. These service elements can include resources such as people (number, skills, and duration), tools, and spare parts. An example of this is the action of replacing a valve. The replacement requires several activities, such as dismounting the old valve, installing a new one, and testing the newly installed valve. The execution of these activities requires two technicians with mechanical skills for 1–2 hours for each activity as well as the necessary tools and a spare valve (i.e., service elements). These activities and resources form the service module, and this example aligns with the composition of service modules as described by Böttcher and Klingner (2011), Goldstein et al. (2002), and Iman (2016). A service module for valve replacement containing the necessary service elements or components can be seen to deliver value by performing a service function (de Mattos et al., 2021).

Typically, a service that is provided is a combination of multiple service modules. For example, a maintenance service might include erecting scaffolding, isolating equipment, making a replacement, and subsequently testing it. Each of these actions, with the respective activities and resources they require, forms a distinct service module. These service modules can be modified to the given situation and reused across different contexts. For example, replacing an electrical board would require technicians with electrical skills, a modification from the mechanical skills required in valve replacement. Furthermore, the entire service module of replacement can be substituted with a repair or adjustment service module, encapsulating the functionality without altering other modules, such as erecting scaffolds or isolating equipment. This demonstrates the flexibility of service modules in maintenance for reuse, modification, combination, and substitution (Tuunanen et al., 2012) for customization and configuration in different contexts.

6.1.2 Decomposition in the maintenance company

In the case company, the maintenance service can be decomposed into two main types of maintenance, namely corrective and preventive maintenance. Corrective maintenance responds to failures and breakdowns, whereas preventive maintenance seeks to prevent them. Despite the differing objectives, the work performed is similar. For instance, working at height requires scaffolding to be erected, regardless of the maintenance type. However, the structure, decomposition, and elements of these services vary. This analysis focuses on the corrective maintenance program, which the case company primarily aims to modularize and configure. Figure 1 provides a multilevel decomposition of the corrective maintenance program with a selection of the actions, activities and elements.

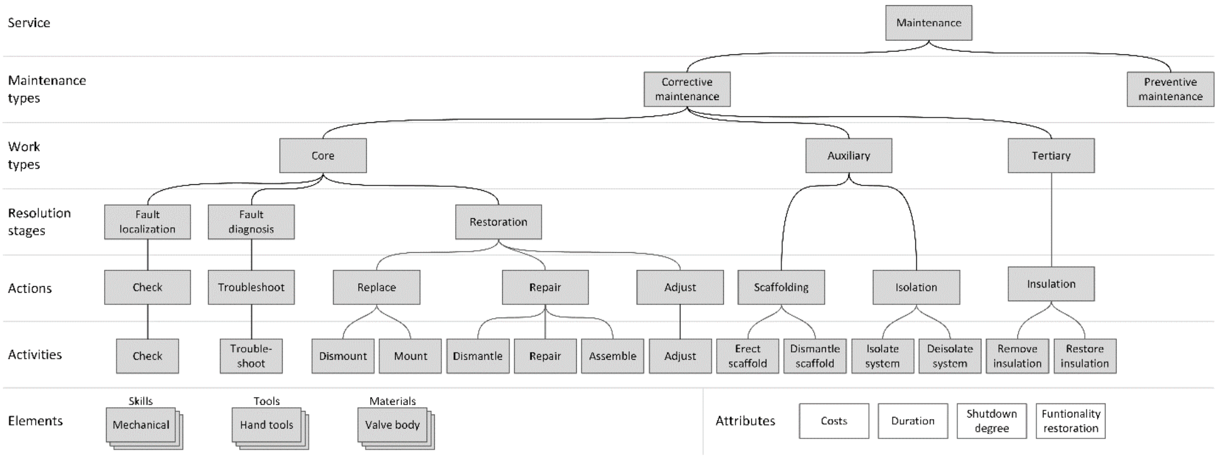
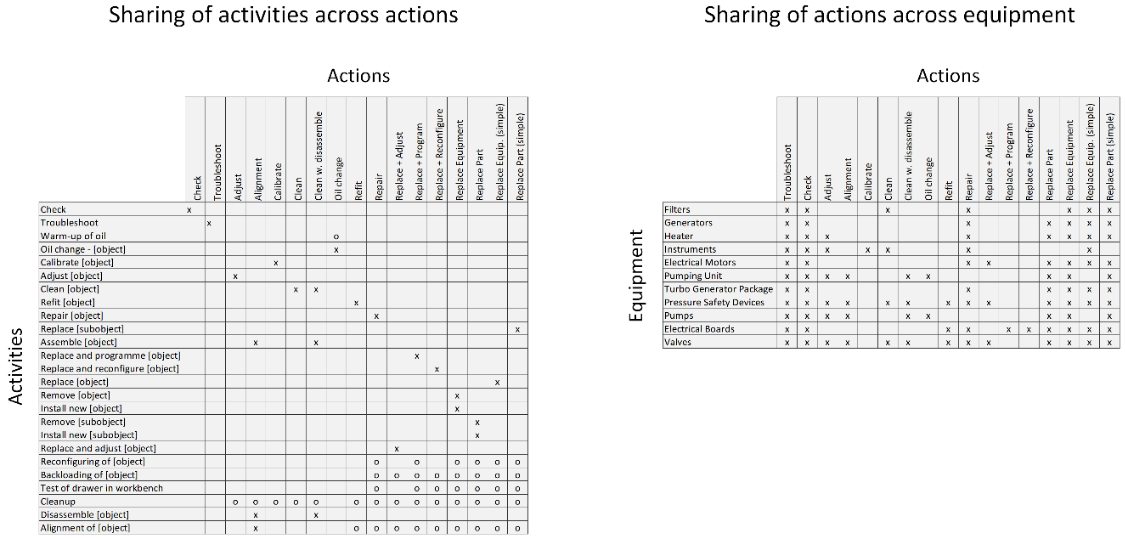


Figure 1. Decomposition of corrective maintenance with a selection of actions, activities and elements.

As illustrated in Figure 1, corrective maintenance encompasses three types of work, namely core, auxiliary, and tertiary work. Core work involves fault localization, fault diagnosis, and restoration of functionality. Auxiliary work supports the core work, such as by setting up scaffolding and isolating the system part for maintenance. Tertiary is secondary work that directly enables the core maintenance, such as removing obstructions. Both auxiliary and tertiary work are prerequisites for the core work, depending on the characteristics of the situation.

Corrective maintenance can be decomposed further into levels of “actions,” “activities,” and “elements.” Actions denote the service being offered, while activities, combined with elements (e.g., skills, tools, and materials), are the combinations required to perform these actions. These combinations form “modules,” each carrying “attributes” such as cost, duration, or shutdown degree.

Historical data from the case company suggests that there had been some inconsistencies in planning corrective maintenance. From 2017 to 2019, 14,057 corrective maintenance services had been planned, encompassing 42,351 activities. Of these activities, 23,667 were distinct variations, indicating a historical lack of formalized reuse and sharing. The introduction of service modularization could substantially reduce this variation. With service modularization, the historical variation can be represented by 37 actions and 61 activities. This entails the sharing of activities across actions and allows for substitution and modification by encapsulating functionality for different contexts (e.g., different types of equipment). Figure 2 illustrates the sharing of activities across actions and the sharing of actions across different equipment types.



Sharing of activities across actions

Actions

Activities	Check	Troubleshoot	Adjust	Alignment	Calibrate	Clean	Clean w. disassemble	Oil change	Refit	Repair	Replace + Adjust	Replace + Program	Replace + Reconfigure	Replace Equipment	Replace Part	Replace Equip. (simple)	Replace Part (simple)
Check	x																
Troubleshoot		x															
Warm-up of oil								o									
Oil change - [object]								x									
Calibrate [object]					x												
Adjust [object]			x														
Clean [object]						x	x										
Refit [object]									x								
Repair [object]										x							
Replace [subobject]																	x
Assemble [object]				x			x										
Replace and programme [object]												x					
Replace and reconfigure [object]													x				
Replace [object]																x	
Remove [object]														x			
Install new [object]														x			
Remove [subobject]															x		
Install new [subobject]															x		
Replace and adjust [object]											x						
Reconfiguring of [object]										o		o		o	o	o	o
Backloading of [object]										o	o	o	o	o	o	o	o
Test of drawer in workbench										o		o	o	o	o	o	o
Cleanup			o	o	o	o	o		o	o	o	o	o	o	o	o	o
Disassemble [object]				x			x										
Alignment of [object]				x					o	o	o	o	o	o	o	o	o

Sharing of actions across equipment

Actions

Equipment	Troubleshoot	Check	Adjust	Alignment	Calibrate	Clean	Clean w. disassemble	Oil change	Refit	Repair	Replace + Adjust	Replace + Program	Replace + Reconfigure	Replace Part	Replace Equipment	Replace Equip. (simple)	Replace Part (simple)
Filters	x	x				x				x					x	x	x
Generators	x	x								x				x	x	x	x
Heater	x	x	x							x				x	x	x	x
Instruments	x	x	x		x	x				x						x	
Electrical Motors	x	x								x	x			x	x	x	x
Pumping Unit	x	x	x	x			x	x						x	x		x
Turbo Generator Package	x	x								x				x	x	x	x
Pressure Safety Devices	x	x	x	x		x	x		x	x	x			x	x	x	x
Pumps	x	x	x	x			x	x						x	x		x
Electrical Boards	x	x							x	x		x	x	x	x	x	x
Valves	x	x	x	x		x	x		x	x	x			x	x	x	x

Figure 2. Sharing within the decomposed structure.

The multi-level decomposition of corrective maintenance enables the effective formation of service modules by providing a manageable structure of decomposed entities and their interfaces.

6.1.3 Interfaces in the maintenance company

The sequential character of maintenance activities is important for the successful delivery and execution of the maintenance service. The process of performing maintenance typically involves three phases, namely preparation, amendment, and closure. The preparation phase includes the activities required for preparing the job site for the core maintenance job, while the amendment phase includes activities to perform the core maintenance job, and the closure phase involves activities for concluding the job and restoring the job site. An example of a maintenance job that illustrates the three phases and interfaces among maintenance activities is presented in Figure 3.

In general, logical interfaces (Böttcher and Klingner, 2011) exist among the maintenance activities, primarily between the activities in the preparation and closure phases, since preparation activities often need to be undone during closure (e.g., erecting and dismantling scaffolding). The amendment phase also has logical interfaces within it, such as disassembling and assembling activities. The temporal interface (Bask et al., 2010; Böttcher and Klingner, 2011), where one activity follows another in sequence, is a crucial interface in maintenance. For example, since scaffolding must be erected before commencing the main work, a temporal interface, such as "Erect scaffold" and "Repair equipment," therefore exists between activities. All activities have temporal interfaces that describe how they interact and connect with each other.

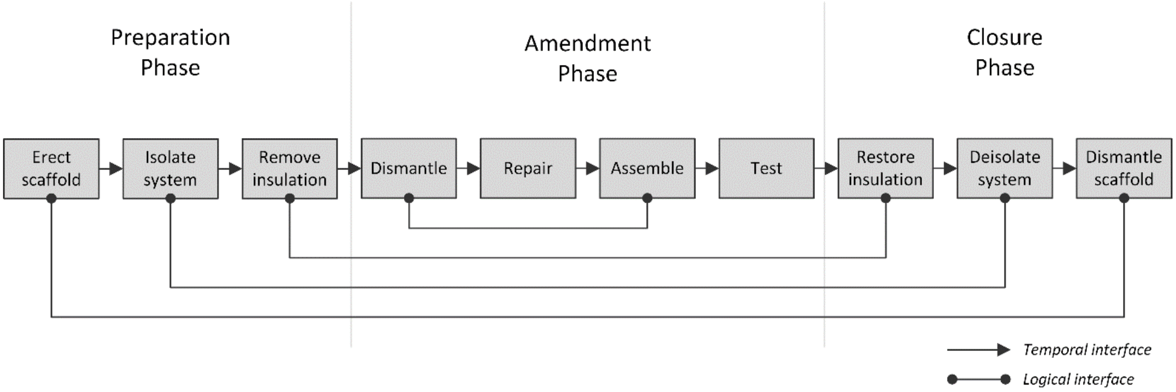


Figure 3. An example of a maintenance job entailing temporal and logical interfaces

Both the logical and temporal interfaces are essential in mapping out the flow and sequence of maintenance activities. However, contrary to the literature findings, this study did not identify any information, material, or external interfaces.

6.1.4 Service architecture in the maintenance company

Creating a visual representation of the entire architecture was found to be challenging due to the complexity of incorporating decomposition, modules, the elements comprising the modules, sharing, reuse (on both module and element levels), and interfaces. This complexity was approached by making individual flow diagrams using the three sequential phases (i.e., outlined in the previous section) for specific equipment types as a framework for integrating and combining modules, as described by Bohmann et al. (2003). However, these diagrams were developed for specific contexts only, not to encompass the entire architecture.

Since service modularization and architecture in this study were intended to be applied in a service configuration setting, a suitable knowledge model and structure were selected to represent it. The architecture can be represented in several tables to be used by a configuration system. The service architecture design model for configuring corrective maintenance in the case company is presented in Figure 4. This model incorporates the scope and boundaries in terms of the applicability of actions for various equipment and their sharing. It also describes the service modules in terms of activities and service elements, including the reuse of these. Additionally, the model describes the relationship between activities (i.e., interfaces).

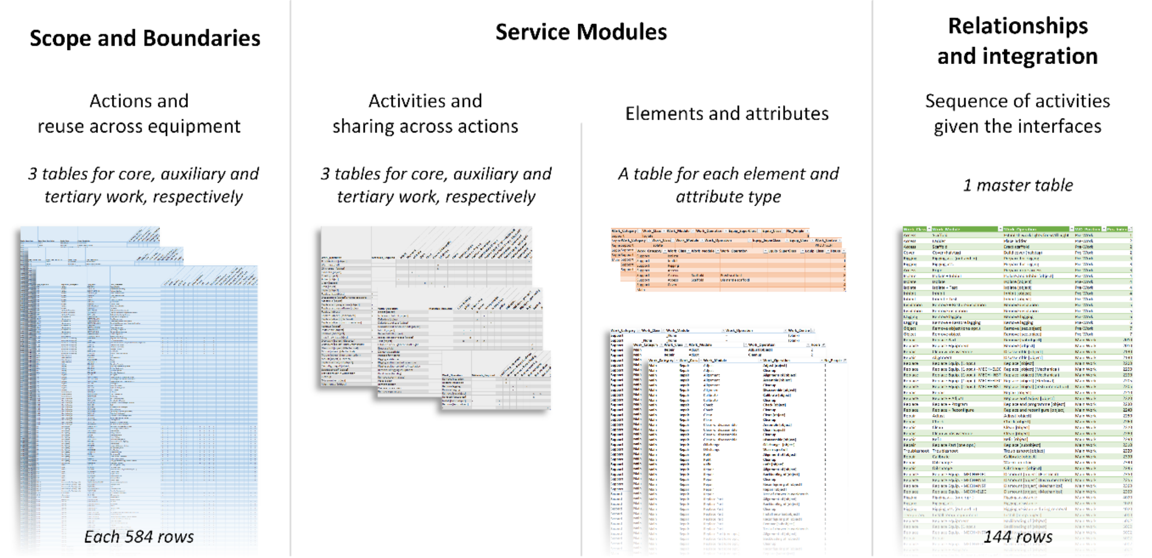


Figure 4. Architecture of corrective maintenance for configuration

6.2 Case company B – the commissioning company

Case company B designs and implements processing plants tailored to the unique needs of customers in the pharmaceutical, chemical, and food industries. As part of the product development process, the case company offers a commissioning service to its customers. ‘Commissioning services’ refers to the process of converting a newly built or rebuilt facility into an operational unit while ensuring its safety and performance. This involves testing installed equipment, initial start-up, and troubleshooting of the newly built plant. Given the unique character of each developed plant, the corresponding commissioning service also has a distinctive design. The past experience of the case company has shown many challenges, including insufficient specification of the commissioning services, insufficient oversight of future commissioning needs and resource allocation during the early project planning phase, and the need to gather knowledge from numerous experts for the design of each commissioning service.

To enhance performance and enable learning effects, the company is seeking to introduce a standardized, modular approach for configuring commissioning services. Furthermore, the application of configuration systems is being considered to automate the customization and configuration based on specific product specifications (i.e., the design of the processing plant).

6.2.1 Service modules in the commissioning company

In the case company, the definition of commissioning services involves identifying the necessary commissioning activities, determining the required resources and time for each activity, and establishing the most effective and efficient order for their execution. Based on this, each commissioning activity was modeled as a distinct module with a clearly defined purpose and interfaces and attributes such as resources and durations. This approach is consistent with previous research (Bask et al., 2010; Böttcher and Klingner, 2011; Goldstein et al., 2002; Iman, 2016). Specifically, the "resource" attribute encompasses the number of resources required and their roles, and the "duration" attribute describes the estimated time required for the delivery of the commissioning activity in hours or working days.

Unlike the case of the maintenance services, predetermined variants of the service modules were established to serve as catalog alternatives that would cater to varying service requirements, as noted in previous research by Tuunanen et al. (2012). These variants differ primarily in the resources and durations they require. For example, the I/O testing of a valve may necessitate different personnel (i.e., resources) or a different amount of time (i.e., duration), depending on the type of valve or accessibility.

6.2.2 Decomposition in the commissioning company

The commissioning service can be decomposed into three phases, namely installation qualification (IQ), operation qualification (OQ), and process qualification (PQ). The IQ phase can be decomposed further into different plant subsystems that include different testing procedures, such as I/O tests and pressure tests, depending on the subsystem. For instance, including a pressure test of a valve may only be necessary if a particular valve type requires it and is part of the system design, and the time and resource allocation depend on the number of valves to service, their location, and accessibility. Figure 5 illustrates a simplified section of the modeled installation qualification phase, including the decomposition, modules, variants, and interfaces.

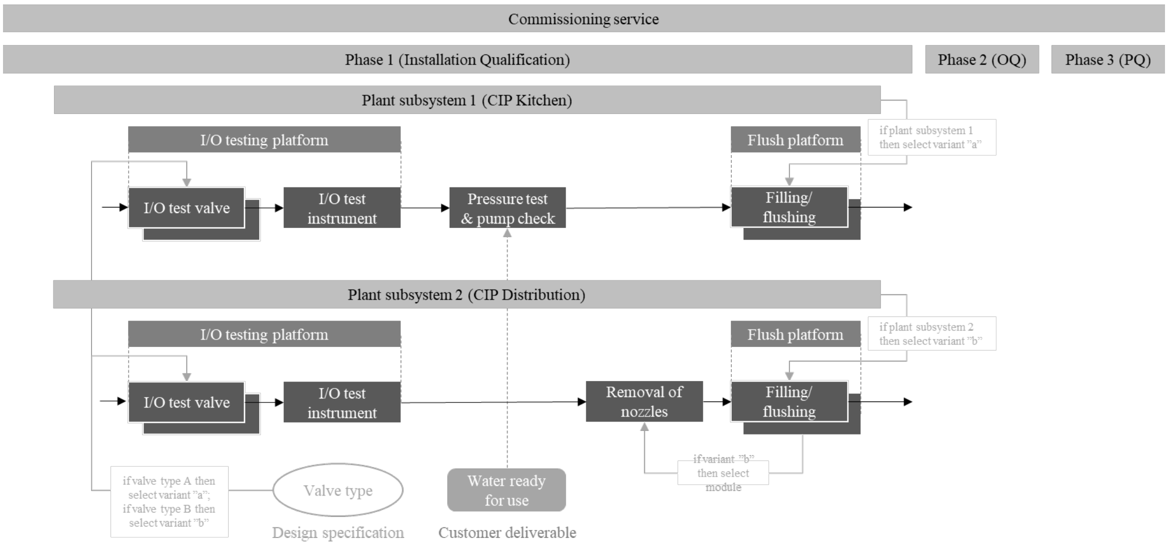


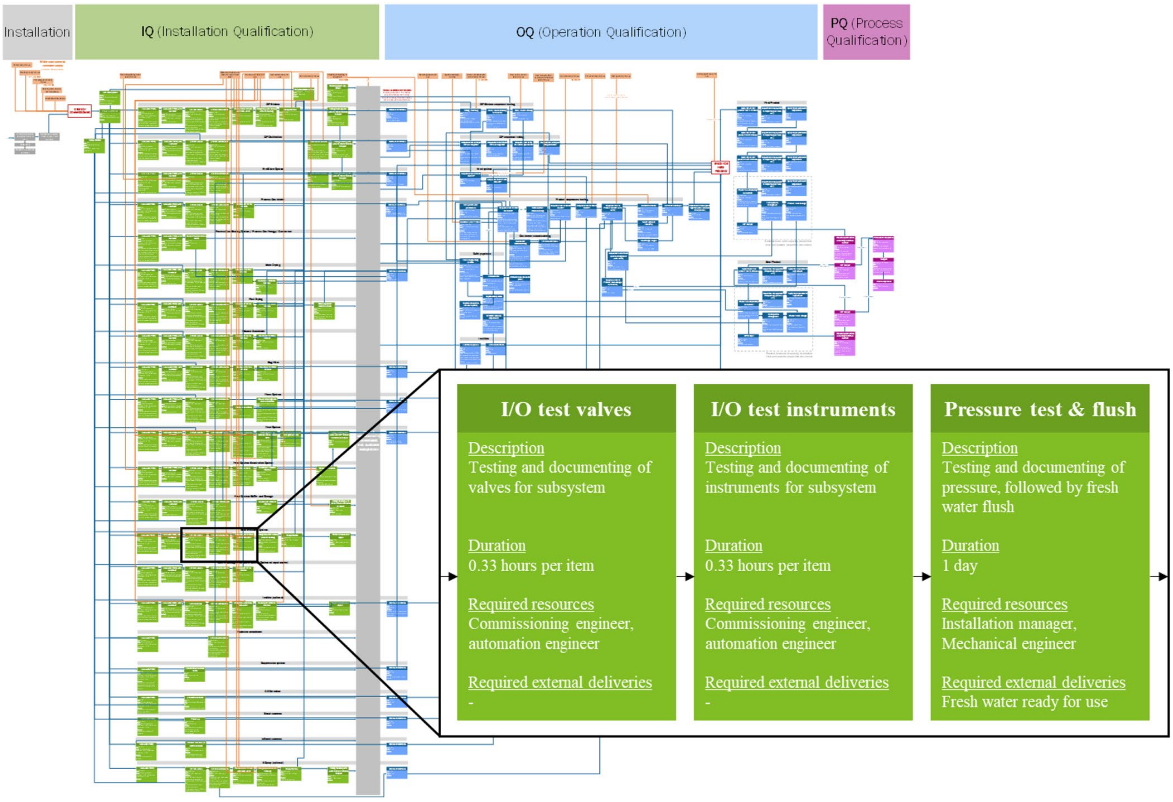
Figure 5. Simplified illustration of a section of the installation qualification phase of the commissioning service

6.2.3 Interfaces in the commissioning company

Commissioning service design includes logical, temporal, and external interfaces. In terms of the logical interfaces, some service modules or variants require the inclusion of others, as seen in Figure 5. Temporal interfaces define the execution order of modules. For each module, interfaces are modeled as lists of modules that need to be executed before or after the present module. These lists range from one to 36 modules as predecessors or successors. External interfaces were are defined, given that the case company usually provides the processing equipment of a new facility, while other contractors or service customers are responsible for the erection of a building and the supply of utilities. This entails external interfaces; for example, as seen in Figure 5, customers ensure water supply before pressure testing can be performed. Additionally, interfaces between modules and product specifications are defined. These specify the inclusion of modules in service offerings based on the existence of a certain product specification, such as the inclusion of an “I/O test valve” if a valve is included in the product specification. Furthermore, the estimated duration of the I/O test valve module should be calculated based on the number of valves in the product design.

6.2.4 Service architectures in the commissioning company

Figure 6 presents a visual model of the entire architecture that is structured around the three phases of IQ, OQ, and PQ. The model depicts the service modules, variants, and interfaces and includes the last few activities of the preceding installation phase to provide details of the transition to commissioning. While the use of static module variants makes the model easier to visualize, some modularization perspectives, such as sharing and reuse, have been omitted. The inset of Figure 6 shows three different variants of service modules with descriptions of activities, duration, and required resources.



I/O test valves

Description
Testing and documenting of valves for subsystem

Duration
0.33 hours per item

Required resources
Commissioning engineer, automation engineer

Required external deliveries
-

I/O test instruments

Description
Testing and documenting of instruments for subsystem

Duration
0.33 hours per item

Required resources
Commissioning engineer, automation engineer

Required external deliveries
-

Pressure test & flush

Description
Testing and documenting of pressure, followed by fresh water flush

Duration
1 day

Required resources
Installation manager, Mechanical engineer

Required external deliveries
Fresh water ready for use

Figure 6. The visual representation model of the service architecture of commissioning services (Mueller et al., 2022)

A total of 204 services module variants are formulated with 20 additional external modules defined for customer deliveries that are required for commissioning service delivery. These external modules depict the value co-creation between the commissioning provider and the customer and include deliveries such as on-site water and electricity provision and equipment cleaning before commissioning. Interfaces and attributes are represented as rules and constraints, consisting of both soft constraints that can be overridden and hard constraints that are fixed. Overall, there are 5603 soft and 5382 hard constraints. Hard constraints include module requirements and plant design information, while soft constraints cover default selections, durations, and resource allocations. As in the maintenance case, the visual representation of the architecture has been converted into a tabular format to serve as a knowledge base for the configuration software. More details on the approach for configuring commissioning services can be found in Mueller et al. (2022).

The case company offers an average of four commissioning services per year to its customers. Looking into the historical service offerings to compare them to the modularized service, four were chosen that had been executed around the same time between 2014 and 2018. However, the company's previous unsystematic approach to service design resulted in significant differences in structure and nomenclature between the phases of OQ and PQ, respectively, of the historical services, making direct comparisons challenging. As a result, the comparison of the newly developed architecture and the historical set of services is limited to the IQ phase of the commissioning services. However, the IQ phase of the modular architecture consists of 31 distinct service modules. In comparison with the 22 to 26 distinct modules of each historical service, it appears that the level of complexity did not improve by applying modular architecture. However, across all four historical services, the total sum of distinct modules was 55. This suggests that the introduction of a modular service design reduces the complexity significantly if it is being utilized for the generation of multiple service offerings.

7 Evaluation of the application of modularization for maintenance and commissioning services

The findings from the two case studies have been summarized in relation to the aspects of service modularization covered in the literature, and a summary is presented in Table 5.

Table 5. Summary of case study findings in relation to the literature

Literature	**Case Company A**	**Case Company B**
Service	**Maintenance services**	**Commissioning services**
Service Module		
- Well-defined specific function	- Maintenance service modules are formed around specific maintenance actions (e.g., valve replacement).	- Commissioning service modules are distinct with defined purposes, interfaces, and attributes.
- Consists of elements/components	- Reconfigurable elements include activities (e.g., dismount, mount) and resources (e.g., people, tools, spare parts).	- The elements are the necessary commissioning activities, the required resources, and time for each activity.
- Can be reused, modified, and replaced for different contexts	- Service modules and elements can be modified, combined, and substituted in different contexts.	- Predetermined variants for varying service requirements
Decomposition		
- Partitioning of information, processes, and services into modules	- Decomposed into corrective and preventive maintenance - Corrective maintenance is partitioned into core, auxiliary, and tertiary work.	- Decomposed into installation qualification, operation qualification, and process qualification phases
- Levels of decomposition	- Decomposed into levels: actions, activities and elements	- Each phase has its own modules and decomposition structure.
Interfaces		
- Standardized, stable interfaces between modules	- Logical and temporal interfaces are crucial in maintenance (e.g., erecting scaffolding before commencing the main work, then dismantling it).	- Logical, temporal, and external and interfaces with product specifications

- Enable substitution without disrupting the entire service	- Interfaces describe how activities interact and connect; this allows for mix-and-matching modules (e.g., adding auxiliary and tertiary work when needed).	- Constraints and rules for configuring modules
Service Architecture		
- Framework for integrating and combining modules	- Visual representation of architecture challenging - Flow diagrams used for specific contexts - Service architecture represented in tables for the configuration system	- Visual representation of architecture structured around the decomposed commissioning phases - Transformed into tabular format for the configuration system

The findings of case studies A and B fulfill the design criteria and requirements for a service configurator, as outlined in the literature. Specific problems within their respective service domains were addressed (Hellström et al., 2016), uncertainty and the co-creative nature of services were considered (Aldanondo and Vareilles, 2008; Hellström et al., 2016; Liu and Xu, 2009), and the approaches were based on modular service designs (Aldanondo and Vareilles, 2008; Hellström et al., 2016; Liu and Xu, 2009). Both case studies emphasize the importance of modular service design structures and the incorporation of context, technical solutions, and the service delivery process (Edvardsson et al., 2005; Guillon et al., 2021; Hellström et al., 2016; Lovelock and Gummesson, 2004). Overall, these case studies demonstrate the applicability of service modularization for configuration. In the following, the potential benefits, as described in Section 3, are evaluated using the case studies.

7.1 Cost reduction and profitability

The application of a modular approach demonstrates the potential for cost reduction through the reuse and sharing of service modules. In the case of maintenance services, historical data show that there has been a lack of formalized reuse and sharing, resulting in a large number of distinct variations in maintenance activities. With service modularization, the historical variation can be substantially reduced, standardized, and reused, potentially leading to better customer value and profitability (Pekkarinen and Ulkuniemi, 2008), improved service utilization for multiple clients (de Blok et al., 2010b), and enabling economies of scale (Dörbecker and Böhmann, 2015). The same is the case for commissioning services where the establishment of activities as distinct modules with clearly defined purposes, interfaces, and attributes facilitates standardization and reusability. The prospect of decoupling the activities allows for concurrent engineering to decrease lead time (Prasad, 1999).

7.2 Customization and variety of services

The application of modularization for maintenance services enables a high degree of customization and service variety, as posited in the literature (de Blok et al., 2010b; Pekkarinen and Ulkuniemi, 2008). Service modules can be modified, combined, or substituted to accommodate different contexts, thereby addressing a broad scope of maintenance needs. For commissioning services, predetermined variants of the service modules are utilized, which cater to varying service requirements. The predefined variants allow for flexibility in adapting the commissioning services to specific plant requirements, such as different equipment types or accessibility constraints. The flexibility enables standardization and customization balance (Rahikka et al., 2011), adaptation to customer-specific needs (Dörbecker and Böhmann, 2015), and the opportunity to easily reuse and reconfigure modules (Kazemi et al., 2011).

7.3 External collaboration and outsourcing

The modularization of maintenance services allows for functionality packaging and flexibility within the module elements (Bask et al., 2010, 2011). These aspects create opportunities for collaboration with external partners and outsourcing of specific modules or services. For commissioning services, the definition of external interfaces reflects a key aspect of external collaboration and outsourcing, thereby enabling these. The company also facilitates value co-creation with its customers by defining the need for customer deliveries, such as on-site water and electricity provision.

7.4 Increase in flexibility and responsiveness

For maintenance services, the ability to adapt and fine-tune services in terms of actions, activities, and elements, and the combination of these, enables quick adaptation to diverse maintenance requirements, aligning with the recognition in the literature of the flexibility and responsiveness of modular systems (Ho et al., 2009; Kazemi et al., 2011; Rahikka et al., 2011). The modularization of commissioning services in the case company potentially increases flexibility and responsiveness. The predefined service module variants and their interfaces enable the quick and efficient customization of service offerings based on specific product specifications. This flexibility allows the case company to respond rapidly to customer requirements and changes in project scope. Moreover, the modular nature of the commissioning services allows for easy reconfiguration and adjustment during the project execution phase.

7.5 Simplification of complex systems

Both cases have effectively applied the principles of modularity to simplify a complex maintenance service system. The multi-level decomposition, along with the identification of modules and interfaces, has provided a clear, manageable structure. This aligns with the assertion in the literature that modularity reduces complexity and improves transparency in service and process design (Böttcher and Klingner, 2011; Langlois, 2002).

The case studies of both the maintenance company (Case Company A) and the commissioning company (Case Company B) exemplify the successful application of modularization and highlight the potential advantages of implementing modularization concepts in service configuration. The benefits, as suggested by both cases, can include cost reduction, service customization and variety, enhanced opportunities for external collaboration and outsourcing, increased flexibility and responsiveness, and the simplification of complex systems. Despite these potential advantages, the actual realization of these benefits post-implementation requires empirical validation. Further research is recommended to explore additional aspects of modularity, such as the role of external interfaces and the full potential of external collaboration and outsourcing.

8 Discussion and conclusion

The aim of this study is to provide insights that can guide the successful application of service modularization for researchers and practitioners alike. This section discusses the implications for researchers and practitioners and suggests directions for future research.

8.1 Implications for researchers

Research in the field of service modularity is characterized by a lack of empirical studies, especially outside traditional domains, such as healthcare, logistics, IT-related services, and financial services (Brax et al., 2017; Dörbecker and Böhmann, 2013; Iman, 2016). By applying service modularization in companies that offer maintenance and plant commissioning services, new application areas for service modularity and modular service architectures have been successfully explored. The research presented in this paper adds to the understanding of service modularity and its benefits and provides insights into the applicable designs of modular service architectures (Brax et al., 2017; Dörbecker and Böhmann, 2013). The versatility and applicability of service modularization principles in operational contexts are underscored by the real-world application.

8.2 Implications for practitioners

Insights for practitioners aiming to modularize their service portfolios are offered in the research. The case studies have shown that practitioners can be aided in systematically structuring the service design and that the decomposition, modules, interfaces, and architectures help with the efficient creation of modular services. The potential of service modularization, in terms of cost reduction and profitability, customization and variety of services, external collaboration and outsourcing, increase in flexibility and responsiveness, and simplification of complex systems, was showcased by the case studies. A decrease in service complexity by reducing the number of distinct service variants that need to be handled by the company was also observed. Furthermore, an overview of the variety in the service portfolio was provided, enabling informed decision-making. In this regard, the modular decomposition of the service can facilitate the efficient management of the responsibilities for service design and delivery.

8.3 Limitations and further research

Given the design of this research project, only the immediate effects of applying service modularization in the case companies could be evaluated. In addition to the short-term effects of introducing a modular service design, the long-term effects, such as increased learning effects or challenges in managing and evolving modular service architectures over time, play an important role (Böttcher and Klingner, 2011; Brax et al., 2017; Dörbecker and Böhmann, 2015). Therefore, future research efforts should focus on investigating the long-term effects.

The intention of applying service modularization as presented in this paper was to enable the operational use of service modularity in an organization, rather than to focus on the strategic aspects of modular architectures. The strategic aspects of modular service architectures have been investigated in existing papers (Geum et al., 2012; Løkkegaard et al., 2016). An opportunity for future research efforts could be to join the operational and strategic aspects of service modularity to revise a company's placement in the market and facilitate the road-mapping of initiatives. In this regard, service innovation and new service developments were omitted in this study, but they could be investigated in this further research direction.

The case studies presented in this paper were conducted in collaboration with two case companies. The services offered by the companies differ in complexity and sales frequency. However, future research could investigate if the findings of this study can be replicated in other industries, such as for services that cannot be considered processes.

Further research could also focus on the modeling of multiple service architectures. In the case of the maintenance services explored in this paper, the maintenance was decomposed into corrective and preventive, to be modeled separately. The sharing and reuse of modeling principles, and the service modules, interfaces, etc. across these, were not explored. Other industries may also require different service architectures for designing and modeling their service offerings. These could be industries operating in heterogenous markets and countries that might require separate architectures. Further research could investigate the modeling of these, and the sharing and reuse across them, perhaps incorporating the modularization concept of platforms, which is a topic growing in research attention (Brax et al., 2017).

9 Conclusion

This paper explores the application of service modularization in maintenance and commissioning services. Through two case studies, the paper demonstrates that service modularization can be successfully applied in these domains, facilitates service configuration, and potentially leads to benefits such as cost reduction, the customization and variety of services, external collaboration and outsourcing, increased flexibility and responsiveness, and the simplification of complex systems. The findings provide conclusive operational insights for both researchers and practitioners and highlight the potential of applying service modularization to improve service design and delivery.

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A.5 Paper E

Title:

Modular maintenance instructions architecture (MMIA)

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Journal:

Journal of Quality in Maintenance Engineering

Abstract:

Purpose –The study consists of a literature study and a case study. The need for a method via which to handle instruction complexity was identified in both studies. The proposed method was developed based on methods from the literature and experience from the case company.

Design/methodology/approach – The purpose of the study presented in this paper is to investigate how linking different maintenance domains in a modular maintenance instruction architecture can help reduce the complexity of maintenance instructions.

Findings – The proposed method combines knowledge from the operational and physical domains to reduce the number of instruction task variants. In a case study, the number of instruction task modules was reduced from 224 to 20, covering 83% of the maintenance performed on emergency shutdown valves.

Originality/value – The study showed that the other methods proposed within the body of maintenance literature mainly focus on the development of modular instructions, without the reduction of complexity and non-value-adding variation observed in the product architecture literature.

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Modular Maintenance Instructions Architecture (MMIA)

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Abstract

Purpose

The purpose of the study presented in this paper is to investigate how linking different maintenance domains in a modular maintenance instruction architecture can help reduce the complexity of maintenance instructions.

Design/Methodology/Approach

The study consists of a literature study and a case study. The need for a method via which to handle instruction complexity was identified in both studies. The proposed method was developed based on methods from the literature and experience from the case company.

Findings

The proposed method combines knowledge from the operational and physical domains to reduce the number of instruction task variants. In a case study, the number of instruction task modules was reduced from 224 to 20, covering 83% of the maintenance performed on emergency shutdown valves.

Originality

The study showed that the other methods proposed within the body of maintenance literature mainly focus on the development of modular instructions, without the reduction of complexity and non-value-adding variation observed in the product architecture literature.

Introduction

With increasing production complexity comes increasing maintenance complexity. As facilities grow in size and production volume, ensuring that the right maintenance takes place at the right time becomes difficult (Agergaard et al., 2021; K. V. Sigsgaard et al., 2021; K. v. Sigsgaard et al., 2021). The instructions describing the actions to take during maintenance are essential in the maintenance process. Low-quality instructions lead to low-quality maintenance work, as well as extra idle time spent understanding the instructions. When instructions are written in a free-text format for individual pieces of equipment, the amount of variation becomes large in production plants with hundreds of thousands of pieces of equipment. When the variation becomes too large, it becomes difficult and time consuming to evaluate the actions taken during maintenance, making it difficult to make decisions about how maintenance should be performed in the future (Agergaard et al., 2021).

The study presented in this paper was performed in a case company that has seen increasing complexity and variance in its maintenance instructions. The operational portfolio contains many instructions with little to no variation in effect but many variants in formulation across two languages. This increases the time it takes to formulate and understand the maintenance instructions. The complexity has had a negative effect on the quality of the maintenance and the time spent on idle tasks, such as reading the instructions. The complexity of the instructions has also made it difficult to evaluate the current maintenance situation because the amount of variation is so large that the maintenance is no longer comparable.

Several studies have shown that more precise and consistent job instructions enable less skilled personnel to carry out maintenance tasks that would otherwise require more experienced technicians (Harris, 1994). Within the field of maintenance instructions, several techniques for standardizing instructions have been proposed, including the task-oriented adaptive maintenance system (TOAMS) (Huang et al., 2015) and customized maintenance documents (Huang et al., 2014). These methods aim to customize maintenance descriptions based on the particular tasks at hand and the end-user experience. Furthermore, Toscano (2000) investigates the use of interactive electronic technical manuals (IETMs), which seek to provide users with just-in-time instructions for maintenance tasks. These methods seek to modularize maintenance instructions and make them configurable to individual maintenance job requirements. However, the methods do not consider whether the variation found in the maintenance instructions is value-adding or non-value-adding. Because unnecessary modules within a configurable architecture are complex and time-consuming to maintain, this paper proposes the Modular Maintenance Instructions Architecture (MMIA) as a method for evaluating and formulating a maintenance instruction architecture. The method uses knowledge from both the operational and physical domains to evaluate the value addition of maintenance instruction variants.

The MMIA was created for multicomponent systems, while the methods identified in the literature are limited to single-component maintenance, making the method more suitable for large production facilities. When creating modules for multicomponent systems, other dimensions play a role in the decision-making because they must differentiate between action differeneces and differences in the physical and process dimensions. Differences in the physical dimension occur when there are different types of equipment that have variable requirements in terms of maintenance. Differences in the process dimension occur when multiple pieces of equipment are being maintained at different stages at any given time (K. V. Sigsgaard et al., 2021). The study presented in this paper was shaped by the following research question:

How can linking various maintenance dimensions help decrease the complexity of maintenance instructions?

This paper first presents the approach to the research question. A literature review then highlights methods from the maintenance and instruction digitalisation literature. The literature review is supported by the methods of value-addition analysis, derived from product architecture theory, as an addition to the maintenance and instruction literature. The method developed in collaboration with the case company is then highlighted. Finally, a case study using the proposed MMIA method is presented. The study evaluates real maintenance instruction data for a set of safety-critical valves.

Research approach

The research question was approached with the design research methodology (DRM) (Blessing & Chakrabarti, 2009). The need for a method for the evaluation of the value-addition of variety was observed in the case company. The company had lost the overview of the variation in the maintenance instructions and was struggling to make decisions about changes on a larger scale. Approaches to the standardization of maintenance instructions were identified in the literature, but the identified studies did not take the value addition of the variants into consideration. Instead, approaches taken from product and service modularization led to the conceptualization of the proposed method, the Modular Maintenance Instruction Architecture (MMIA). The method was applied in the case company to further iterate and test its applicability. The development of the proposed MMIA and the case study were performed over a six-month period. The case company is a major production company that operates major, continuous production facilities. To limit the scope of this initial study, the case study focused on a systematic analysis of 231 variants of maintenance instructions that describe the preventive maintenance planned for 1,941 safety-critical valves.

Knowledge about the company's maintenance process was collected through internal documents and the company's Computerized Maintenance Management System (CMMS). Information on the maintenance jobs performed on the safety-critical valves was also collected from the CMMS. The data included all maintenance performed over a five-year period. Information about the maintenance jobs included the number of hours, the dates of the performed maintenance, and the maintenance instructions. The physical characteristics and locations of the valves were also extracted.

The findings from the case study were validated through workshops, meetings, and semi-structured interviews with internal maintenance experts, including maintenance workers, maintenance responsibles, system responsibles, and others. The response and feedback received from these key company figures has been vital to the validation of the results of the analysis and the assessment of the developed model.

The study presented in this paper was performed during an MSc project and a BSc project at the Technical University of Denmark, Department of Mechanical Engineering, Section of Engineering Design and Product Development.

Literature review

This section introduces literature on maintenance instructions and the digitalization of documents. The identified methods on maintenance instructions and the digitalization of documents fail to account for the complexity and non-value-adding variety involved in the instructions used for maintenance in large production companies. Product architecture methods have successfully been applied to handle complexity and identify non-value-adding variety. The review is therefore further supported by the product architecture literature.

Maintenance instructions

This section introduces the literature on maintenance instructions. Maintenance instructions are the descriptions of the actions to be performed during the maintenance. As such, the literature in this section describes the action dimension of maintenance (K. V. Sigsgaard et al., 2021).

Maintenance instructions, plans, operations, or tasks are descriptions of the maintenance to be performed (Dansk Standard, 2016). This paper uses the term "maintenance instructions" to refer to a collection of set tasks for completing a maintenance goal. Instructions can be non-knowledge-based or knowledge-based. Non-knowledge-based tasks describes details of the action to be performed so that the person following the instructions does not need any prior knowledge (Jacobs, 2017). A non-knowledge-based instruction might read, "Take a sample from the oil using the pipette in the test kit. Put sample into test liquid and wait 5 minutes for reaction. Note amount of water in oil using the color scale from the test kit." Knowledge-based instructions require the person performing the task to have knowledge of the task at hand outside of the instructions (Jacobs, 2017). An example of a knowledge-based task might read, "Measure water in oil."

Paper-based instructions have, until recent years, been the cheapest and easiest way to achieve portable instructions. However, the introduction of tablets and smartphones has changed this significantly. In most major companies, an increasing share of the internal documentation is being digitalized. One example is the US Army, which converted 17,000 pieces of paper to digital files as a part of its Army Digitization Program (Toscano, 2000). As a result of this digitalization, a large amount of information is available in a new way. This can allow for the communication of the instructions in more detailed formats, such as animations and videos, which can improve user understanding (Pham et al., 2000). Several methods have been proposed for the digitalization of documents. The following paragraphs highlight a selection of methods used to digitalize manuals and instructions.

In maintenance, the development of interactive electronic technical manuals (IETM) is a result of the industry moving away from paper-based, "a to z" documents and toward digitalized versions that ensure that the correct instructions are presented at the right time. Introducing this format of instructions improves the instructions, making it possible to involve personnel with fewer skills. This indicates that non-knowledge-based instruction is more easily achieved using this type of format. The digitalized instructions then function as a means of reducing the demand for experienced technicians within maintenance departments (Pitblado, 1991). Similar results are seen in newer studies on the application of augmented reality (AR) in maintenance instructions. When introducing AR solutions instead of paper- or PDF-based methods, the amount of time spent on maintenance, as well as the number of errors, is reduced (Fiorentino et al., 2014; Havard et al., 2021; Mourtzis et al., 2020).

Pham et al. (2000) suggest a type of knowledge-based manual that allows a system to decide what instructions are needed based on user inputs. In comparison to paper-based instructions, in which all necessary and unnecessary steps will need to be shown, only the necessary information is included for each individual case, without having to increase the number of instructions. This type of system can provide tailored solutions that fit the level of expertise of the technician (Huang et al., 2014).

Horn (1993) discusses the use of the theory of structured writing to facilitate the change from sequential, printed paper-based instructions to chunks of information configured by a computer system. Structured writing is defined as "a precise modular concept ('information blocks') that are firmly grounded in a taxonomy of information types" (Horn, 1993, p. 4). Information blocks are basic units that replace a paragraph and contain text and graphs.

Setchi et al. (2006) outline the methodology of "intelligent product manuals" (IPMs), which are an intelligent way to show consumer-product user manuals to end-users. Primarily, IPMs utilize the Internet and rests on the same idea of applying expert knowledge, product life-cycle information, and hypermedia to provide just-in-time support (Pham et al., 2000).

The methods introduced in this section focus on how to represent and convert the structure of the instructions into digital solutions. However, none of the identified methods evaluate whether the amount of variation within the operations is value-adding. The following section explains how this was achieved in product and service architecture research.

Product architecture

Performing development product by product leads to many products that have overlapping attributes. Having many products increases complexity, but with their overlapping attributes, this complexity tends not to provide value (Meyer & Lehnerd, 1997; Wilson & Perumal, 2009). However, variance is required to be competitive, making a trade-off occur between supplying a large amount of variety and not introducing large production costs (Simpson et al., 2014). Modularized product architectures offer a solution to such increased portfolio complexity (Marc H. Meyer & James M. Utterback, 1992; Mortensen et al., 2019; Otto et al., 2016) and have been successfully adopted in many companies over the last three or four decades (Meyer & Lehnerd, 1997; Wilson & Perumal, 2009). More recent years has seen an introduction of product architecture and modularization approaches in service portfolio management (de Blok et al., 2014; de Mattos et al., 2021; Eissens-van der Laan et al., 2016; Johnson et al., 2021; Løkkegaard et al., 2016). Likewise, the study by K. V. Sigsgaard et al. (2021) showed promising results on the part of an initial step into the application of product architecture approaches in a maintenance management context. Services and maintenance are similar in the sense that they are operational and provide intangible deliverables that provide value. However, where services are tailored to be delivered to a customer, the recipient of value in maintenance is the asset or production owner that requires safe, continuous production (K. V. Sigsgaard et al., 2021). This section introduces concepts from the product, service, and maintenance architecture and modularization literature to add to the application of architectures and modularization in maintenance.

Product architecture is a widely studied subject that has a number of definitions. One widely accepted definition of the product architecture was given by Ulrich (1995): "(1) the arrangement of functional elements; (2) the mapping from functional elements to physical components; (3) the specifications of the interfaces among interacting physical components" (Ulrich, 1995, p. 420). As such, a product architecture is an arrangement of a product's functional elements into a number of physical building blocks (Voss & Hsuan, 2009). These building blocks are referred to as modules and can be combined and matched under certain constraints described by the architecture (Schilling, 2000). In order to reap the benefits of a modularized product program, the interfaces between the modules must be kept static. If interfaces are changed, not all modules will be combinable with one another, ultimately limiting the customizability of the program (Meyer & Lehnerd, 1997; Mortensen et al., 2016). When deciding on modular decomposition, various drivers can act as the force that leads to decision-making. For products, these module drivers can be carry over, common unit, upgrading, or technical specifications (Ericsson & Erixon, 1999). When designing modularized product architectures, it can be a good idea to evaluate the value-addition of the module variants included in the final program. The value of a variant can be evaluated in terms of a trade-off between commonality with other parts and the variance delivered to the market. Non-value adding variance is, then, variance occurring in the product program that does not deliver value to the customer. A variety of indices that quantify the commonality of a product family have been proposed for use in evaluating the configuration of future families (Thevenot & Simpson, 2006).

Service archictures and modularization can help transform services from *ad hoc* activities to repeatable and configurable service offerings, but research into the topic is still new (Johnson et al., 2021). Because the subject of service architectures is still new, definitions are still being formulated. However, the literature review by de Mattos et al. (2021) combined definitions from the service architecture literature to define a “service architecture” as a description of boundaries of the service system and a decomposition of the modules, interfaces, boundaries, and resources that define the architecture. Likewise, the definitions of the terms “modules” and “interfaces” are still largely studied on a case-by-case basis (de Blok et al., 2014; de Mattos et al., 2021; Eissens-van der Laan et al., 2016). The combined definition posed by de Mattos et al. (2021) defines a service module as a set of elements that can offer value to the client and a service interface as connections among these service elements in the form of the people, information, and rules that govern information flows. This definition reflects the multidimensionality of services because service, process, physical, and human aspects have an effect on the decomposition of the service system in modules and interfaces (Eissens-van der Laan et al., 2016). The effects of service modularity include the reduction of complexity, flexibility, reuse, the reduction of process time, and more (de Mattos et al., 2021). Eissens-van der Laan et al. (2016) emphasize the importance of ensuring minimum dependencies across all dimensions in the defined service modules to improve the configurability of the modules.

The introduction of product and service architecture approaches in maintenance was proposed by K. V. Sigsgaard et al. (2021). Inspired by the three domains of market, product, and production, which, when aligned, allow the greatest benefits to be reaped (Andreasen et al., 1996; Mortensen et al., 2010, 2011, 2016), the study introduced the three dimensions of maintenance: physical, action, and process. The architecture was then visualized through a combined overview of the three dimensions. The physical overview included a segmentation of the assets in matrix format. The action dimensions are mapped by the effects on the equipment condition from no effect to better-than-perfect maintenance, and the impact on the system is mapped from no impact to production loss. The processes dimension is a mapping of the maintenance processes as they happen, showing dependencies across the life-cycle of the maintenance job (K. V. Sigsgaard et al., 2021).

MMIA – Conceptual model

Introduction

This section presents the conceptual MMIA model. The main purpose of the model is to enable the reduction of non-value-adding variance and present a TO-BE architecture of modular maintenance instructions. This is achieved by creating an AS-IS overview of the existing maintenance instructions and the equipment on which they are performed. The foundation of the model is an overview of the variation of the maintenance instructions and the relationship between the two dimensions — action and physical. Because the instructions being analyzed are all assumed to be at the same stage of the process dimension (K. V. Sigsgaard et al., 2021), this dimension not included in defining the value of the variation present in the instructions.

First, the current maintenance instructions are analyzed by creating an overview of the AS-IS architecture. The understanding of an architecture in this study is based on the service architecture definition of de Mattos et al. (2021), wherein an architecture is the description of the boundaries of the service system and a decomposition of the modules, interfaces, and boundaries. The AS-IS overview consists of a mapping of the AS-IS maintenance instructions and the equipment on which they are used in a matrix format. The rows of the matrix represent the tasks that make up the instructions, and the columns represent groups of equipment. Based on the overview gained from the AS-IS architecture, the non-value-adding tasks can be identified, and the TO-BE architecture can be formulated. The TO-BE architecture is identified by removing the non-value-adding variance and defining a set of task modules that cover the maintenance requirements. A similar matrix format is then used to visualize and communicate the TO-BE architecture.

The details regarding the creation of the MMIA model are introduced in the following sections. These sections introduce how to achieve the elements of the architectural overview and, finally, a full overview of the model. The first section introduces how to map out the instructions. The next section introduces how to segment the equipment, and the third section introduces how to link the two dimensions together. The final section introduces a full overview of the model. The model is shown using maintenance instructions for a selection of fictional bikes.

Linking instructions

The first step in the AS-IS analysis is to link the instructions in a structured format that facilitates the analysis of the maintenance instructions, down to the individual tasks. It is difficult to compare the many unique maintenance instructions compiled from multiple tasks, making decomposition into tasks an important step. Simar to a service module, in which the module is an element or set of elements that deliver value (de Mattos et al., 2021), a single task is an element or set of elements that delivers value to the maintenance goal. As such, a task or maintenance action module is a maintenance action or set of actions that can be performed independently of the remainder and is not dependent on the prior or subsequent action in the instructions. Figure 1 shows the steps in delimiting the instructions as follows: (1) the full instructions, (2) the instructions split into tasks, and (3) the similar tasks grouped. By decomposing the instructions into tasks, a full list of maintenance actions can be compiled. This is the full list of action module variants in use in the as-is architecture.

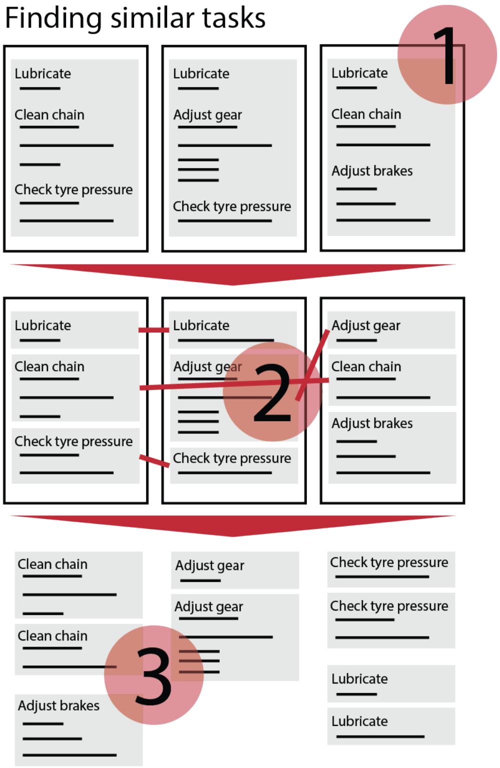


Figure 1: Delimiting instructions into tasks and grouping. 1: The starting format of the instructions. 2: The instructions delimited into independent tasks. 3: The tasks grouped by similarities in effect.

Once the instructions are separated into individual action modules, it is possible to identify similar tasks because the similarities are now clearer. The tasks are segmented into groups based on the effect of the task. At this stage, it is important to note differences that may be drivers of necessary variance (e.g., a tire change on a race bike requires a different set of tools than the same task on a mountain bike). The toolset drives the necessary variance, even though the “tire-change” operation may seem identical. It is important to ensure that these types of variations are still visible after delimitation.

Grouping equipment

The next step is to gain an understanding of the physical dimension of the maintenance. The tasks that must be performed are heavily dependent on the physical aspects of the object being maintained (K. V. Sigsgaard et al., 2021; K. v. Sigsgaard et al., 2021). In the MMIA, the physical systems are separated into groups by physical characteristics (Figure 2). For instance, bikes with hydraulic brakes are put in one group, and bikes with wire-brakes are put in another because hydraulics and wires are maintained using two significantly different methods. The grouping gives insight into how the physical parameters drive the maintenance variations identified from the tasks in the instructions. The relevance of different parameters is highly dependent on the equipment at hand. To ensure the grouping characteristics are well-defined, they are identified in collaboration with experts. The number of details obtained about the equipment should be scoped according to expert insight into what and how much maintenance variance is driven by the different physical parameters. The grouping of the equipment enables the identification of unnecessary variance across equipment that has the same parts. It is also an analysis of the maintenance requirements, providing insight into the effects of the maintenance currently being performed. Three groups were formulated for the bike example (Figure 2). The groups were formed based on gear type, the presence of suspension, required tire pressure, and types of brakes.

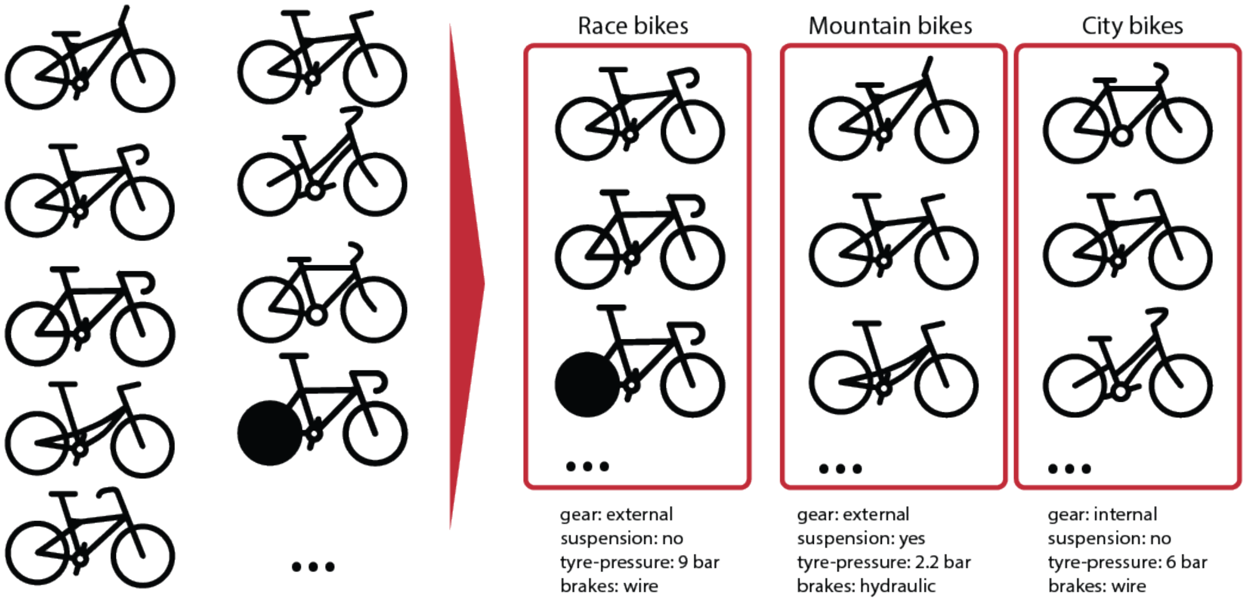
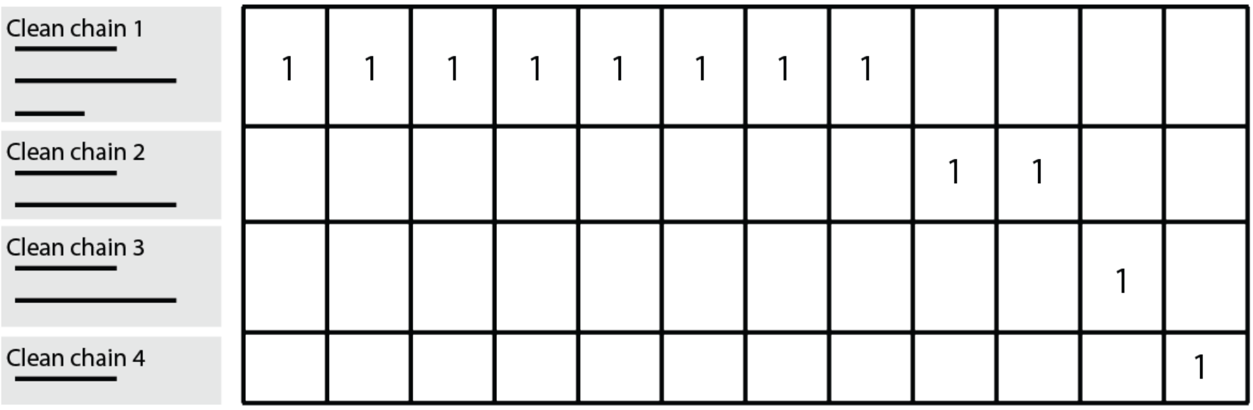


Figure 2: The bikes are grouped according to the characteristics of the bike parts. This allows the comparison of different types of maintenance within groups that can be maintained in the same way.

The dimensional link

The link between the action dimension and the physical dimension is key to the usability of the proposed model. The main drivers of value-adding variance are the physical characteristics of the maintained equipment because different types of equipment ultimately need different maintenance. Furthermore, it is impossible to find patterns in the maintenance across different pieces of equipment without using the action dimension (K. v. Sigsgaard et al., 2021). It is rarely interesting to consider single pieces of equipment individually, because there tends to be greater savings potential when considering multiple pieces of equipment. For example, one might want to consider how the differences between mountain bike gear systems and city bike gear systems affect the maintenance of the bikes and how this can be optimized. The grouping of equipment is based on the possibility of executing operational tasks on that group. For example, if bikes are grouped according to suspension type, "check for suspension leakage" is expected to apply to all bikes within that group. All equipment in the group should have similar maintenance requirements. It is impossible to achieve a group that is similar in every aspect. As such, the limitations of the grouping should be made clear when the TO-BE situation is formulated.

The relationship between the dimensions is the key element of the model because it enables different patterns to be observed. The relationships reveal the use of tasks across the equipment and equipment groups. If a task has a high degree of re-use across equipment types, it is likely very generic and could form the basis of new modules. An example can be seen in Figure 3: "Clean chain 1" is used on most bikes, while 2, 3, and 4 are only used on one or two bikes. Diagonality in the matrix implies high variance, while horizontality implies a high degree of reuse. Thus, the patterns in the matrix can be used as indicators of what should be investigated further.



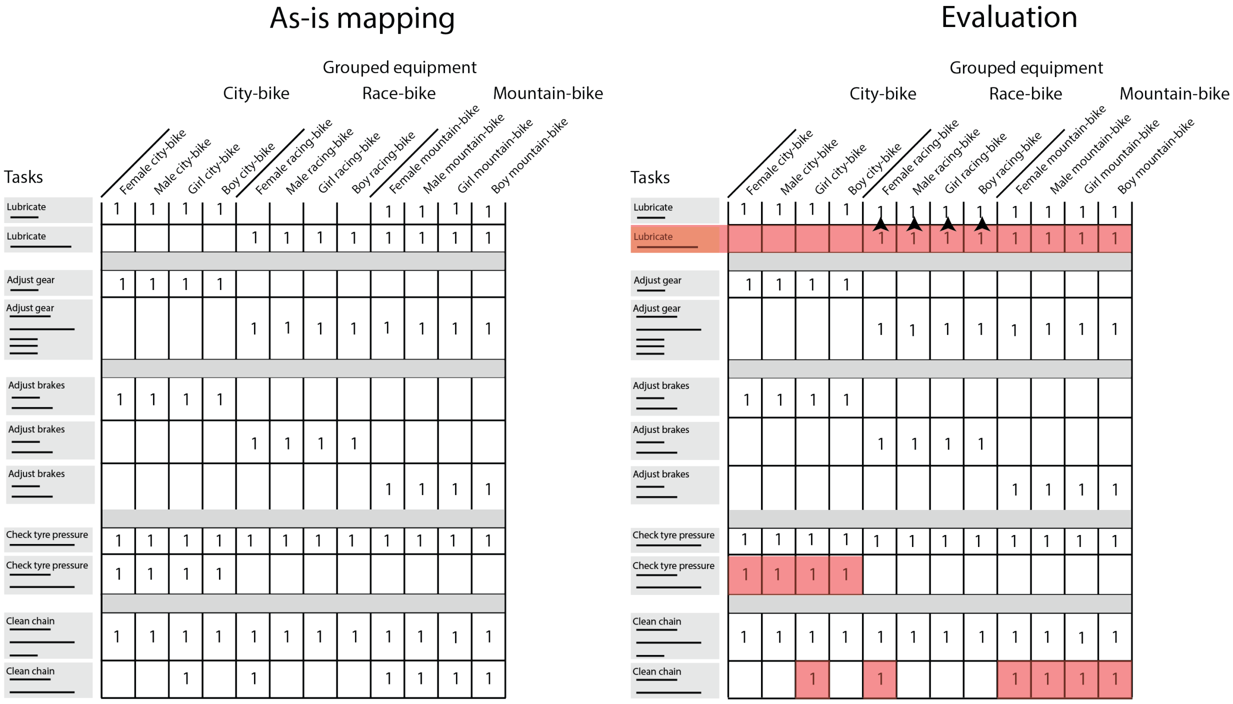
Clean chain 1	1	1	1	1	1	1	1	1				
Clean chain 2									1	1		
Clean chain 3											1	
Clean chain 4												1

Figure 3: An example of a pattern for chain-cleaning tasks.

Architecture

The MMIA consists of two architectural overviews: the AS-IS architecture and the TO-BE architecture. Both are based on the same matrix format, with tasks as rows and grouped equipment as columns. The input tasks and equipment groups are the results described in the previous three sections. The AS-IS architecture view shows the action module variants currently in use against the physical dimensions. The TO-BE architecture is thus a representation of the reconfigured architecture in which all action module variants are value-adding to the physical dimension.

The AS-IS architecture for the example of bicycle maintenance is shown in Figure 4. The matrix on the left side of the figure shows the maintenance performed on the bicycles. A "1" in the matrix indicates that the maintenance task is used for the given equipment group. The groups along the columns were created based on the commonality of the structure and parts of the bikes. This overview makes it possible to identify variations and similarities in the instructions for each bike variant because bikes consisting of the same parts can be maintained in the same way.



As-is mapping

Tasks	Grouped equipment City-bike Female city-bike	Male city-bike	Girl city-bike	Boy city-bike	Race-bike Female racing-bike	Male racing-bike	Girl racing-bike	Boy racing-bike	Mountain-bike Female mountain-bike	Male mountain-bike	Girl mountain-bike	Boy mountain-bike
Lubricate	1	1	1	1					1	1	1	1
Lubricate					1	1	1	1	1	1	1	1
Adjust gear	1	1	1	1								
Adjust gear					1	1	1	1	1	1	1	1
Adjust brakes	1	1	1	1								
Adjust brakes					1	1	1	1				
Adjust brakes									1	1	1	1
Check tyre pressure	1	1	1	1	1	1	1	1	1	1	1	1
Check tyre pressure	1	1	1	1								
Clean chain	1	1	1	1	1	1	1	1	1	1	1	1
Clean chain			1		1				1	1	1	1

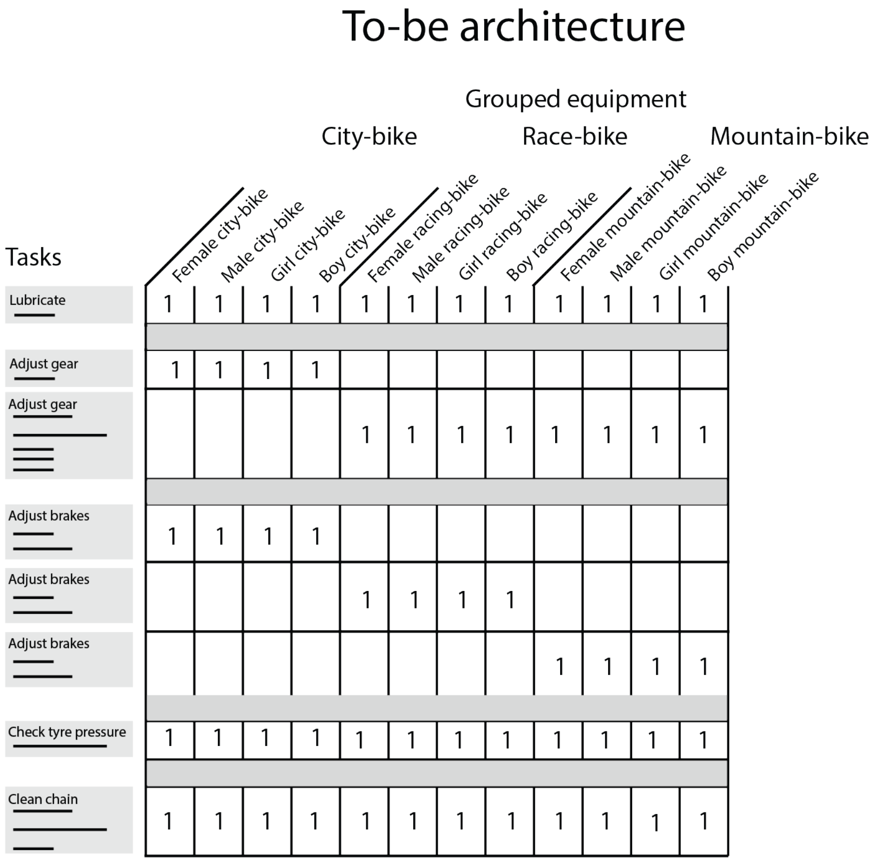
Evaluation

Tasks	Grouped equipment City-bike Female city-bike	Male city-bike	Girl city-bike	Boy city-bike	Race-bike Female racing-bike	Male racing-bike	Girl racing-bike	Boy racing-bike	Mountain-bike Female mountain-bike	Male mountain-bike	Girl mountain-bike	Boy mountain-bike
Lubricate	1	1	1	1	1	1	1	1	1	1	1	1
Lubricate					1	1	1	1	1	1	1	1
Adjust gear	1	1	1	1								
Adjust gear					1	1	1	1	1	1	1	1
Adjust brakes	1	1	1	1								
Adjust brakes					1	1	1	1				
Adjust brakes									1	1	1	1
Check tyre pressure	1	1	1	1	1	1	1	1	1	1	1	1
Check tyre pressure	1	1	1	1								
Clean chain	1	1	1	1	1	1	1	1	1	1	1	1
Clean chain			1		1				1	1	1	1

Figure 4: The AS-IS architecture for the example of bike maintenance. LEFT: The complete AS-IS overview. RIGHT: Identifying non-value-adding variance in the AS-IS architecture.

Using the AS-IS overview, the value addition of the variants can be evaluated. Value addition is evaluated by comparing the variance found in the proposed actions to the value delivered to the physical dimension. If there is no significant value in the variance in the output of the mainteancne task, the task variance is marked as non-value-adding. The right-hand side of Figure 4 shows examples of non-value-adding variants that can be eliminated. At the top of the matrix are two variants of lubrication tasks applied throughout all three product groups. Because the maintenance within a group can be the same, the extra variant adds complexity without adding value. Therefore, one of the task variants can be chosen, and the other eliminated. A similar situation can be seen for “check tire pressure” and “clean chain.” In both cases, a variant can be removed because one task is enough. For the “adjust gear” tasks, two variants of the task are in use. In this case, the use within the equipment groups is more inconsistent. To enhance the performance of the maintenance, both variants are needed, so both are kept.

When the non-value-adding variance is identified, it can be removed to create an improved TO-BE situation (Figure 5). The TO-BE architecture is then used as the basis for creating new maintenance instructions by combining the task modules. Combinations of the modules can make every instruction unique while still consisting of well-defined modules that are easily updated whenever the requirements change. A requirement change could come from new parts being introduced or from a change in the product. When the instruction requires an update, only the affected module must be updated rather than the entire instruction.



To-be architecture

	Grouped equipment											
	City-bike				Race-bike				Mountain-bike			
Tasks	Female city-bike	Male city-bike	Girl city-bike	Boy city-bike	Female racing-bike	Male racing-bike	Girl racing-bike	Boy racing-bike	Female mountain-bike	Male mountain-bike	Girl mountain-bike	Boy mountain-bike
Lubricate	1	1	1	1	1	1	1	1	1	1	1	1
Adjust gear	1	1	1	1								
Adjust gear					1	1	1	1	1	1	1	1
Adjust brakes	1	1	1	1								
Adjust brakes					1	1	1	1				
Adjust brakes									1	1	1	1
Check tyre pressure	1	1	1	1	1	1	1	1	1	1	1	1
Clean chain	1	1	1	1	1	1	1	1	1	1	1	1

Figure 5: The TO-BE architecture. The non-value-adding variants have been removed.

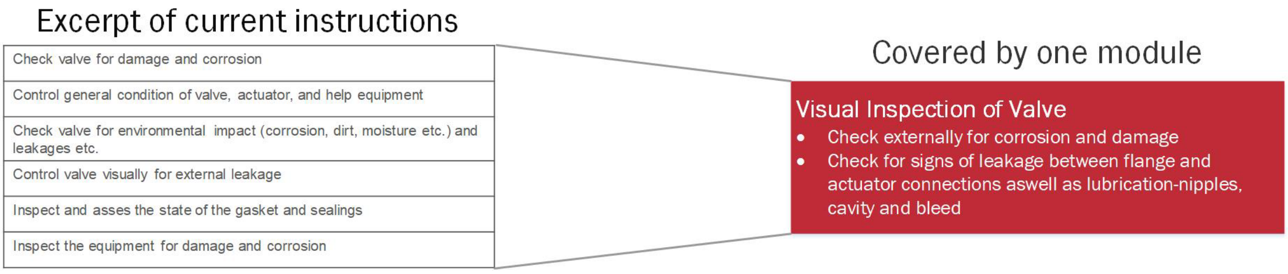
Case Study – Application of the model

To test the applicability of the model, a case study was conducted at a large production company. The company operates large, offshore, continuous production plants, which require an increasing amount of maintenance due to the age of the plants and the rough offshore environment. The plants consist of a large number safety-critical valves, and their functionality is essential to running safe plants. These valves are maintained to ensure their functionality, but the instructions for valve maintenance have a large amount of variation. This has made them difficult to manage because a full overview of the actions to be taken regarding the safety-critical valves is not available. The scope of the case study includes a total of 5,636 maintenance instructions for 1,941 valves across four assets.

The first step in the study was to collect the data. Three datatypes were the cornerstones of the analysis: the physical characteristics of the equipment, the historical data on the execution of maintenance, and the maintenance instructions. The maintenance instructions were 1–10 pages long and consisted mainly of tasks in a bullet-point format. A few instructions were so different from the remainder that they were marked as outliers and excluded from the scope. This decision was made in collaboration with experts on company maintenance, and the jobs were rare jobs that only occurred with large intervals and involved many steps outside of the normal process.

Due to the large amount of text, the process was automated. A database of all the tasks was created by running a script in Python that separated the bullet points into rows by identifying the bullet point character and line changes and making a separate entry between the line changes and bullets. All tasks were then compared to identify similarities. If two or more tasks were the same in every respect, only one version was included in the final overview. Due to the large amount of data at this stage, only tasks that were completely similar in every respect were marked as similar. Somewhat similar tasks were kept separate. The tasks were then imported to a spreadsheet. This final spreadsheet included 413 unique tasks.

To understand whether the content of the tasks was unique or consisted of variations of the same tasks, the entire library of tasks was manually categorized. This was done by reading each task and assigning it to the appropriate group. One group could, for instance, be “visual inspection” — each time a task had “visual inspection” in the text or something related to visual inspection, it would be included in the corresponding category. Figure 6 shows an example of the variants of visual inspection tasks that were covered by one module in the to-be architecture. The categorization and grouping of the tasks was a type of subjective analysis that would not necessarily produce the same output if repeated by someone else. Some tasks were more challenging to group, either because they were unique to a certain kind of valve or because the required knowledge was not available. To ensure that the assumptions made were correct, the identified opportunities for variance minimization were verified by maintenance experts from the case company, as shown in Figure 4, right.



Excerpt of current instructions

Check valve for damage and corrosion
Control general condition of valve, actuator, and help equipment
Check valve for environmental impact (corrosion, dirt, moisture etc.) and leakages etc.
Control valve visually for external leakage
Inspect and asses the state of the gasket and sealings
Inspect the equipment for damage and corrosion

Covered by one module

Visual Inspection of Valve

- Check externally for corrosion and damage
- Check for signs of leakage between flange and actuator connections aswell as lubrication-nipples, cavity and bleed

Figure 6: Examples of the variance in as-is instructions that could have been covered with a single module.

Historical data were used to form the link between the action dimension data and the physical dimension. The historical data were obtained from the case company’s CMMS. The system contains reports on the findings, states, and repairs performed during maintenance on each valve; information on when each valve was maintained and what set of instructions was used; and the physical characteristics of the valves, such as type, size, and medium. In building a data model from the historical data, the link between the executed maintenance tasks and the actual valves and their characteristics was formed.

The AS-IS architecture was presented in a workshop with company experts with two objectives in mind: (1) verify the collected data, the cleaning processes, and the manual categorization process and assumptions and (2) develop the TO-BE architecture by collaboratively eliminating non-value-adding variation.

The AS-IS architecture overview revealed that none of the physical parameters drove the variation found in the instructions. This showed that it was possible to use the same task for multiple valves. Many of the tasks were variations for situations involving exactly the same physical characteristics. For instance, when a worker checks the visibility of the tag number of a valve, a new method is not needed for every valve. Inputs from the experts indicated that many of the tasks were outdated and included unwanted procedures and content. The categorization of the tasks enabled the experts to quickly point out entire categories and define when the tasks needed to be the same or unique. In collaboration with the experts, the number of tasks that could be modularized was 224, leading to 20 modules and covering 60% of the instructions. This covered the maintenance instructions for 83% of valves. The modules covered the same tasks as before but were simplified and improved in quality. The collaboration with the company maintenance experts ensured that the resulting task modules were all feasible. The remaining 40% of tasks (189) could not directly be modularized, and it was necessary to keep them AS-IS. The final modules and examples of the module variants can be seen in Figure 7. The figure shows the modules in the center and the module variants as puzzle blocks whose interfaces will only fit in specific modules.

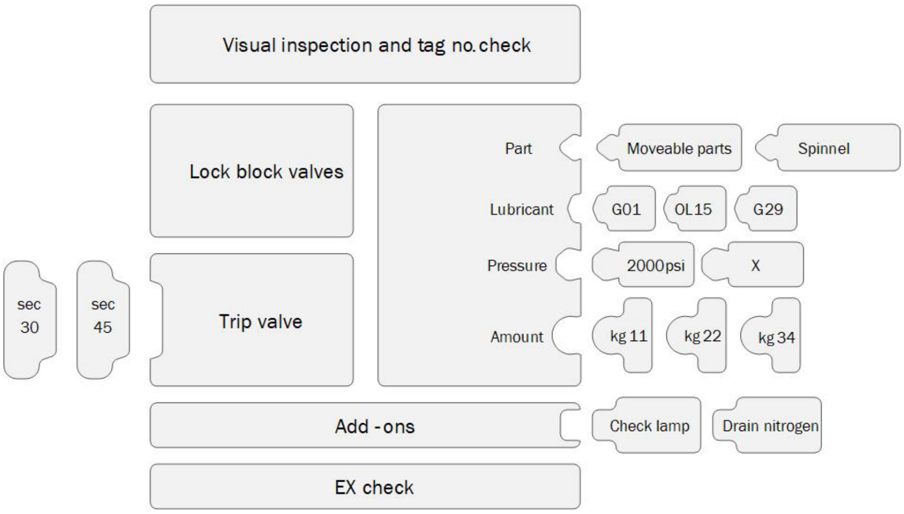


Figure 7: Visual representation of the modules (central blocks) and examples of the module variants (smaller blocks) defined for the modular maintenance instruction architecture at the case company.

Discussion

The study described in this paper shows the potential of simplifying maintenance instructions by reducing the non-value-adding variants and modularizing the remaining tasks to achieve maintenance configurability. The modular instructions reduced complexity by reducing non-value-adding variance, while the maintenance can still be differentiated to suit variations in the physical requirements of the equipment.

The proposed method, the MMIA, is a systematic method applied with the goal of reducing the non-value-adding variety in maintenance instructions so as to achieve a greater overview of maintenance actions. The advantage of using the proposed MMIA is that it provides insights into the current situation, which provides an understanding of the changes necessary to move from an overly complex AS-IS to the desired, optimal TO-BE architecture. The method is based on product and service architecture approaches, as well as the definitions of maintenance and service architecture and modularization (de Mattos et al., 2021). Similar to service architectures, the maintenance architecture is based in multiple dimensions, being dependent on the physical, action, and process dimensions. However, the client, in maintenance, is, instead, the operator of the facilities, who is also the responsible for the maintenance. The application of the approaches and definitions of architectures and modules indicates the usefulness of these in maintenance management, but clear definitions of maintenance architectures and modularization are still in the early stages. This also means that the definitions of commonality indices (Thevenot & Simpson, 2006) and module drivers (Ericsson & Erixon, 1999) are not yet fully formed for maintenance modularization. This is reflected in the needs of the results from the method to be evaluated by experts in the case company. More studies beyond the case-based scope are needed to define these aspects in larger scopes and in other companies and industries. A clear drawback of the proposed MMIA is that it is necessary to include a large number of experts in order to verify the findings. This is an extra step that requires a great deal of time and resources because the experts must do much work as well. However, these experts were already spending large amounts of time reading and understanding the various maintenance instructions. Improving the maintenance instruction architecture will improve the time spent on analyzing the maintenance being performed, providing a return on the time invested.

The results of the case study showed that it was possible to gain repeatability and reduce the complexity of the maintenance instructions by minimizing the non-value-adding variation in the maintenance. The resulting modules and module variants were defined by the value the actions delivered in terms of the physical characteristics of the production equipment. Because the decomposition of the tasks was performed to minimize dependencies across the modules (Eissens-van der Laan et al., 2016), the interfaces between the modules are more defined by the requirements of the physical dimensions, i.e., equipment characteristics, than by the dependencies in the action dimension. This study focused more heavily on the development and configuration of the TO-BE architecture than the longer-term use and upkeep of the architecture. More longitudinal studies are needed to show whether the longer-term benefits of the TO-BE architecture reflect those outlined in service architecture studies, such as the reduction of process time, quality improvement, and possibilities for work improvement (de Mattos et al., 2021), or product architecture studies, such as the reduction of development time, a quicker response to changes, and the reduction of costs (Harlou, 2006).

The method differs from those identified from the maintenance instruction research because it focuses on reducing non-value-adding variety. As such, it can be used as an input or starting point for the methods highlighted in the literature section, such as the TOAMS (Huang et al., 2015), customized maintenance documents (Huang et al., 2014), or AR implementation (Fiorentino et al., 2014; Havard et al., 2021; Mourtzis et al., 2020). From a maintenance architecture perspective, the method especially focuses on the links between the phsyical and action dimensions (K. V. Sigsgaard et al., 2021). The process dimension was excluded from the MMIA. Because the instructions all are considered to be in the planning stage, they are all considered to have the same level of maturity. The modularization of the instructions can, similarly, be an input into the action view, as proposed by K. V. Sigsgaard et al. (2021). Future longitudinal studies should also focus on the effects of the process dimension when the architecture is used to plan, perform, and evaluate the maintenance.

The study of the proposed MMIA method indicates the usefulness of the method, but it is based only on one case company with one type of equipment. Further work should therefore focus on evaluating the model by testing it in other contexts, on other types of equipment, and on a larger scale. Such work would also be a further contribution to the applicability and definition of maintenance architectures and modularization initially proposed by K. V. Sigsgaard et al. (2021).

Conclusion

This paper presents a method for evaluating the variations in maintenance instructions by linking the instructions to the dimensions of maintenance. The connection across the dimensions made it is possible to identify and remove non-value-adding variation in the maintenance tasks. A case study was used to show how a Modular Maintenance Instructions Architecture (MMIA) can be achieved using the proposed method. The MMIA breaks down maintenance instructions into idendependent, comparable tasks and links this to equipment to enable an evaluation of the value addition of the task variation. The case study resulted in a reduction of 224 tasks to 20 unique tasks. The 20 unique tasks were able to cover the maintenance of 83% of the pieces of equipment studied in the scope.

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A.6 Paper F

Title:

Applying performance measures before, during, and after configurator development

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Abstract:

Configurators are widely used by engineering-oriented companies to support specification processes by automating tasks such as producing quotes, operation plans, and bills for materials. While studies have shown that configurators can have a range of benefits, such as reducing lead times, improving product quality, and reducing resources, they have also pointed to several challenges. To address these challenges, the existing literature has provided various approaches for the development and implementation of configurators. This paper takes a different focus to contribute to improving the success of configurator projects by focusing on the role of performance measures. Specifically, it argues that selecting and using the appropriate performance measures at certain points of a configurator project will have a significant influence on its success. To support this argument, a framework was developed, based on the literature, for selecting and applying performance measures in configurator projects. The framework was tested through a longitudinal case study in a company implementing a configurator for the maintenance of oil platforms. The case study demonstrated the usefulness of the framework that had been developed and the value of placing a greater focus on performance measures in configurator projects.

Applying Performance Measures Before, During, and After Configurator Development

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ABSTRACT

Configurators are widely used by engineering-oriented companies to support specification processes by automating tasks such as producing quotes, operation plans, and bills for materials. While studies have shown that configurators can have a range of benefits, such as reducing lead times, improving product quality, and reducing resources, they have also pointed to several challenges. To address these challenges, the existing literature has provided various approaches for the development and implementation of configurators. This paper takes a different focus to contribute to improving the success of configurator projects by focusing on the role of performance measures. Specifically, it argues that selecting and using the appropriate performance measures at certain points of a configurator project will have a significant influence on its success. To support this argument, a framework was developed, based on the literature, for selecting and applying performance measures in configurator projects. The framework was tested through a longitudinal case study in a company implementing a configurator for the maintenance of oil platforms. The case study demonstrated the usefulness of the framework that had been developed and the value of placing a greater focus on performance measures in configurator projects.

Keywords: Configurators; performance measurement; performance management; configurator projects; configuration systems

1 INTRODUCTION

Configurators are widely used in engineering-oriented companies to support specification processes such as generating quotes, operation plans, and bills for materials (Hvam *et al.*, 2008). Companies develop configurators with the aim of improving internal business processes, reducing lead times, achieving on-time delivery, improving quality, decreasing resource consumption, and optimizing products (Haug *et al.*, 2019; Kristjansdottir *et al.*, 2018). While many companies benefit from the use of configurators, many also encounter significant challenges in realizing these benefits, sometimes resulting in the abandonment of projects after they have been initiated (Haug *et al.*, 2012; Haug *et al.*, 2019b; Ladeby and Oddsson, 2011; Walcher and Werger, 2011).

To address the challenges of configurator projects, the existing literature has provided several approaches for their development and implementation (e.g., Haug *et al.*, 2012; Hvam *et al.*, 2006, 2008; Forza and Salvador, 2006). This paper takes a different focus by investigating the role of performance measures in relation to the success of configurator projects. Specifically, without agreement on an approach to select performance measures, doing so is subject to the risk of bias (Tiihonen *et al.*, 2013), which may lead to misalignment between the objectives and evaluation results. Furthermore, the approaches taken for configurator development and projects tend to have a one-sided focus on evaluating the implications of configurators after they are in operation. At the same time, the leading indicators and process compliance measures have not been receiving much attention (e.g., Trentin et al., 2012; Myrodia et al., 2017; Zhang and Shafiee, 2022), which implies that performance results may become too generic and not provide sufficient knowledge of performance drivers. Finally, the planning of performance evaluation is typically not made in the early phases of configurator projects (e.g., Schobel et al., 2018; Wang et al. 2019; Campo Gay and Hvam, 2022), which implies that the collection of configurator performance data is not aligned with performance needs. Therefore, there are too few data available for implementing performance matrices at a later stage, and resources are wasted on collected data that have little use.

As suggested by the discussion above, selecting and applying the appropriate performance measures at certain times in a configurator project may play a central role in ensuring its success (Hvam *et al.*, 2008; Haug *et al.*, 2019; Kristjansdottir *et al.*, 2018). In this context, the performance measures described in the literature, such as the number of errors, use of man-hours, processing time, accuracy, and completeness, are mainly quantitative (Haug *et al.*, 2019). However, as argued earlier, the conventional approach that begins with developing a configurator and goes on to conducting its performance evaluation may lead to inaccurate evaluations because of inadequate data availability and improper focus and measures. To address these issues, the aim of this paper is to develop an approach for the evaluation of configurator projects. In doing so, this paper addresses the following question:

> *How can companies ensure that the evaluation of configurator projects is aligned with the development and implementation of such systems?*

To address this question, this paper begins by reviewing the relevant literature to identify the metrics used for evaluating configurators and the type of data required. On this basis, a structured approach is developed for integrating performance evaluation into configurator projects with the purpose of both better realizing the potential benefits and reducing the chances of such projects being abandoned. The approach is then tested through a longitudinal case study. Finally, the paper provides a discussion of the findings and a conclusion that addresses the research question.

2 LITERATURE REVIEW

The application of configurators has been reported across various industries. The literature review presented in this section aims to identify the existing performance metrics for configurator projects by focusing on the alignment between the performance metrics and performance objectives of configuration. Specifically, it investigates the performance measures of configuration systems in terms of the different perspectives of performance indicators, sources, and early-stage planning of data collection for performance evaluation and also finds whether proxy evaluation measures have been used instead of more suitable measures due to data availability limitations.

To identify relevant and recent studies, a search of the Web of Science and Scopus databases was conducted to identify English publications from the previous 15 years. This was done using the following search strings for titles, abstracts, and keywords: “configurator AND (product OR sales),” “configurator AND (performance OR impact) AND (product OR service OR operation),” and “configurator AND develop* AND performance AND (product OR service).” The papers identified in these searches (i.e., those that evaluated the performance of configurators) are summarized in Table 1. As shown in the table, most of these studies focused on product and service configurators in the engineering design, construction, and production fields. It can also be seen that the quantitative data used for performance evaluation were mainly collected from the empirical data of case companies, questionnaires, and experiments, while interviews were the most popular method for qualitative data collection. Nevertheless, performance considerations and data gathering needs were barely addressed prior to configurator development in the reviewed studies.

The following sections summarize the performance measures applied in the reviewed studies, which have been organized into four main perspectives, namely, effectiveness, efficiency, process compliance, and overall measures, to assemble a comprehensive performance structure for operational services (Ge *et al.*, n.d.). An overview of the summarized performance measures is provided in Table 2. Hereafter, the challenges and limitations uncovered by the existing studies are summarized and discussed.

2.1 Perspectives of configurator performance measurement

2.1.1 Effectiveness

Performance indicators, taken from the perspective of effectiveness, demonstrate the extent to which a configurator meets its design objectives. These indicators can be categorized as specification output or product/service quality measures. Specification output demonstrates the thoroughness of information output generated by the configurator, which is crucial for fulfilling the features and requirements of deliverables. Mueller et al. (2022) provided a qualitative comparison of the resulting content between existing and configurator-supported commissioning specification processes in an engineering-to-order company. Tiihonen et al. (2013) characterized the attributes of a series of product sales configurators to examine the modeling variety and demonstrate the applicability of the presented configurator. Gerth et al. (2016) used the number of deliverables, including blueprints and documents, to quantitively compare the detail level of specifications in construction engineering. Nevertheless, product/service quality, a more common measure in the literature, reflects the effectiveness of a configurator through the quality of the deliverables. A typical way to quantify the quality of deliverables is to measure the number of errors. This can be done by counting returns on production lines due to product configuration systems (Kristjansdottir *et al.*, 2018) or evaluating the deviations in results from the configurator (Schobel *et al.*, 2018; Wang *et al.*, 2019). The quality of deliverables can also be compared in the form of variations of the final product through qualitative analysis on a higher level (Gerth *et al.*, 2016).

2.1.2 Efficiency

The efficiency perspective focuses on the resources required to support a configurator. A majority of the reviewed studies reported performance measures on the productivity of configurators in terms of time and/or cost. Time-based performance measures have been proposed under various scopes, including the runtime to complete each task, runtime for the entire configuration process, and total lead time of product or service delivery (Bredahl Rasmussen *et al.*, 2021; Gerth *et al.*, 2016; Kristjansdottir *et al.*, 2018; Mueller *et al.*, 2022; Schobel *et al.*, 2018; Tiihonen *et al.*, 2013). In addition, time-based performance indicators can be used to reflect human resource consumption, typically seen in man-hours (Campo Gay and Hvam, 2022; Kristjansdottir *et al.*, 2018; Mueller *et al.*, 2022). Other common cost factors include configurator development, user training, operations, maintenance, and software licensing (Bredahl Rasmussen *et al.*, 2021; Kristjansdottir *et al.*, 2018; Shafiee *et al.*, 2019, 2021).

Another approach for measuring efficiency is to evaluate the parameter complexity of both the knowledge input and operation input required for a configurator. Knowledge input includes all the necessary information that needs to be gathered prior to the start of a configuration process. A simple way to compare knowledge input complexity is to compare the types of documents required for configuration (Mueller *et al.*, 2022). Shafiee et al. (2017) proposed a complexity classification scheme that can be used for quantifying configurator parameter complexity through a number of input attributes and constraints. The method has been applied to a longitudinal case study to examine the development of integrated sales and technical configurators (Zhang and Shafiee, 2022). Operation input represents human interactions with a configurator through the entire configuration process. Schobel et al. (2018) evaluated a service configurator that supported the development of mobile data collection instruments. The authors quantified the operation input by registering and counting the number of operations to complete each configuration task. Considering the occurrence of human error is inevitable and likely to increase when the complexity of interaction increases, simple and clear operation input is preferred for configurators.

2.1.3 Process compliance

In this paper, the term *process compliance* is used to refer to the degree to which the actual configuration process follows designated guidelines and work procedures. This term should be distinguished from *result compliance*, which assesses the outcome of configurators and is therefore categorized from the perspective of effectiveness. In this context, a major implication of introducing configurators is the alignment of specification processes, and consequently, the reduction of non-value-adding elements. While the reviewed studies placed a strong focus on monitoring the resulting quality improvement and complexity reduction from the perspectives of effectiveness and efficiency, the impact of configuration process changes was rarely mentioned (e.g., Bredahl Rasmussen et al., 2021). Thus, a process compliance prospective is utilized in this paper to investigate the implications of standardization on the configuration process.

Table 1: Methods for configurator performance measurement and data collection in the literature

Research work	**Type of configurator**	**Application of configurator performance measurement**	**Main source(s) of quantitative performance data**	**Main source(s) of qualitative performance data**	**Consideration of performance matrices prior to configurator design**
Forza and Salvador (2002)	Product configurator	Voltage transformer configuration at a small company	N/A	Analysis of configuration software; interviews	Not specified
Trentin *et al*. (2012)	Product configurator	176 medium-to-large-size manufacturing plants in machinery, electronics, and automobile supply	Questionnaires	Questionnaires	N/A
Tiihonen *et al*. (2013)	Sales configurator	14 real-world products and 8 partial products or concepts in various industries	Simulated tests	N/A	Not specified
Gerth *et al*. (2016)	Product configurator	Noise barrier design at a construction engineering consultancy company	Empirical data from the finished projects	Interviews	Not specified
Myrodia *et al.* (2017)	Product configurator	Sales quotation generation for premade structural elements at a building company	Empirical data from the company's spreadsheets and configurator	N/A	N/A
Kristjansdottir *et al.* (2018)	Product configurator	Pump specification process at a manufacturing company	Empirical data from the company's internal systems and project reports	Interviews	N/A
Wang *et al*. (2019)	Product configurator	Preference-based laptop specification design in a university	Experiments	N/A	Not specified
Shafiee *et al.* (2019)	Product configurator	Sales process automation at an engineering-to-order company that produces chemical processing systems	Empirical data from the case company	N/A	N/A
Shafiee *et al*. (2021)	Product configurator	Two engineering manufacturing companies focusing on wind and chemical processing industries	Empirical data from case studies; interviews and workshops	Interviews and workshops	Not specified
Bredahl Rasmussen *et al.* (2021)	Product configurator	Order handling process of balcony products at an engineering-to-order company	Questionnaires	Interviews	Not specified
Zhang and Shafiee (2022)	Technical and sales configurator	Technical configuration and sales processes of a catalyst at an engineering-to-order company	Project reports and documents; steering committee meetings	Semi-structured interviews; questionnaires	Not specified
Schobel *et al.* (2018)	Service configurator	Process modeling and data collection services for researchers and clinicians	Experiments	N/A	Not specified
Mueller *et al.* (2022)	Service configurator	Commissioning service at an engineering company that designs and delivers processing plants	Semi-structured expert interviews	Semi-structured expert interviews; workshops	Cost of configurator development and maintenance
Campo Gay and Hvam (2022)	Service configurator	Electronic prescribing system at the medical department of a hospital	N/A	Not specified	Not specified

Table 2: Categorization of configurator performance measures in the literature

Performance perspective	Performance sub-category	Performance measure	Forza and Salvador (2002)	Trentin *et al.* (2012)	Tiihonen *et al.* (2013)	Gerth *et al.* (2016)	Myrodia *et al.* (2017)	Kristjansdottir *et al.* (2018)	Wang *et al.* (2019)	Shafiee *et al.* (2019)	Shafiee et al. (2021)	Bredahl Rasmussen *et al.* (2021)	Zhang and Shafiee (2022)	Schobel *et al.* (2018)	Mueller *et al.* (2022)	Campo Gay and Hvam (2022)
Overall performance	User acceptance	Use of configurator		QL						QT						
		User satisfaction and acceptance									QL					
	Profitability	Return on investment						QT			QT		QT			
		Project profitability										QL*				
		Yearly turnover					QT									
		Contribution ratio					QT									
Effectiveness	Specification output	Number of documents				QT										
		High-level efficacy by applicability			QT											
		Specification detail													QL	
		Number of documents				QT										
	Product/service quality	Product quality		QL*		QL						QL*				
		Satisfaction of configuration outcome							QT							
		Number/reduction of errors	QL					QT			QT			QT		QL
		Accuracy of calculations/estimations					QT					QL*				
Efficiency	Parameter complexity	Number of attributes			QT					QT	QT		QT			
		Number of constraints			QT					QT	QT		QT			
		Required number of operation inputs												QT		
		Required documents													QL	
	Productivity in time/cost	Product delivery time	QL			QT										
		Required manpower	QL					QT				QL*			QT	QL
		Time to complete configuration			QT	QT		QT				QL*		QT	QT	
		Cost/savings on development						QT		QT	QT	QL				
		Cost/savings on training									QT					
		Cost/savings on operation and maintenance						QT		QT	QT	QL				
		Increased sales due to fast response time						QT								
Process compliance	Standardization of procedures	Products specified and ordered following standard measures										QL*				

QL: qualitative; QL*: quantitative value translated by qualitative data; QT: quantitative.

2.1.4 Overall measures

Some of the studies focused on two important aspects of a configurator, namely profitability and user acceptance. Profitability summarizes both effectiveness and efficiency from a financial viewpoint. Return on investment (ROI) is commonly used for measuring profitability and is typically estimated or calculated as a cost–benefit ratio over a period of 3–5 years to increase reliability (Haug *et al.*, 2019; Kristjansdottir *et al.*, 2018; Shafiee *et al.*, 2021). Compared to productivity from an efficiency perspective, ROI also includes product quality and its associated benefits in terms of cost reduction and sales increase (Shafiee *et al.*, 2021). User acceptance measures the capability and willingness of end-users to utilize configurators, taking subjective human perception into account. Such capability and willingness are commonly measured by use count and user satisfaction surveys, respectively (Freitag *et al.*, 2011; Shafiee *et al.*, 2019; Trentin *et al.*, 2012). In addition, Freitag *et al.* (2011) included both potential- and client-related indicators in the performance measurement of service configuration. The authors argued that the potential-related performance of a service provider's resource availability is also relevant, indicating its ability and willingness to provide a service, and that client-related performance, typically interpreted as customer satisfaction, reflects the influence of external factors on service productivity.

2.2 Reviewing the challenges of configurator performance evaluation

While the reviewed studies considered either one or several perspectives to measure the performance of configurators, the establishment of a comprehensive performance structure was lacking. Instead, a selection from common performance indicators measuring quality and cost was widely favored, as it would provide a direct representation of the resulting performance of configurators. However, without an agreed approach to selecting or deriving performance measures, an unguided selection of performance measures is subject to the risk of bias (Tiihonen *et al.*, 2013). Consequently, the linkage between configurator objectives and evaluation outcome becomes weak. For example, if a configurator project only includes measures related to reductions in time and resource use, it may achieve such aims at the expense of specification quality, which can result in costs that offsets such benefits.

It was also observed that many of the performance measures reviewed solely served the purpose of evaluating the implications of configurators after being in operation, but the leading indicators and process compliance measures did not receive enough attention. Performance results become highly generic and do not always provide sufficient knowledge of the performance drivers in configuration processes. In addition, while the incorporation of configurator development costs during the scoping phase was acknowledged (Mueller *et al.*, 2022), the consideration of planning for performance evaluation in the early stage of configurator development was not present. As a result, the design of configurator data collection is not aligned with performance needs. Such misalignment on one side triggers the limitation of data availability in implementing performance matrices at a later stage; on the other side, data collected without a purpose unnecessarily adds to management expense. Therefore, it becomes necessary to develop a performance evaluation approach that is aligned with configurator development at an early stage.

3 A COORDINATED APPROACH TO CONFIGURATOR DEVELOPMENT AND PERFORMANCE ASSESSMENT

Performance measurements are necessary to assess the effect of a configurator on a company's business processes. These measurements are carried out to determine if the configurator is providing the intended benefits. Therefore, the evaluation must be aligned with the scope of the configurator, including its purpose and requirements. This involves ensuring that the appropriate metrics are selected and that the necessary data are available for measurement and evaluation. To support such tasks, this section develops a coordinated approach that integrates configurator development and performance assessment. The approach is outlined in Figure 1, and the subsequent sections describe each of its steps.

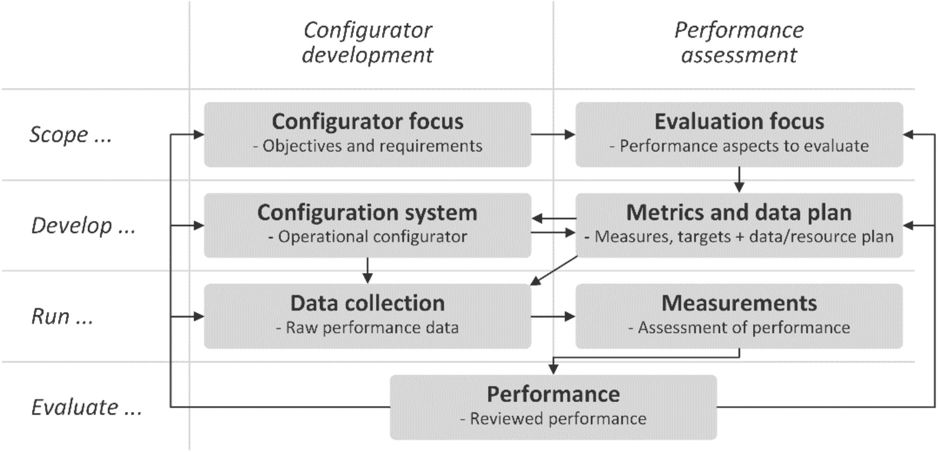

Figure 1: Coordinated approach of configurator development and performance assessment

3.1 Scope: Configurator focus

In configurator projects, it is important to define the scope of the configurator, given their requirements and goals. Several researchers have discussed the scoping of configurator projects (Haug *et al.*, 2019; Mueller *et al.*, 2022; Shafiee *et al.*, 2014, 2018), which involves identifying and defining project objectives and stakeholder requirements. The outcome from the configurator scoping are operational objectives derived from a vision, and explicit stakeholder requirements.

3.1.1 Operational objectives

Configurator implementation has the purpose of improving the current situation into one desired for the future. The vision for how this should unfold may entail fewer process errors, less time, and reduced resources (Shafiee *et al.*, 2014). Choosing the right focus for a configurator project is crucial for its success (Haug *et al.*, 2019). In general, the focus can be either commercial (i.e., sales processes and activities carried out to meet customer requirements) or in terms of product development (i.e., technical processes and activities for selecting and documenting product variants) (Aldanondo *et al.*, 2003; Forza and Salvador, 2006; Haag, 1998; Haug *et al.*, 2019). Different configurator projects have different focuses, which implies that there are different costs and benefits (Haug *et al.*, 2019). The economic feasibility of implementing a configurator differs depending on the company (Forza et al., 2006). To determine a feasible scope, a company should analyze various configuration problems, prioritize them, and decide on the product/service features and functionalities that it should include (Forza and Salvador, 2006; Shafiee *et al.*, 2018). The operational objectives should be formulated based on the scope that has been decided. These may include reductions in lead time and resources, higher quality specifications, general quality improvements, and higher independency from product experts (Shafiee et al., 2014). The operational objectives are to be measured to evaluate the impact of the configurator.

3.1.2 Stakeholder requirements

The requirements of the relevant stakeholders should be determined before configurator development (Haug *et al.*, 2019; Hvam *et al.*, 2008; Shafiee *et al.*, 2014, 2018). Different studies have identified the various stakeholders involved in product configurator projects, including top management, brand/marketing management, research and development, after-sales/service, project management, manufacturing, design, sales, project sponsors, project managers, technical facilitators, model managers, domain experts, change managers, process managers, and programmers. These stakeholders play important roles at different stages of the project and contribute to its success (Haug *et al.*, 2019), and their requirements may be criteria for acceptance or certification (ISO, 2017). Acceptance criteria are the specific requirements that a system must fulfill for it to be accepted by a user, customer, or others, and certification criteria are the standards, regulations, or properties to which the system must conform. These criteria are essential in determining the quality, reliability, and safety of a system, and they include performance, speed, durability, and interface. The requirements can be prioritized according to the importance of delivering each one (Shafiee *et al.*, 2018), thereby providing a focus for the development. The stakeholder requirements will be the boundary conditions to adhere to during development, and conformity to these should be evaluated.

3.2 Scope: Evaluation focus

The next step is to define the scope of the configurator evaluation. The purpose of an evaluation is to reduce risk and increase confidence in the solution (i.e., meeting the requirements and fulfilling its intended purpose). The scope of an evaluation is subject to project constraints, which could be time, cost, resource, and technical limitations. There are many aspects that can be evaluated, and it is important to carefully select the most relevant ones. To ensure that the evaluation is effective, the focus should align with the decided configurator scope. The following subsections describe the aspects of evaluation that should be considered. Ultimately, the outcome of this step will provide a clear understanding of the performance aspects for evaluation to ensure the configurator's success.

3.2.1 Application and success evaluation

Blessing and Chakrabarti (2009) distinguished between application evaluation and success evaluation. Application evaluation aims to determine the usability and applicability of the support (i.e., configurator system) for the intended task (i.e., support business process). Its focus is on identifying whether users can comprehend and use the developed support. Success evaluation aims to assess whether the support is having the anticipated impact, taking into consideration the possibility of unexpected side-effects, with a focus on usefulness. By differentiating between application and success evaluation, two distinct evaluation paths are provided.

3.2.2 Applicability and usability

In terms of usability and applicability, verification and validation (V&V) processes can be used. V&V processes are used to determine whether the developed system conforms to the requirements and satisfies its intended use and user needs (IEEE, 2017; ISO, 2017). The focus is on evaluating the developed system and relations with stakeholders. Verification is about building the system correctly (i.e., conforming to the requirements). This involves a quantifiable assessment of if the criteria of the stakeholders have been met. Validation is about building the right system (i.e., meeting the needs of its users). This involves evaluating with users their acceptance and the suitability of the system.

3.2.3 Success and usefulness

A configuration system's success and usefulness can be evaluated based on its effectiveness, efficiency, and compliance. These factors are related to the operational objectives established during the configurator scoping phase, which includes identifying the business processes to be supported. The impact of the configurator should primarily be measured within the scope of these processes. However, it is possible that processes outside of the scope, such as the indirect effect of reducing the lead time, may also be indirectly affected. Reducing lead time can indirectly improve processes beyond the scope by exposing underlying problems such as unclear instructions or lacking documentation, resulting in improved specifications (Hvam *et al.*, 2008). An example of the direct and indirect impact of a configurator on business processes is depicted in Figure 2.

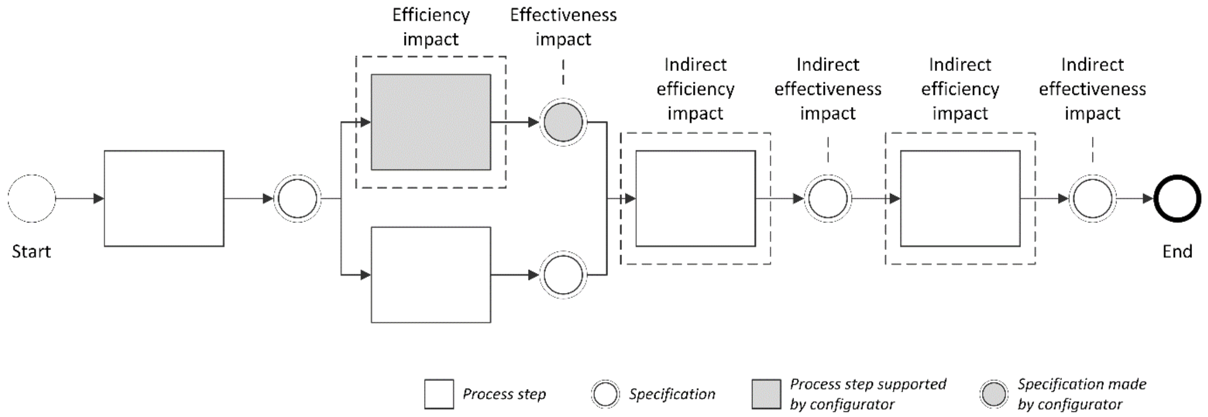

Figure 2: An illustrative example of direct and indirect impacts relative to business processes

It is crucial to distinguish between the direct impact of the configurator's implementation and the potential indirect impact, which may result from other initiatives or factors such as uncovering underlying issues during a development project. Additionally, if the configurator's implementation leads to new business processes, the impact should be compared between the new and the replaced process steps, provided they are encapsulated within the processes. If not (e.g., if the processes require a complete overhaul), measuring from the start to the end of the processes would be more appropriate.

3.3 Develop: Metrics and data plan

The performance evaluation aspects determined in the evaluation scope are on a generic level and need to be translated into concrete performance measures. Such translations are highly case-specific and depend on various conditions, such as the data collection potential, depth of analysis, and available resources. In this section, a question-based heuristic approach derived from the work of Ge *et al.* (n.d.) is applied to guide the determination of performance indicators. The approach involves three steps: interpreting the performance evaluation aspects, establishing performance matrices, and data and resource planning, as illustrated in Figure 3. These steps navigate the establishment of performance matrices from generic evaluation aspects to specific requirements on input data through five interconnected layers, each representing an abstract level. The question-based approach bridges all levels to ensure the alignment of the evaluation objectives and data collection.

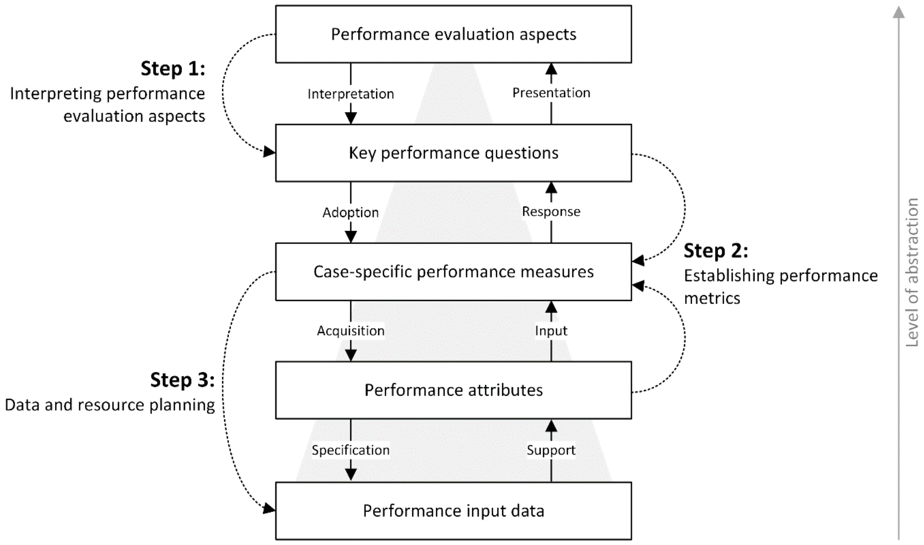

Figure 3: Overview of performance evaluation aspects and maintenance data (adopted from Ge *et al.*, n.d.)

3.3.1.1 Interpreting performance evaluation aspects

The first step is to interpret aspects of performance evaluation through key performance questions. For each performance evaluation aspect, a few performance questions are formulated in a way that can reveal the most critical and relevant information of each aspect. The formulation of performance questions is iterative, whereby design methods such as brainstorming can be utilized at the beginning phase to increase the degree of creativity (Chulvi *et al.*, 2012). Note that each question should only target one aspect and, at the same time, decouple from other aspects when possible. The initial questions are then grouped, sorted, and shortlisted with the aim of comprehensively covering the most representative views of the aspect. The final number of questions for each aspect will preferably be no more than three and should be phrased in a clear, easy-to-understand, and precise way to avoid misinterpretation. A list of key performance questions, in response to the performance evaluation aspects, is obtained at the end of this step.

3.3.1.2 Establishing performance metrics

The second step is to establish performance metrics so that the key performance questions are aligned with measurable performance attributes. A list of the existing performance indicators that are related to the configuration process in the case organization should be obtained at the beginning of this step, if applicable. For each key performance question, it is important to begin by going through the list and checking if any of the existing performance indicators can be adopted to answer the question. Reusing the existing performance indicators from the current performance measurement system, instead of creating new ones, is always preferred, as it can reduce the redundancy across performance metrics and increase management efficiency. If none of the existing indicators can respond to the performance question, a new performance measure should be formulated, specifying the performance attributes and calculations. A list of preliminary performance measures for the configurator project is obtained at the end of this step.

3.3.1.3 Data and resource planning

Data and resource planning begins by establishing the links between performance measures and retrievable data. It is crucial to identify the relevant data sources, such as enterprise IT systems, configurator event logs, surveys, and interviews, and to create a plan for acquiring the data and processing it. The level of effort required to obtain performance results varies. Simple calculations on quantifiable data can be executed by business intelligence software, which can also automatically update the results when new data are available. Dedicated algorithms can evaluate quantifiable data with one-time programming efforts, and the results can also be automatically updated. However, when handling qualitative data such as input data, which involve non-standardized text content that cannot be calculated numerically, a certain level of manual processing is necessary and thus demands greater effort for reporting. This involves determining the appropriate measurement frequency, which may range from daily to monthly or be at the end of each development cycle to ensure the data are collected, processed, and available for the measurements.

In cases where data cannot be obtained, the key performance question should be adjusted to accommodate the issue while still representing its performance evaluation aspect so that new performance measures can be formulated.

3.4 Develop: Configuration system

After both the metrics have been chosen and the data and resource plan has been formulated, the configurator development can commence. A structured development procedure for configurators has been developed by Hvam *et al.* (2002) and Hvam and Ladeby (2007). This procedure is guided by the configurator scope and consists of seven phases from analysis, through design and programming, to implementation and maintenance. The first phase involves examining and modifying the business procedures that are impacted by the configurator. This includes defining and setting limits for the configurator's support of these procedures. Once this has been done, the second phase is to investigate the product/service line and recognize the various modules and their connections. In the third phase, object-oriented methods are used to finalize the configurator design and to define the requirements and the user interface. The fourth to sixth phases include the creation, programming, and deployment of the configurator within the organization. The final phase, the seventh, is centered on the ongoing operation and maintenance of the configurator. The configurator should be developed with the aim of evaluating the impact and if the requirements have been met. For this, the configurator should be built with the capability to collect and store the necessary data on use and impact for making the measurements.

3.5 Run: Data collection

After the development and during the deployment and operation of the configurator, the necessary data for the performance assessment should be collected. To ensure accurate and effective data collection, the data and resource plan should be followed to collect the correct data in a timely manner and using the appropriate resources.

3.6 Run: Measurements

To achieve an assessment of the performance, the collected data should be processed. This involves transforming and cleaning the data to prepare it for analysis using the designated metrics. The outcome consists of performance measurements, and any gaps in the targets can be identified. A report of the assessment can then be made.

3.7 Evaluate: Performance

After conducting the performance assessment, the results can be evaluated against the configurator's scope, targets, and identified gaps. Based on this evaluation, the configurator's impact can be reviewed and an informed decision made about the direction to proceed.

As shown in Figure 1, the following are potential steps to revisit:

- Configurator focus: If the configurator does not address the underlying issues comprising the scoping, a revised scoping is needed.
- Configurator development: Development is continued with an understanding of the features and functionalities to prioritize to overcome the performance gaps.
- Data collection: Additional data are needed, possibly to study the long-term effects and impact.
- Evaluation focus: Changing the focus to evaluate other or additional aspects of the performance.
- Metrics and data plan: If the metrics do not provide an accurate assessment of the performance, other metrics are needed. Additionally, if the selected data are unavailable or difficult to collect, the data and resource plan should be revised.

The configurator development and performance assessment can then be continued to maintain focus and ensure a sustained impact.

4 RESEARCH METHOD

The aim of the empirical study was to investigate the usefulness of the developed approach for integrating performance measures into configurator projects based on the effects of early considerations and preparation for performance assessment measurements. Given the high number of variables involved in such investigations, a case study approach was chosen, since this allows for an in-depth study of the research phenomenon (Voss *et al.*, 2002). The case study was a longitudinal field study that followed the development of a configurator at a company, during which the researchers of this study conducted the performance assessment. This had two main objectives: (1) to evaluate if the proposed approach would support the development process, and (2) to evaluate the suitability of the performance assessment provided by the approach to determine whether the goals and objectives of the configurator implementation had been met.

4.1 Case company

The case company has over 1000 employees and operates large offshore production plants in the North Sea. A large number of maintenance jobs must be prepared promptly to ensure safe and reliable production on these plants. Maintenance work orders are used to specify the details and requirements for maintenance jobs to ensure that such jobs are carried out efficiently and effectively and in compliance with applicable standards and regulations so that a suitable crew can be planned and spare parts ordered in a timely manner. In this context, the company aimed to be able to configure the scope and content of the maintenance work orders, including the required tasks and resources, the parts and materials needed, and the estimated duration. It should be noted that maintenance is a new area of application for configurators, which elevated the importance of properly scoping the configurator, supporting its development with performance measurements, and accurately evaluating the impact of introducing configurators in this field.

4.2 Data collection and analysis

The configurator project in the case company was studied throughout its 12-month development process, from 2021 and 2022 (2 months of scoping and 10 months of actual development). During this period, three data collection processes took place that involved multiple methods to improve the validity of the study (Jick, 1979; Voss *et al.*, 2016). First, data were extracted from the enterprise IT systems and configurator event log to determine the performances before, during, and after the project. Second, during the project, the researchers attended company meetings and workshops to gather participatory observations from the individuals involved in the configurator development process. Additionally, semi-structured interviews were conducted with managers to understand the scope, aim, and targets of the process and with future users to understand the usefulness and applicability of the configurator. Third, data were collected through semi-structured interviews with managers to determine whether the goals and objectives of the configurator implementation had been achieved. Specifically, the managers were asked to evaluate the proposed approach, estimate the impact of the configurator, and assess the alignment between the performance evaluation and configurator scope. The data acquired from the workshops and interviews were analyzed by (1) identifying relevant statements, (2) categorizing statements according to the subject, and (3) synthesizing the categories of statements into generalized descriptions. The data collection process is summarized in Table 3.

Table 3: Data collection

Objective	Data collection method	Attendees/Resources	Sessions
Understand how the proposed approach supported the development process	Semi-structured interviews with managers	1 maintenance manager 1 digitalization manager	4 meetings (60 mins each)
	Semi-structured interviews with users	5 maintenance work preparers	15 meetings (30–60 mins each)
	Participatory observations during meetings and workshops	5 maintenance work preparers 1 maintenance manager	8 workshops/meetings (30–120 mins each)

		1 digitalization manager 2 software developers	
	Extractions from enterprise IT systems and the configurator event log	1 maintenance engineer 1 software developer	2 extractions from the enterprise IT system; weekly extractions from the configurator
Evaluate the effects of the configurator and the accuracy of the performance assessment	Semi-structured interviews with managers	1 maintenance manager 1 digitalization manager	2 meetings (60 mins each)

5 CASE STUDY

This section describes the application of the proposed approach in the case company's *maintenance work* configurator project through the stages of initial scoping, development, and post-development. Hereafter, the proposed approach is evaluated.

5.1 Initial scoping of the configurator

Prior to developing the configurator, an analysis was conducted on the initial situation at the case company. The purpose was to assess issues in the business processes and initial conjectures and observations. The findings of this analysis were then used in scoping the configurator project. Table 4 describes the steps performed and the respective outcomes.

Table 4: The steps and outcomes in scoping the configurator project

Step	**Outcome**
Scope: Configurator focus	The initial observations and conjectures in the case company highlighted issues in maintenance preparation, including repetitive tasks, piling up of work, long lead times, inconsistencies in content and scope, and high variations in quality.
Scope: Evaluation focus	As a representation, the preparation team responsible for pumps and valves was selected as a sample, as their work was typical of most maintenance tasks. It was known that there were no specific compliance guidelines (i.e., work was highly experience-based) other than legislative rules and regulations, so the focus was on assessing efficiency and effectiveness, both direct and indirect.
Develop: Metrics and data plan	The metrics considered for assessing the efficiency and effectiveness are presented as follows: Time (efficiency): - Time to prepare a maintenance job Time (indirect efficiency): - From start to finish—from a notification of a failure to a prepared solution and until the maintenance had been carried out Variance (effectiveness) - Differences/consistencies in the maintenance prepared for the same failures - Differences in the estimated hours for similar work (average, mean, and/or of delta) Rework (indirect effectiveness) - Changes (add, remove, revisions) to the prepared maintenance in later processes Investigate if the notifications of failures were accumulating faster than a solution could be prepared to assess the health of the processes (i.e., if they were constantly under pressure or keeping up): - Number of unsolved notifications of failures then and that had existed over time, normalized by comparing how many persons had been employed in the team over time, and how many failures had been notified over time Data and resource plan: - Most of the data could be collected from the case company's enterprise software system, SAP, and other IT systems. To supply the remaining data, interviews with maintenance preparers and observations of their work were conducted.
Run: Data collection	The necessary data for the assessment, as specified in the data plan, were collected over a period of 1 month.
Run: Measurements	Data and measurements were prepared and cleaned using Qlikview business intelligence and data visualization software. For some of the measurements that were not to be reused during or after development, the analyses were done using Microsoft Excel.
Evaluate: Performance	There was the potential for developing a configurator for maintenance preparation. The aim should be to make the time-consuming preparation process quicker, enabling faster resolution of failures.

	Additionally, the quality of the specifications was improved and the non-value-adding variance decreased by introducing consistency in terms of content, structure, comprehensiveness, and descriptions to, for example, minimize the need for later changes, revisions, and reworking.

As shown in Table 4, the coordinated approach proposed in this paper ensured a structured process for making informed decisions about the scope of a prospective configurator in the case company, resulting in a prioritized focus area with clearly specified boundaries.

5.2 Performance assessment during development

Based on the initial investigation of the current situation, the case company decided to build a configurator. This configurator should generate maintenance operations lists that would include task descriptions, the necessary competencies to complete the task, the required number of people, and the duration, as well as the necessary materials and tools required. The following section presents the implications of using the proposed approach for the configurator's development.

Since maintenance is a relatively new domain for configurators, it can be a challenge to set specific performance objectives and targets to be achieved by implementing a configurator because the impact is not yet fully understood. Thus, the objectives and targets were discussed extensively among the company employees, managers, and configurator project members. With the objective of improving the quality of the specifications, expediting the time-consuming preparation process, and decreasing the non-value-adding variance of maintenance work descriptions, the following targets for the configurator project were formulated:

1. **Effectiveness target**: Achieve a reduction in preparation errors from 5% to below 2%
2. **Efficiency target**: Reduce time consumption by 80%
3. **Process compliance target**: Attain a 95% reduction in the variability of work descriptions

The case company's approach was iterative and aimed to develop an initial configurator with basic functionality to test and improve upon. The development phase lasted 10 months, including 2 months dedicated to initial development before launching to key users followed by 8 months for further development and refinement, with more intense development efforts at the beginning. Once the configurator had been launched, the performance could be measured, with a focus on evaluating the use of the configurator, the effectiveness impact, and the efficiency impact. Detailed quantitative measurements for these aspects can be seen in Figure 4. The selection of measurements was a result of the time constraints (i.e., being able to make valid measurements within the time available) and data availability (i.e., being able to acquire certain data).

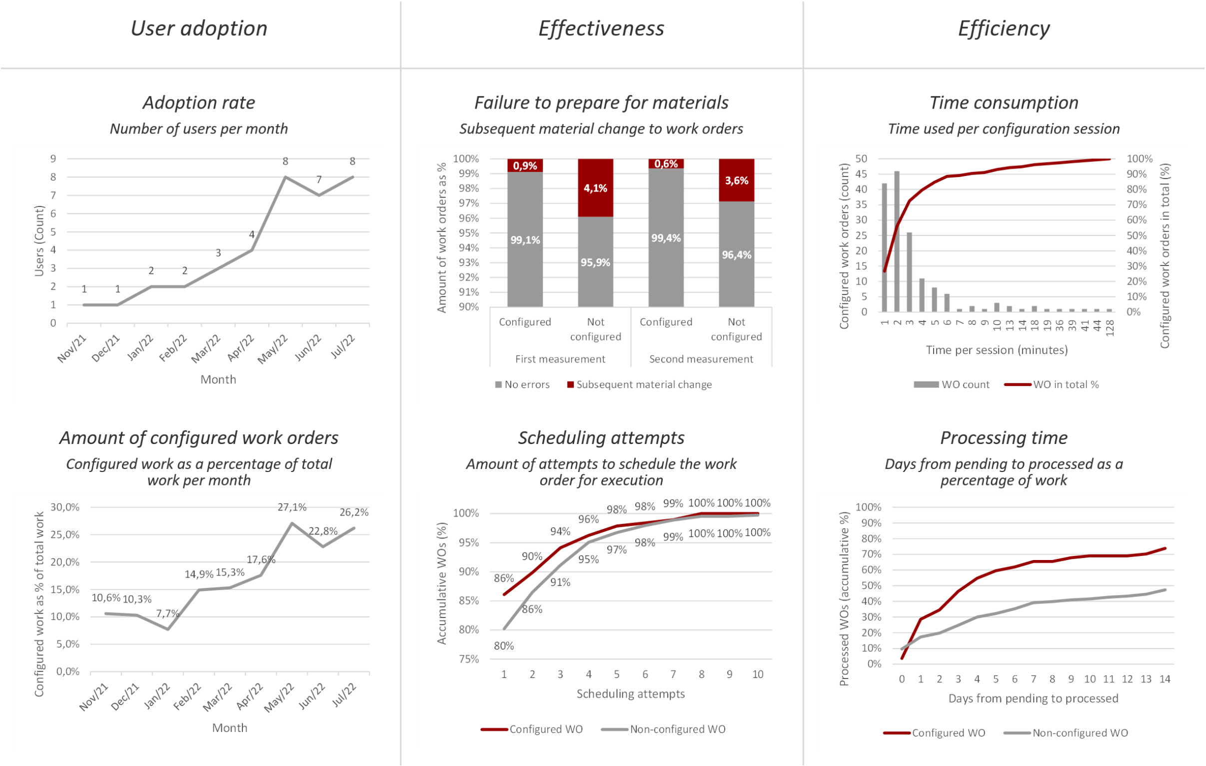

Figure 4: Quantitative performance measures used in the development of the configurator

The measurements presented in Figure 4 provide valuable insight into the developed configurator. In terms of the use of the configurator, the number of users of the system was an important metric for measuring the adoption rate. Another useful measure was the number of work orders configured relative to the total number of work orders created, which enabled measurement of the extent to which the configurator had been used over time.

In terms of effectiveness, an important measure that was identified was the amount of rework required later on in the maintenance delivery process. Specifically, failing to prepare materials was measured, for example, in cases in which the scope of the work order was to replace a piece of equipment but a spare part was not accounted for. This measurement required some complicated manual data extractions, resulting in only two measurements being made. However, both measurements showed the configurator to have had a positive impact. Another measurement was of the number of attempts made to schedule work orders for execution, which reflected issues such as uncertainties about the scope of work, imprecise estimations of duration, and necessary tasks that had not been prepared. The positive effectiveness impact was also evident here, and it is worth noting that the non-configured work required up to 23 attempts before completion.

To measure efficiency, the time spent on configuration was used to reflect the direct efficiency impact. Users' sessions on the configurator were measured from start to finish, and the results showed that the majority of users only took a few minutes to configure work orders, at an average of 2.5 minutes, and 5 mins or less to generate 85% of the work orders. While a direct comparison with non-configured work orders could not be made, as the time taken was not logged, maintenance planners stated that it typically took 10–30 minutes to prepare such work orders. Therefore, it can be concluded that the configurator had a positive direct efficiency impact. Another measurement was of the processing time from when a failure was observed and a work order was pending preparation to it being prepared and processed. It was found that many configured work orders were prepared faster than non-configured ones, indicating that the backlog of pending work orders was being cleared more quickly. Users also reported that the repetitive and simple work orders could be quickly and easily completed using the configurator, allowing them to focus their efforts on more complex tasks.

Regarding process compliance, the configurator inherently enhanced compliance through transparent and traceable knowledge-based decision support. The work orders generated by the configurator were based on the content of a knowledge base. The knowledge base was assembled based on historical data and discussions with domain experts about best practices, regulations, standards, guidelines, etc. Before the implementation of the configurator, it was found that there were 23,667 different wordings for 43,351 maintenance activities. The use of the configurator significantly reduced this to 66 standardized activities that could be combined and matched for 581 defined equipment types. It was possible for users to make changes to the output (e.g., change the wording or duration add tasks). These changes were measured and manually evaluated for non-compliance or for the need to update the knowledge base.

In conclusion, the case company achieved its initial targets for the configurator. The number of errors related to materials was less than 1%. The average time spent on work preparation using the configurator was measured and compared to the times reported by maintenance preparers, resulting in a time reduction of 75–92%. Additionally, the variability of work descriptions was reduced by more than 99%, indicating increased consistency and standardization. The initial targets had been fulfilled.

After its launch, a total of 19 versions of the configurator were developed and implemented, which included fixing general bugs such as outliers, irregularities, and blank fields. However, more significant issues were identified through measurements, including those of stability and speed. Lost and crashing sessions were observed in the data, and the application was slower than the users had expected. Additionally, one-time measurements revealed that some of the maintenance activities targeted by the configurator were not part of the configured work. Investigations of and updates to the configurator and knowledge base were made to better cover these. The data necessary to make these measurements were not available without considering the data collection early on and incorporating it into the design of the configurator.

5.3 Performance assessment after development

Throughout the configurator’s development, relevant measurements were obtained and secured to continuously monitor and evaluate the performance after deployment. A digital dashboard was created using QlikView software for key employees to track the system’s performance, with a particular focus on assessing changes. This involved examining whether usage remained consistent and if there had been any changes, either positive or negative. The monitoring involved oversight of the target gaps and evaluating if the current state could sustain their achievement or if adjustments were necessary, such as setting new targets, further development of the configurator, or introducing new metrics. The effects of the configurator throughout its development are summarized in Table 5. Overall, the company was satisfied with the effects and the performance of the configurator that had been developed and would continue to increase further the number of users and the configurator’s usage.

Table 5. Effects of the configurator project throughout the development

Dimension	**Measure**	**Effect of the configurator project**		
		Before development	***End of development***	***4 months after development***
User adoption	Number of users per month	N/A	3	8
User adoption	Configured work as a percentage of total work per month	N/A	15.3%	26.2%
Effectiveness	Subsequent material change rate	6.1%	0.9%	0.6%

Effectiveness	Percentage of work orders executed on the first scheduling attempt	51.1%	73.5%	86.1%
Efficiency	Configuration session completed within 5 minutes	N/A	84.7%	88.2%
Efficiency	Percentage of work orders from pending to processed within 14 days	48.5%	74.0%	72.1%
Process compliance	Maintenance activity wordings	23667	66	66

5.4 Evaluation of the case study

As the description of the configurator project in the previous sections suggests, the strong focus on performance measures helped the company steer the project in a fruitful direction, in the sense that the configurator was continuously modified to increase the benefits produced. Thus, the case study demonstrated the value for configurator projects of using performance measures from early on in the process. A central explanation for the company's structured use of performance measures was the application of the approach developed in this paper. By following the development process and adopting an approach incorporating performance assessment, the progress of development could be monitored and evaluated. This ensured that the focus was on achieving the targets and taking informed actions to reach them. The continuous review of performance and the ability to make changes enabled the development to become more agile. The value of the approach is summarized in Table 6, which is based on the statements made by employees in the case company during the interviews.

Table 6. Evaluation of the proposed approach

Objective	**Evaluation**	**Explanation**
Supporting the development process	Ensured a structured process for making informed decisions about the scope of the prospective configurator	The maintenance manager and the maintenance engineer perceived the approach as providing guidance in assessing the existing situation and identifying opportunities for the configurator, leading to the company being more confident in the scope of the configurator, resulting in a prioritized focus area with clearly specified boundaries.
	Ensured that performance was measured before and during implementation	Without this approach, the digitalization manager and software developer considered it likely that they, for example, would have overlooked many relevant measures before and during implementation.
	Ensured that relevant performance information was acquired to perform iterative development cycles to focus the development efforts	Both the digitalization manager and software developer believed that the approach enabled them to justify the direction of the next development cycle based on performance assessment, avoiding subjective decisions.
	Ensured comparable and stable measurements during the project stages to measure the impact of the implemented changes	The digitalization manager found that the approach enabled continuous monitoring of development progress and performance, replacing the time-consuming analyses they would have considered conducting towards the end or after development.
	Helped define a common performance perception for all the stakeholders involved	The maintenance and digitalization managers, maintenance preparers, and maintenance engineer all stated that the approach facilitated a common perception of performance to be shared and discussed among stakeholders, as opposed to each stakeholder having their own formal or informal perception, which might be difficult to align.
	Made it possible to account for changes to the configurator and plan the performance assessment accordingly to maintain measurements	The digitalization manager and software developer expressed that the structured approach enabled them to justify changes to improve the performance of the configurator, and it enabled accounting for these changes in the assessment (e.g., ensuring usage data were still collectible).
	Required more effort for performance assessment planning early on in the development phase to improve performance evaluation quality	The digitalization manager found that they had to put more effort into the planning and selection of measures and into the collection of data earlier on in the project but recognized the necessity of this to improve the accuracy and quality of the performance assessment.

Ensuring the completeness and accuracy of the performance assessment	Ensured a fit between the objectives and requirements and the evaluation of the developed configurator	The maintenance and digitalization managers perceived the systematic approach to have instilled confidence in the company, affirming that the configurator was not just successful but one that had been specifically designed to address the company's challenges.
	Ensured that the necessary data were available for measurements during early-stage performance consideration and planning	Both the maintenance and digitalization manager stated that the systematic approach had helped ensure the collection of data. This included usage data stored in the configurator and certain data extracted from the ERP system, that would otherwise have been difficult to obtain.
	Ensured an appropriate comparison between the existing situation and the achieved target situation and during the transition between them	The maintenance manager stated that a more reliable and trustworthy comparison had been established because the foundation for the assessment relied on the same measures and data.
	Ensured a transparent and reliable assessment of the impact achieved by implementing the configurator	The maintenance and digitalization managers both found that the company had gained confidence in the configurator's impact due to the clearly traceable and well-defined process from the selection of measures, through the sourcing of data, to performing the impact assessment.

6 DISCUSSION

In this section, the implications of the findings for practitioners and researchers are discussed and directions for future research suggested.

6.1 Implications for research

The present study was prompted by the findings from the reviewed literature, which showed that a structured approach to performance assessment was missing. To address this gap, the present study developed a structured approach to performance evaluation in configurator projects, covering configurator scoping, development, and post-deployment phases. A case study demonstrated the usefulness of the proposed approach in the process of developing and deploying a configurator. Specifically, the use of the approach led to performance insights that informed decision-making throughout the development process, which was achieved by providing a structured approach from an early stage. Furthermore, the approach helped overcome data availability issues by promoting performance assessments throughout the development phase. Overall, the case study demonstrated the crucial role of performance evaluation in configurator projects as well as the positive prospects of using configurators for maintenance work orders. With these findings, the present study extends the existing research on the development and implementation of configurators (e.g., Haug *et al.*, 2012; Haug *et al.*, 2019b; Hvam *et al.*, 2006, 2008; Forza and Salvador, 2006; Ladeby and Oddsson, 2011; Walcher and Werger, 2011).

6.2 Implications for practice

The proposed approach provides a structured approach for practitioners to support the development of a configurator and be able to evaluate its impact. In the case study, the approach was found to be useful and helpful in scoping the configurator project and carrying out measurements for development in an agile and iterative way. This enables practitioners to proactively iterate to better achieve their objectives and requirements. It is not a one-time measurement but a continuous process of evaluation and improvement, also after deployment. The case also demonstrated that configurators can be applied in the maintenance field to configure work orders with significant improvements. Given the life cycle of IT systems, the developed configurator must be maintained and regularly reviewed for further development. In this regard, assessments and evaluations can also be made to ensure ongoing effectiveness and alignment.

6.3 Limitations and further research

The present study has some limitations and opportunities for future research. The proposed approach was tested in only one case company, which calls for further testing in multiple case studies to assess its generalizability and validity (Voss *et al.*, 2002). A potential area for investigation could be the application of the approach for developing configurators in new fields, such as service configurators (Mueller *et al.*, 2022), to support exploring whether the same benefits can be achieved in these domains. The present study focused on proposing an approach encompassing several aspects of performance assessment and evaluation. However, due to the scope of the study, details regarding each aspect were not fully provided. Further research could investigate these aspects in detail in relation to the proposed approach of this study.

7 CONCLUSION

The study highlights the need for a comprehensive performance structure and a coordinated approach that integrates development and performance assessment. The proposed approach ensures data availability early in development, provides continuous evaluation for focused development, and promotes a transparent and reliable assessment of the impact achieved by implementing a configurator. Since this approach was applied in a case company, the study shows that it can help stakeholders to make informed decisions, provide valuable performance information, and ensure a fit between the configurator scope and the performance evaluation. Conclusively, this can lead to more effective and efficient configurator projects that align with the intended aims and goals.

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