A Digital Assistance System for Maritime Commissioning Processes

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Abstract

This dissertation proposes a Digital Assistance System (DAS) consisting of an authoring assistant, a commissioning assistant, and a Digital Twin to address maritime commissioning challenges. The authoring assistant improves commissioning plan creation by employing automation. The commissioning assistant uses IoT technology to streamline testing and documentation. The Digital Twin connects the DAS to the shipyard's IT infrastructure. The evaluation of the DAS shows reduced execution times and error rates, with high usability. The evaluation also identifies long-term benefits such as digital certification and efficient maintenance planning.

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Hamburg, October 2024 Ahmed Elzalabany

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List of Abbreviations

BOM	Bill of Materials
BPMN	Business Process Modeling and Notation
CAD	Computer-Aided Design
DAS	Digital Assistance System
DSR	Design Science Research
ERP	Enterprise Resource Planning
IoT	Internet of Things
IT	Information Technology
PLM	Product Lifecycle Management
UML	Unified Modeling Language

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1 Introduction

Shipbuilding is an example of a *One-of-a-Kind Production* (OKP) process, in which the design and manufacturing processes are engineered to meet the customer's unique requirements and specifications [Stei12, P. 1]. In contrast to mass production, the OKP process is characterized by inherent uncertainties and necessitates a relatively longer time for its completion. For example, on average, a cruise ship takes 36 months to construct and launch [Seew15]. The long duration necessary for the transfer of the ship to the customer results in significant expenses for both the shipyard and the customer, which adversely impacts the business. Hence, shipyards are actively pursuing strategies to minimize the delivery time of ships to customers, while also maintaining or enhancing the overall quality.

The transfer of the ship to the customer occurs in the shipbuilding industry upon completion of a process known as *ship commissioning*. When all specified standards and requirements are satisfied and verified, a ship is successfully commissioned. Ship commissioning, which is a vital aspect of the shipbuilding process, lasts at least 12 months and involves the testing of all systems and components on the ship. This long time is owing to the ship's large number of components, as well as the complicated arrangements of these components. To maximize efficiency, the commissioning process runs concurrently with the production process, thereby minimizing time and increasing throughput.

Ship commissioning encompasses three primary processes, namely preparation, implementation, and documentation. The process of commissioning preparation entails the creation of technical documents that are specifically tailored for each individual component within the ship. These documents outline the procedures and methods for conducting tests and verifying the functionality of the components. Additionally, time plans for commissioning are created during the preparation process. Once the preparation process has been concluded, the commissioning implementation process commences by executing all the designated testing procedures as outlined in the preparation documents. The process of commissioning implementation occurs across several stages of shipbuilding, involving the participation of different stakeholders. Ultimately, the outcomes of the implementation process are documented through the use of checklists and protocols, which are signed by all stakeholders, so signifying a successful completion and handover of the ship.

1.1 Motivation

The commissioning process follows a traditional paper-based workflow. The use of physical paper for printing testing documents, time plans, and protocols results in various deficits. The dependence on paper hinders the efficiency of creating, editing, and distributing the documents required for commissioning. This practice poses challenges in extracting information and often results in errors during the implementation of commissioning tests. Moreover, the process of documenting testing outcomes on physical paper is both time-consuming and unreliable, which increases the likelihood of undetected errors and subsequently leads to a decrease in quality.

Furthermore, performing commissioning activities while the ship is still under construction causes conflicts and disruptions. The current shipbuilding workflow is incapable of maintaining a dynamic overview of all production tasks that may interfere with the commissioning process. Consequently, it is currently unavoidable for commissioning personnel to experience losses in productivity due to such interferences and disruptions. In addition, commissioning tests must be performed in a correct order, as defined by the technical dependencies between the ship components. However, such technical dependencies are not properly documented due to the ship's large number of components and the inability to accurately represent all technical dependency paths using paper documents. An incorrect task execution sequence results in a loss of time and effort, which also leads to a decline in quality.

Upon analysis of the deficits associated with the commissioning process, it is evident that the absence of a centralized information management system emerges as a prominent factor contributing to these deficits. Enhancing the efficiency of information flow and utilizing digital technologies within the maritime commissioning field has the potential to improve the processes of creation, provisioning, and interpretation of information. Digitalization is experiencing significant growth in multiple sectors within the maritime industry, including production, maintenance, and retrofitting. This trend is primarily driven by the need to address challenges arising from ineffective information management.

Research in the maritime domain investigates various technological solutions aimed at addressing typical deficiencies in workflow processes. One instance of such technology includes digital assistance systems that are equipped with navigation and visualization capabilities. Digital assistance systems are interactive multimodal information systems that offer dynamic information provision to field workers, thereby mitigating the issues of clutter generated by paper documents. The utilization of a digital assistant in the shipbuilding sector has been found to enhance workers' productivity and enhance the quality of work when compared to traditional workflow methods [Hala18, P. 145, Melu22, P. 107].

A digital assistance system is commonly integrated with a sophisticated information management infrastructure, which is in turn connected to the shipyard's Product Lifecycle Management (PLM) and Enterprise Resource Planning (ERP) systems. For example, a Digital Twin-based infrastructure facilitates the creation of a virtual and dynamic representation of the shipbuilding process. This enables the acquisition of real-time data from production, which can be utilized for enhanced planning and collaboration. Accordingly, a digital assistance system that utilizes a Digital Twin infrastructure can be applied in the maritime commissioning field to solve the problems resulting from the conventional paper-based workflow.

1.2 Research Objectives

The primary aim of this dissertation is to design and implement a digital assistance system for enhancing the productivity of commissioning personnel and improving the overall quality of their work. The assistance system aims to reduce the effort required to prepare commissioning content, provide commissioning personnel with real-time data from the production field to prevent conflicts and disruptions, and automate the documentation process to save time and reduce errors. To achieve this objective, the following three steps are required:

Identification of Deficits in the Commissioning Process

A digital assistant supporting maritime commissioning personnel aims to eliminate conventional workflow deficits. Therefore, analyzing and determining the causes of such deficits is necessary. The analysis result identifies areas with potential for improvement and provides the requirements for developing the digital assistance system.

Development of a Digital Assistance System to Improve the Process

The initial stage of development involves the construction of models that represent the maritime commissioning process in terms of its structure and behavior. Additionally, appropriate technologies are selected to establish the necessary infrastructure for the digital assistance system. Moreover, it is imperative that the digital assistance system infrastructure incorporates interfaces to facilitate the retrieval of data from the shipyard's existing PLM and ERP systems.

The digital assistance system serves the commissioning personnel by reducing the manual effort required to carry out the tasks in all processes of commissioning. In the preparation process, the assistance system is designed to automate the process of authoring technical documents so that the commissioning personnel does not have to manually create an inspection sheet for every component in the ship from scratch. The system users can reuse testing data from other ships to automatically create inspection sheets with low effort.

During the process of commissioning implementation, the digital assistance system aids workers by retrieving work packages that are not in contradiction with the ongoing production activities. This strategy enhances workers' productivity by eliminating the need for preparatory visits to the production site in order to ascertain the absence of disturbances at the site. In addition, the digital assistance system has the capability to provide support to workers by selectively activating work packages that meet all technical dependency requirements, hence minimizing the occurrence of errors resulting from performing tests in the wrong sequence.

For test documentation, workers use measurement devices to read data from components and systems within the ship. The integration of Internet of Things (IoT) technology into the digital assistance system's infrastructure enables an effective documentation strategy by automating the acquisition of measurement data from the ship components. This approach has the potential to reduce the time and effort while simultaneously enhancing the precision of documentation.

Moreover, the utilization of a reliable digital documentation system can facilitate the effective storage and retrieval of data, while also presenting the opportunity to perform electronic certification of commissioning protocols. The use of electronic certification has the potential to improve coordination among all stakeholders, leading to increased efficiency in the final acceptance stage.

Assessment of the Developed Digital Assistance System

The developed digital assistance system should provide advantages over the conventional commissioning workflow. Moreover, the system should offer easy integration into the existing shipyard infrastructure and user-friendly handling. Consequently, the developed system must be systematically evaluated against the conventional workflow in terms of productivity, quality, integration capability, and user acceptance.

1.3 Research Methodology

This dissertation emerged as a result of a three-year research project called *smart.START*. The project was funded by the German Federal Ministry for Economic Affairs and Climate Action and involved three major shipyards as industry partners [Wirt23]. Therefore, the definition of requirements and development of the digital assistance system for maritime commissioning have taken place in close collaboration with professionals from the partner shipyards.

Involving industry experts was necessary to acquire knowledge about the conventional process of commissioning and to ensure that the solution to be developed attains industry relevance. Therefore, it was essential to conduct the research and development work in accordance with a research methodology that allows for continuous and iterative solution development while simultaneously contributing to a theoretical knowledge base. Due to its adaptability to an agile and iterative development workflow, the Design Science Research (DSR) methodology [Hevn04, P. 80] was utilized for requirement definition and solution development.

The DSR research methodology is well-suited for different fields including engineering and information technology. The primary objective of DSR is to advance scientific knowledge and technology in the selected domain through the creation of innovative *artifacts* that are specifically designed to solve the problems identified in the research process. Examples of such artifacts include models, methods, and software prototypes. The implementation of DSR yields novel artifacts and design knowledge (DK) which explains how the created artifacts may improve (or hinder) the domain in which they are utilized. Figure 1 illustrates the research framework of DSR.

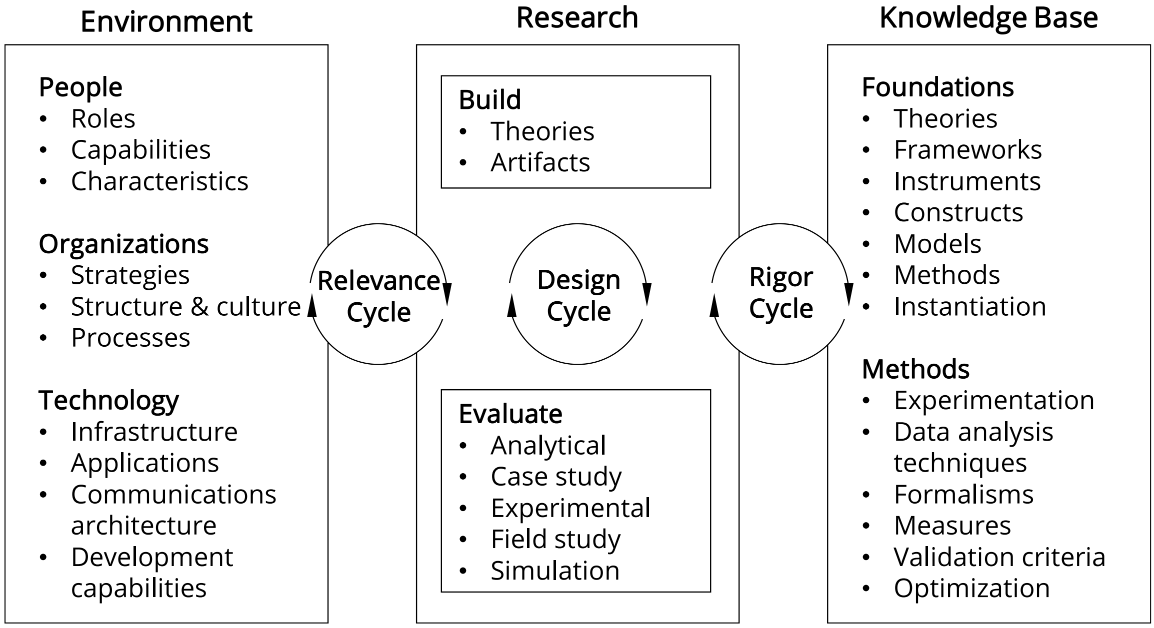


Figure 1: Design Science Research framework [Hevn04, P. 80]

The DSR framework operates on three levels explained as follows:

- **Environment**: defines the research problem by considering the affected stakeholders (people and organizations) and the existing or planned technologies. In this dissertation, the environment level encompasses the shipyards, their personnel, and the existing information technology infrastructure of the shipyards.
- **Research**: includes theories to address the identified problem and the design of relevant artifacts. The research level also contains the evaluation results in the form of case studies, simulations, or experiments. In the context of this dissertation, the research level includes the activities and methods for developing and evaluating of the DAS.
- **Knowledge base**: contains the scientific foundations, e.g., theories and models, and the methods for scientific research work, e.g., data analysis techniques and measures. In this dissertation, the knowledge base comprises discoveries related to the improvement of maritime commissioning processes through the utilization of the DAS.

The above-mentioned levels are interconnected by three iterative cycles. These cycles are explained as follows:

- **Relevance:** in this cycle, the researcher identifies the research problem and consistently evaluates it in relation to the stakeholders' requirements to assure relevance of the research. Simultaneously, the artifacts that have been created undergo iterative examination inside this cycle to verify their relevance to the problem, as seen by the stakeholders. In the context of this dissertation, the relevance cycle entails collaborating with shipyard experts to define the essential criteria for developing a DAS capable of addressing the limitations of the conventional maritime commissioning workflow.
- **Design:** the development of artifacts follows a cyclical process. The objective of the design cycle is to create artifacts, assess their performance in practice, and continually improve upon them. Within the scope of this dissertation, the design cycle entails the iterative process for developing the DAS and consistently evaluating its effectiveness by subjecting it to real use case scenarios from the shipbuilding industry.
- **Rigor:** this cycle establishes a connection between the research level and the knowledge base. The activities encompassed within this cycle entail the examination of relevant scientific foundations to assess their appropriateness in addressing the problem at hand, as well as the augmentation of the knowledge base in alignment with the developed artifacts. In the context of this dissertation, the rigor cycle involves the systematic process of acquiring knowledge to improve the workflow of maritime commissioning.

1.4 Dissertation Structure

Figure 2 shows the dissertation structure based on the previously defined research objectives (Section 1.2).

Chapter 2 presents an overview of the fundamentals required for comprehending the process of maritime commissioning and its significance in shipbuilding. Furthermore, this chapter provides a review of the research conducted on the utilization of digital technology within the maritime sector.

Chapter 3 conducts an analysis on the process of commissioning, focusing on identifying and discussing the deficits and limitations observed in the processes of commissioning preparation, implementation, and documentation.

Chapter 4 presents the problem statement by examining the problem context, its significance, and the research objectives. Additionally, the chapter outlines the requirements for developing an effective solution for maritime commissioning.

Chapter 5 models the commissioning process in terms of structure and behavior. The models serve as the theoretical framework for the design of the digital assistance system.

Chapter 6 introduces the digital assistance system that has been developed and explores various features that have been developed in accordance with the requirements outlined in Chapter 4.

Chapter 7 discusses the evaluation carried out to examine the potential of integrating the developed DAS in the industry and the resulting advantages in terms of productivity and usability.

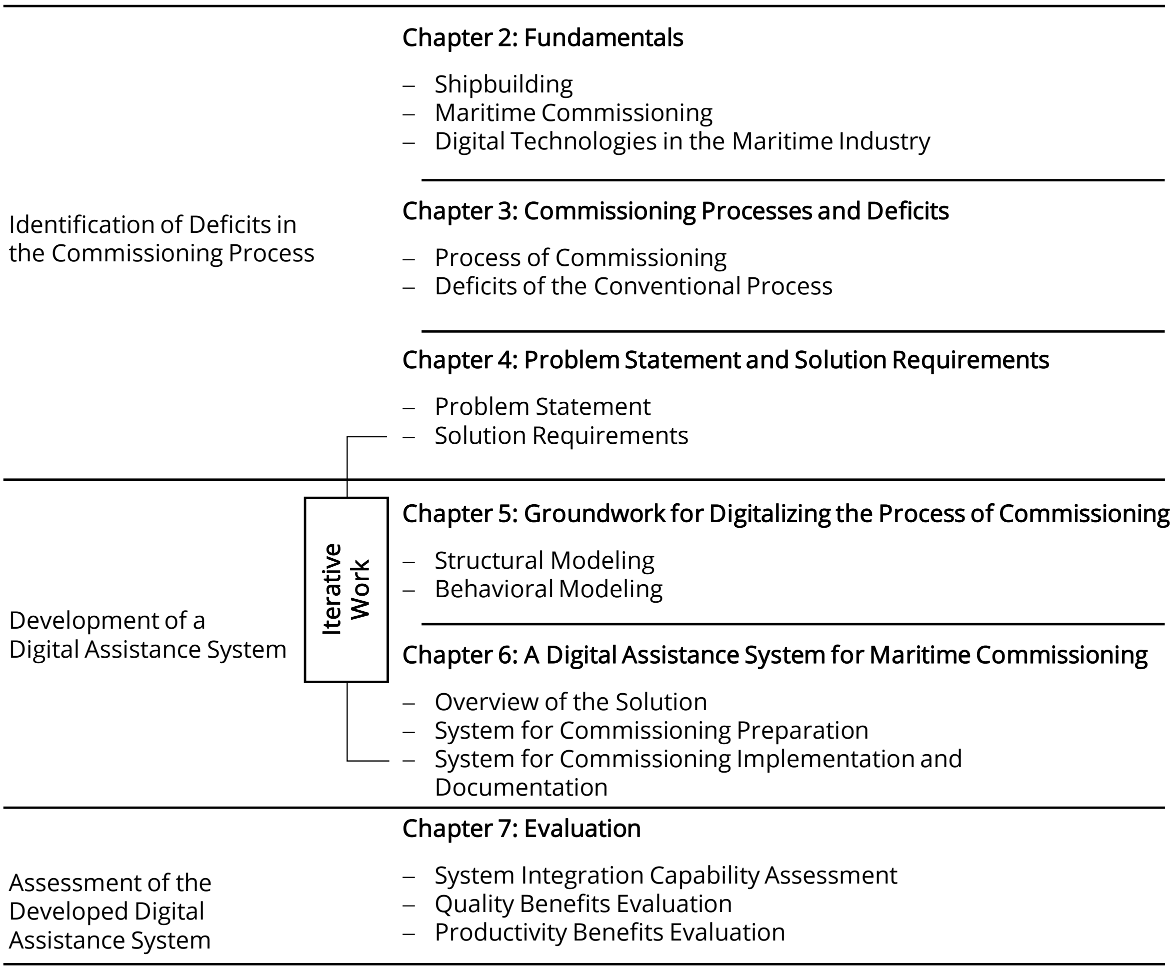


Figure 2: Dissertation structure

2 Fundamentals

This chapter provides an overview of the foundational concepts and identifies key areas of research that are relevant to comprehending the topic of this dissertation. First, the chapter provides an introductory overview of the shipbuilding process (Section 2.1). This section clarifies the characteristics of shipbuilding and briefly outlines the associated activities within the process of shipbuilding. The purpose of giving this introduction is to illustrate the significance of the maritime commissioning stage within the process of shipbuilding. Section 2.2 gives an introduction to maritime commissioning, which is the primary topic of this dissertation. This section offers definitions, objectives, and key characteristics of maritime commissioning. Finally, the chapter provides a review of the research works pertaining to the use of innovative digital technologies in the field of production, with a specific focus on the domain of shipbuilding and maritime commissioning (section 2.3).

2.1 The Process of Shipbuilding

As stated earlier, the central subject of this dissertation pertains to ship commissioning, which is also referred to as maritime commissioning. To have a comprehensive understanding of maritime commissioning, it is necessary to begin by offering a concise summary of the shipbuilding process. In Section 2.1.1, an overview of the shipbuilding process is provided, which includes an examination of defining characteristics and associated activities of the process. Moreover, Section 2.1.2 provides a concise overview that highlights the significance of ship commissioning within the shipbuilding process. Section 2.1.3 provides a brief summary of innovation within the shipbuilding industry, concentrating specifically on the potential for digitalization to increase productivity and improve the overall quality of shipbuilding.

2.1.1 Characteristics

Shipbuilding is considered one of the oldest industries in human history [Stor95, P. 5]. Until the first half of the previous century, Europe had held a dominant position in the industry, but Japan emerged as a market leader in the 1970s until being surpassed by China and South Korea starting from 2006 [Mick11, 201]. Ships are highly complex products that cost over \$200 million to build in the case of large cargo carriers [Bruc21, P. 1]. On the other hand, building and delivering a cruise ship, which consists of around 10 million components obtained from 800 suppliers, requires an average of 36 months [Seew15] and can cost up to \$1000 million [Bruc21, P. 1]. Consequently, shipbuilding is recognized as one of the most fiercely competitive industries globally [Mick11, 11]. Therefore, to gain a competitive edge, shipyards must strive to increase the quality of their ships, minimize costs, and reduce the building time [Bert03, P. 63].

From the manufacturing paradigms point of view, shipbuilding is regarded as a One-of-a-

Kind production (OKP) process due to the frequent changes of design and construction methods that the shipbuilding process undergoes [Stei12, P. 1]. Tu summarizes the characteristics of the OKP paradigm as "*high customization, great uncertainties in production control, complicated and dynamic production systems*" [Tu11, P. 2]. Unlike mass production companies, which create prototypes to develop optimal design and manufacturing processes, this approach is neither cost-effective nor practical for OKP companies, such as those involved in shipbuilding. As a result, the production of ships must be successful on the first attempt, leading to uncertainties in design, planning, scheduling, and cost estimation [Xie11, P. 11].

To ensure the successful manufacturing and commercialization of a highly complex product like a ship, the shipyard must implement a production system that involves securing orders and building the ship in accordance with the client's specifications, quality benchmarks, and financial constraints. Furthermore, Tu states that managing such a complex production system requires accurate information about the Bill of Materials (BOM), Bill of Operation (BOO), engineering limitations and dependencies throughout all stages of production [Tu11, P. 19f.]. Tu also references to the model by MacCarthy et al. for general production processes of customized goods, which is illustrated in Figure 3 [MacC03, P. 296f.].

Process	Characteristics
Order taking and coordination	Customer dialogue management, interpretation of customer preferences, identification of a product solution, and generation of order details.
Product development and design	Design of the product while taking into account adherence to internal and external standards.
Production validation and manufacturing engineering	Confirming the design's manufacturability and translating it into manufacturing procedures and rules, including generating a BOM and providing routing and processing instructions.
Order fulfillment management	Scheduling the production process, monitoring, and controlling the process.
Order fulfillment realization	Executing internal and external (supplier) manufacturing activities.
Post-order process	Product delivery, installation, warranty claims, and maintenance.

Figure 3: General manufacturing processes [MacC03, P. 296f.]

Given that ships are One-of-a-Kind/customized products, the model shown in Figure 3 is applicable to the shipbuilding process. However, to obtain a more comprehensive overview of the shipbuilding process and the significance of ship commissioning, a model specifically designed for shipbuilding is required. Thus, Figure 4 presents a process model that outlines the stages, most significant activities, and outputs involved in the shipbuilding process. This model is based on the activity map described by [Bruc21, P. 9–11].

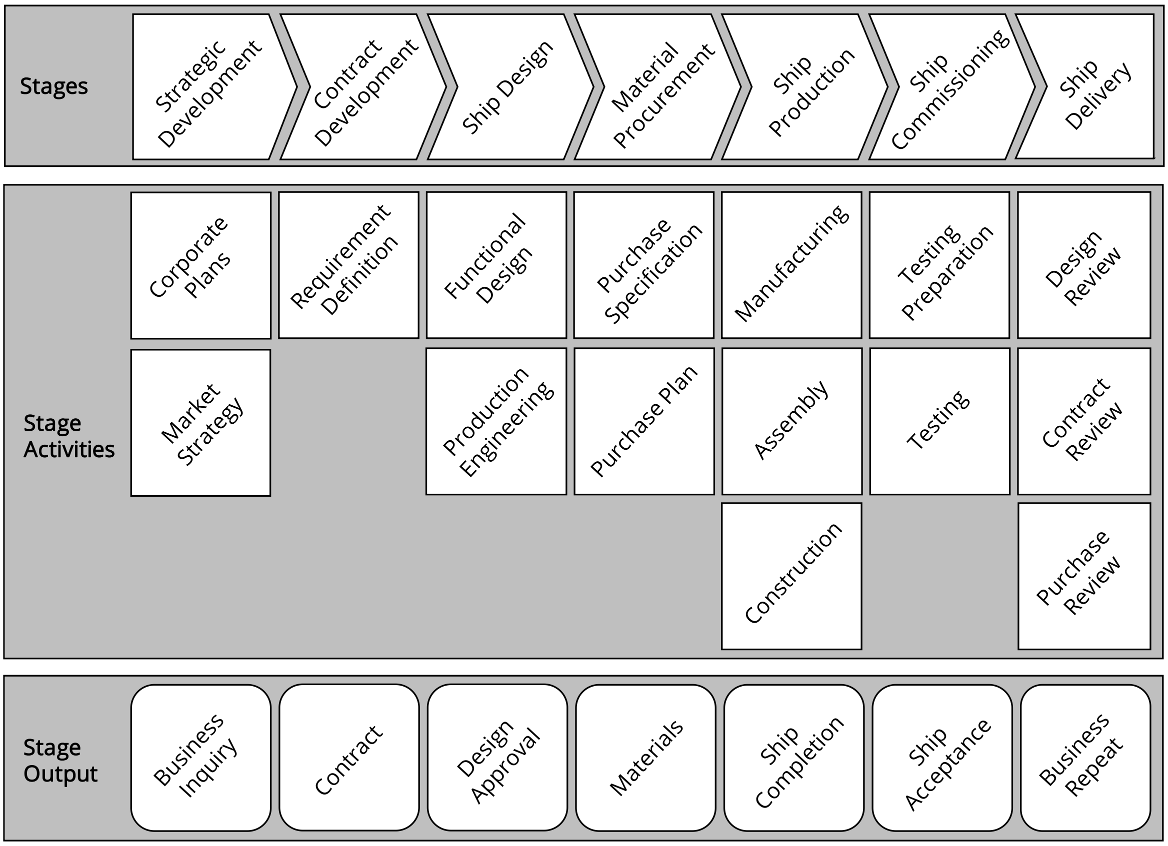


Figure 4: Shipbuilding process according to [Bruc21, P. 11]

Bruce describes the stages of shipbuilding as follows [Bruc21, P. 10–14]:

- **Strategic Development**: this stage involves the shipyard's strategic planning to effectively construct and market their products, aiming for a favorable market position. The desired outcome is the receipt of successful client inquiries.
- **Contract Development**: following the receipt of an inquiry, this stage involves communication between the shipyard and the client to clarify requirements and ultimately reach a contractual agreement.
- **Ship Design**: during this stage, extensive communication takes place among the shipyard's design team, suppliers, and the client to finalize a design that encompasses functional and financial specifications, as well as the engineering aspects of the production process.
- **Material Procurement**: in this stage, the shipyard procures the necessary materials from external suppliers.
- **Ship Production:** once the materials are available, the production phase begins, which can be divided into manufacturing, assembly, and construction processes.
    - **Manufacturing**: this involves the creation of ship components, such as

    steel plates, profiles, and pipes.
    - **Assembly**: parts are assembled into larger units.
    - **Construction**: assemblies, parts, and equipment are installed at the designated construction site.
- **Ship Commissioning**: this stage entails the verification of all installed parts, assemblies, and equipment, ensuring their proper functionality. It also involves conducting sea trials to ensure compliance with safety standards and client and regulatory requirements.
- **Ship Delivery**: upon completion, the ship is delivered to the client, accompanied by training, maintenance plans, and a commitment to address any deviation from the specified requirements.

2.1.2 Commissioning: a Vital Process in Shipbuilding

Shipbuilding is a highly complex process and it is important to emphasize that the activities involved in shipbuilding are interdependent and can overlap. For example, the initial contract between the shipyard and the client specifies the operational and architectural requirements but does not include detailed technical plans or final design. The specific technical requirements and detailed design are then determined while the ship is being built [Hell17, P. 103], which means that the design stage overlaps with ship production.

The overlapping of processes is important for reducing the idle time and for increasing the productivity in shipbuilding [Stor95, P. 60]. However, this overlapping leads to inefficient workflows due to conflicts between shipbuilding activities. Alongside the inherent complexity and interdependencies of the shipbuilding process, Lyu and Gunasekaran identify the following characteristics of shipbuilding as contributing factors to an inefficient workflow in the shipyard [Lyu93, P. 58f.]:

- **High complexity of product**: due to the ship's large volume, weight, and high number of components.
- **Lack of optimal coordination and teamwork**: due to the overlapping of processes.

In addition to the negative impact on productivity and cost, an inefficient workflow can also have detrimental effects on the quality of the ship produced. Scholars suggest that implementing *Total Quality Management* from the ship design phase can improve the ship's quality [Adam91] [Lyu93, P. 59]. According to Piette, commissioning can be considered as a part of Total Quality Management [Piet95, P. 1]. Section 2.2 offers precise definitions for commissioning and demonstrates the characteristics and objectives of commissioning. However, in this section, it is satisfactory to acknowledge that commissioning is a vital process in shipbuilding that starts from the design stage and extends until the delivery of the ship. The primary objective of commissioning is to ensure high quality and compliance to client requirements and regulatory standards [Stor95, P. 158].

2.1.3 Innovation in Shipbuilding

As stated in Section 2.1.2, shipbuilding processes overlap, and because of the overlapping, conflicts between the shipbuilding activities arise, and information flow becomes inefficient [Hell17, P. 103], leading to uncertainties, lower productivity, and higher cost. Overall, due to the high complexity of shipbuilding, it is crucial to achieve better coordination and information management to enhance the shipbuilding process.

Bruce states that due to the cyclical nature of the global industry, shipyards have placed a greater emphasis on improving productivity. This has been made possible by the rapid progress in computer technology, which has found utility in shipyard operations and design. Initially used for office functions like payroll in the 1960s, computers now play a substantial role in information management, supporting various activities of the shipyard. [Bruc21, P. 7f.].

Continuing the advancements in shipbuilding technology, the field is now embracing a *fourth industrial revolution* to further improve processes, achieve energy efficiency, and increase productivity [Stan18, P. 118]. As a result, several research works aim to optimize the process of shipbuilding by employing innovative technologies.

For example, in the planning stage, Heinig explores the utilization of virtual technologies to facilitate the assembly process in complex production projects, like shipbuilding. He develops a system that incorporates Virtual Reality (VR) to create assembly plans and Augmented Reality (AR) to visualize the plans [Hein15, P. 148]. Additionally, Titov proposes a concept that transparently involves customers in the design phase of large assemblies by leveraging AR technology to visualize different design options. This approach proves to enhance productivity by improving communication between contractors and customers, leading to higher-quality final designs [Tito16, P. 137f.].

To reduce product uncertainties in shipbuilding, which is a characteristic associated with OKP, Sikorra proposes a digital planning process that enables estimation of structures and components in the early phase of shipbuilding. Furthermore, the proposed system can calculate process parameters, which is useful for more realistic determination of execution times, schedules of production tasks, and resources [Siko21, P. 135].

Section 2.3 discusses additional research works that explore the integration of new digital technologies in production management. The purpose of discussing these works in Section 2.3 is to demonstrate how digitalization can improve the production process, and to emphasize the notion that there is still further scope for improving maritime commissioning through digitalization. Nevertheless, before discussing these works, it is important to provide a comprehensive explanation of maritime commissioning, which is the focus of this dissertation.

2.2 Maritime Commissioning

The production process begins after the customer places an order for a new product, and ends when the product is manufactured and delivered to the customer. Delivering capital goods with high investment volumes to a customer requires extensive effort and a long time. The product manufacturer must verify that all customer requirements are fulfilled and that the product complies with all standards and norms. In the maritime industry, a newly produced ship is delivered to the customer at the end of a process called *ship commissioning*.

To gain insight into the commissioning process, Section 2.2.1 presents relevant definitions of *commissioning*. Additionally, Section 2.2.2 lists the primary objectives of the commissioning process, while Section 2.2.3 briefly outlines the key characteristics of the process.

2.2.1 Definitions

Weber asserts that the term *commissioning* lacks a universally accepted and standardized definition. According to Weber, the absence of such a universal definition can be attributed to limited scientific research in the field of commissioning in comparison to other domains within mechanical and process engineering [Webe19, P. 1]. Even though this dissertation focuses on maritime commissioning, research in building and process plant commissioning is regarded in this dissertation to compensate for the lack of literature on maritime commissioning. This is viable since that equipment and systems in process plants and buildings also require commissioning, and the process in such fields incorporates the same principles applied in maritime commissioning.

In the field of building commissioning, Yoder et al. define the term *commissioning* as follows [Yode92, P. 264]:

> *"Commissioning is a set of procedures, responsibilities, and methods involved in advancing a total system from a state of static physical installation to a state of full working order in accordance with the design intent."*

Translated from German, Baumann describes the act of commissioning in more detail as follows [Baum82]:

> *"The commissioning of a technical system takes place after the completion of assembly and successful operational functional tests [...]. During the commissioning period, which can extend over a more or less extended period depending on requirements and agreements, various operational tests are conducted at different nominal loads. The performance of the technical*

> *system is also verified during this process. After confirmed performance, the performance certificate is provided. This certificate pertains to both the technical system and the production. Upon successful completion of the performance certificate, the responsibility for the technical system generally transitions from the manufacturer to the customer. This process is also referred to as the transfer of risk. Afterward, the operation of the technical system commences."*

According to the DIN EN ISO 12100, and translated from German, commissioning is defined as follows [DIN 11, P. 1]:

> *"The commissioning of machines and systems serves to check functions and properties as well as the detection and elimination of faults and thus corresponds to the final testing phase of a machine or system and is therefore the responsibility of the manufacturer, even if performed on the operator's premises."*

The previously mentioned three definitions all converge on a same underlying concept, namely that commissioning is a process in which a system is subjected to a series of testing procedures, with the aim of validating its functionality and promptly identifying any potential flaws or deviation from design objectives. After completion of commissioning, the system being commissioned can be safely placed into operation.

2.2.2 Objectives of Commissioning

Commissioning has developed from a start-up process for putting the system in working order to an essential process integrated into the entire product's lifecycle. The upscaling of commissioning is due to regulatory standards and benchmarking laws that enforce extensive checks and inspections. In addition to fulfilling customer requirements and regulations, manufacturers and contractors in competition strive to deliver the highest quality product in the shortest time at the lowest cost. The commissioning process contributes towards achieving these goals by acting as a strategy for quality management, risk management [Mill11, P. 150f.], and cost-effectiveness [Baec11, P. 4].

Quality

In One-of-a-Kind Productions, quality is an essential characteristic that significantly influences the customer's purchase decision, and the quality of a product is determined by the ability to fulfill customer requirements and the perception of added value and benefits to the customer. As mentioned in Section 2.1.2, commissioning can be regarded as a part of *Total Quality Management* [Piet95, P. 1f.].

In the context of building commissioning, Sterling and Collett mention that commissioning has evolved from a start-up process to a quality assurance process [Ster94, P. 32]. The authors state that commissioning achieves quality assurance through the implementation of several activities and processes including the following:

- **Component testing:** an activity in which pre-functional performance tests are conducted to verify the functionality and certification readiness of the components prior to their installation and integration.
- **System integration testing:** an activity in which functional performance tests are conducted to validate the proper integration of all components, ensuring that the resulting systems operate in accordance with the defined requirements.
- **Documentation:** an essential process that involves the creation of documents to verify compliance with requirements and specifications. This process entails recording the outcomes of functional performance tests and producing certification of readiness documents. Additionally, documentation include the creation of system operation and maintenance manuals, which include instructions for optimal operation and regular testing procedures aimed at maximizing the longevity of the commissioned product.

The aforementioned discussion demonstrates that the systematic implementation of commissioning results in advantageous quality outcomes, therefore emphasizing quality as a primary objective of the commissioning process.

Cost and Time

Increasing the complexity of a product is directly associated with higher risks and a higher likelihood of encountering faults and deviations from requirements during production. Such risks and faults contribute to unnecessary costs and production delays. By implementing commissioning, it is possible to reduce risk-associated costs and delays. To comprehend how commissioning can mitigate costs associated with risk, it is crucial to provide further clarification regarding the types of costs due to issues and faults, the definition of risk, and its relationship to costs.

According to Altweis and McIntosh [Altw01, P. 5], costs resulting from faults or issues can be categorized into two types: *Issue Resolution Cost* (IRC) and *Issue Effect Cost* (IEC). IRC refers to the costs of fixing an issue, while IEC are the costs that appear due to the effects of an issue until the issue is resolved. IRC include repair, replacement, installation, and professional costs. IEC include depreciation, maintenance, revenue loss, productivity, and energy costs.

As for risks, any deviation from the expected that poses threats and uncertainties on objectives is a *risk*, and *risk management* is the set of activities to prepare an organization for facing such risks [ISO 18, P. 1]. In complex productions, risks for the owner can be manifested in the probability of non-lasting savings and no return on investment. Such risks appear due to early equipment malfunction and legal disputes regarding failure to achieve intended design objectives.

Commissioning aims to mitigate risks for the owner by early detection of faults through the implementation of extensive testing procedures [Mill11, P. 151]. Performing fault detection and resolution via commissioning is more cost-effective when done prior to product delivery, resulting in reduced IRC and IEC. Furthermore, commissioning is essential for developing precise maintenance plans and establishing frequent testing programs that are custom-designed to align with the condition of equipment observed during commissioning [Ster94, P. 32]. Implementing such maintenance plans after product delivery mitigates the likelihood of premature equipment failure, thereby preventing unnecessary periods of inactivity and subsequently decreasing IEC.

McClain et al. show in a study that building commissioning provides an average return of $1 per every dollar spent on commissioning and $2.30 per rebate dollar spent. The benefits are calculated per building and grouped into three categories: design and construction, operation, and occupant benefits [McCl07, P. 1077f.].

As for mitigating production delays via commissioning, the process of commissioning contributes to early identification of faults and problems, hence facilitating rapid modifications, while maintaining the original project timeline [Haas06, P. 8]. To avoid delays and save time, the process of commissioning includes an initial testing stage known as *Factory Acceptance Testing* (FAT) [IEC 06, P. 9]. FAT verifies that the equipment meets the specifications of the design by subjecting it to isolation testing prior to installation. The manufacturer conducts this type of testing by utilizing modeling and simulation techniques, including Hardware-in-the-Loop [Baci05, P. 3194] (see Section 3.1.2). By identifying faulty equipment prior to installation and assembly, production delays can be avoided. This saves time compared to if the fault had been discovered after installation and assembly.

2.2.3 Characteristics

During the commissioning process, professionals from different departments work together to plan and implement the commissioning procedures. The following subsections discuss the important characteristics of the commissioning process.

Commissioning Personnel

Due to the variety of tasks performed throughout the processes of commissioning and the different activities of production, it is crucial to assemble a group of specialists from different disciplines. The assembly of such a group is the first step that marks the beginning of a commissioning project [Haas06, P. 15].

It is common to categorize workers in production and manufacturing environments into *direct* and *indirect* labor. Direct labor represents individuals working directly in the process, performing tasks that directly affect the final product, such as machine operation and assembly. Indirect labor includes personnel not directly involved with manufacturing the product but have responsibilities such as process planning and control. Commissioning personnel can also be grouped in a similar structure where direct labor is referred to as the *commissioning team*. The commissioning team includes engineers and technicians that perform commissioning tests, solve issues caused by improper installation or deviation from requirements and specifications, and document the process. Indirect labor in commissioning is referred to as the *commissioning authority*. The commissioning authority is a group of personnel responsible for creating commissioning test specification documents, planning, scheduling, and monitoring the implementation of commissioning tests [ASHR05, P. 4].

The commissioning personnel also includes external individuals such as subcontractors and manufacturer's representatives that provide documents, installation, startup, and testing of components supplied by third-party providers. Moreover, members of classification societies and owners take part in commissioning to ensure adherence to requirements, regulations, and standards.
Figure 5 lists the main types of personnel in commissioning and their responsibilities [Haas06, P. 15–25].

Group		Role	Responsibilities
Internal	Indirect	Commissioning Lead	• Assembling commissioning team • Defining process requirements • Assigning activities to commissioning team
		Design Professional	• Authoring commissioning test specifications • Authoring issue logs and checklists
		Quality Management Coordinator	• Applying standards and norms • Reviewing and authorizing commissioning tests
		Planner	• Defining milestones and deadlines • Scheduling commissioning tests
	Direct	Engineer/ Technician	• Implementing commissioning and acceptance tests • Fixing errors and faults • Documenting commissioning results in issue logs
External	Indirect	Subcontractor	• Attending pre-design meetings • Supplying equipment • Providing technical documents of equipment • Authoring functional test specifications for equipment • Developing training plans for building staff • Integrating milestones into commissioning schedule
	Direct	Manufacturer's Representative	• Implementing functional tests for equipment • Executing equipment startup • Fixing errors and faults
		Classification Society Representative	• Taking part in acceptance tests

Figure 5: Types and responsibilities of commissioning personnel [Haas06, P. 15–25]

Phases of Maritime Commissioning

The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) incorporates commissioning as an integral part of the entire *building production process* and allocates commissioning tasks across the phases of the building production process, namely: pre-design, design, construction, and operation [ASHR05, P. 2]. However, the commissioning phases may differ according to the project for which commissioning is applied [Haas06, P. 28].

Unlike buildings, ships are not stationary and operate in water, and it would be late to begin identifying problems when the ship is sailing. Therefore, inspecting critical equipment and systems on the ship must be performed when the ship is still in dock as well during sea trials. According to Bruce [Bruc21, P. 10], the generalized phases of maritime commissioning are:

- Testing
- Ship trials
- Acceptance and delivery

Testing is performed when the ship is docked and usually takes place in parallel to construction work. Shipyards refer to this phase as *Harbor Acceptance Testing* (HAT). HAT mainly includes two main types of tests: installation tests and functional tests. The objective of an installation test is to confirm the accurate installation of a component. Depending on the equipment, the test may be conducted by either a subcontractor, a commissioning agent from the shipyard, or both.

On the other hand, functional tests focus on validating the performance and behavior of equipment. When conducting functional testing, the commissioning agent creates conditions similar to those encountered during ship trials and carefully observes the equipment's response and behavior. The method of verifying functionality depends on the equipment being tested. Visual inspection is often employed for simple mechanical systems, such as doors and windows. On the other hand, electrical and control systems require a signal-based inspection to confirm their functionality. For example, to test an alarm triggered by a reading from a temperature sensor, the commissioning agent can use a setpoint generator to simulate a temperature reading and verify if the alarm will be triggered.

When ship construction and HAT are finished, the ship can go on trial in a phase referred to as ship trials or *Sea Acceptance Testing* (SAT). The main objective of SATs is to verify that the ship adheres to classification societies' and governmental authorities' standards and regulations. During SATs, the ship is evaluated regarding energy consumption, safety, and proper equipment behavior. SATs can be either global or system-based. Global tests are performed on the entire ship to measure performance, speed, maneuvering capabilities, and other global properties. In contrast, system-based tests can be performed when the ship is docking, for example, in the case of anchoring. Measurements during SATs could be either discrete or continuous [ISO 05, P. 5].

Issues are detected and fixed during the HAT and SAT phases. When all issues are fixed, the ship can begin the acceptance phase where all stakeholders initiate a closure. During the acceptance phase, all relevant documents for ship operation and maintenance, as well as, issue logs and checklists are evaluated and delivered to the owner. Finally, the ship is accepted once the owner agrees to delivery and the stakeholders sign all legal documents [Bruc21, P. 212].

Technical Dependencies

The growing emphasis on sustainability and energy efficiency causes the design of buildings and ships to increase in complexity. The integration of automation technologies adds another layer of complexity to the interfaces between different systems and subsystems. Due to the complexity of control systems, various methods exist in designing, verifying, and validating controllers to avoid errors that would later be detected during implementation and testing [Reij18].

Moreover, complex systems require professionals from diverse specializations collaborating to build the systems [Alva09, P. 412]. Given this collaborative effort, it is crucial to coordinate the sequence of work activities precisely to prevent errors [Eppi12, P. 1f.]. Consequently, when commissioning these complex systems, testing must be conducted in the correct sequence that respects the *technical dependencies* among the systems, ensuring effective testing and proper functionality. Therefore, commissioning test preparation, implementation, and documentation must take into account the technical dependencies.

2.3 Digital Technologies

The main objective of this dissertation is to develop a digital solution that enhances the efficiency of the commissioning procedure. In order to achieve this objective, Section 2.3 examines relevant research works that are centered on improving the shipbuilding process as a whole through digitalization, with a specific emphasis on the commissioning process.

In Section 2.3.1, an introduction of *Industry 4.0* and its relevance in the shipbuilding industry is provided. Section 2.3.2 introduces the concept of *Digital Twins* and is followed by a discussion on the implementation of *Digital Assistance Systems* (DAS) throughout the production lifecycle in Section 2.3.3. Section 2.3.4 emphasizes the application of the *Internet of Things* in the realm of production and commissioning. Finally, Section 2.3.5 presents commercially available digital solutions that specifically target and address the commissioning process.

2.3.1 Shipbuilding 4.0

In the last decade, a significant movement has emerged advocating for the digitalization of the shipbuilding industry. This movement aligns with the fourth industrial revolution, known as *Industry 4.0*. The term first originated in Germany in 2011, and the concept was later adopted by the German Federal Ministry for Economic Affairs and Energy as a means for developing the traditional industry [Manh15].

Industry 4.0 encompasses the application of various technologies and concepts to digitally transform the industry as a whole. Lasi identifies the following technologies and strategies as the fundamental components of Industry 4.0 [Lasi14, P. 240]:

- **Smart factory**: an environment where sensors, actors, and autonomous systems are integrated in machinery to provide highly automated manufacturing.
- **Cyber-physical systems**: merging of physical and digital realms in both the production process and the products. Seen, for example, in preventive maintenance, where process parameters of mechanical components experiencing wear and tear are digitally captured. The system's condition is determined by combining the physical system with its digital representation.
- **Self-organization and individualization**: manufacturing systems adopt strategies for independent decision-making through digitalization and product intelligence.
- **Adaptation to human needs:** manufacturing systems are designed to follow human needs and promote factors such as ergonomics and safety.
- **Corporate social responsibility**: shifting focus of corporates towards resource-efficiency and sustainability.

The shipbuilding industry still confronts challenges stemming from the complex manufacturing process. The frequent changes during construction and the lack of standardized procedures create difficulties in meeting the requirements of quality, safety, and cost efficiency. As a result, shipyards experience financial losses [Stan18, P. 113]. To address these issues, digitalization is being implemented. Furthermore, as stated by Sullivan et al., digitalization within the maritime industry is propelled by four key factors [Sull20, P. 250]:

- **Evolving policies**: government initiatives that promote digitalization.
- **Market demands**: pressure from the market necessitates digitalization.
- **Technological advancements**: customer requirements drive the incorporation of modern technology in the maritime industry.
- **Diverse technological landscape**: the availability of various embedded systems technologies contributes to the ability of integrating digitalization in different contexts.

That being said, digitalization in the maritime industry is still at its early stages due to a lack in awareness of digitalization benefits, high cost of implementation, and lack of standard workflow in digitalization [Iwań23, P. 2][Sull20, P. 249]. Therefore, further research in maritime digitalization is ongoing, encompassing several points of interest. These include artificial intelligence (AI), virtual and mixed reality technologies, additive manufacturing, Internet of Things (IoT), and the integration of intelligent algorithms with product life cycle management systems (PLM) and CAD [Sánc20, P. 7]. Additionally, current research investigates the concept of *digital twinning*, which works by building a dynamic digital representation (twin) of a physical system for monitoring and predicting the behavior of the system throughout its entire lifecycle [Grie17, P. 92].

The subsequent sections examine the relevant technologies and classify them into three main categories: Digital Twins, Digital Assistance Systems (DAS), and the Internet of Things (IoT). These categories are then discussed in relation to their significance in the shipbuilding industry and in commissioning of ships and buildings.

2.3.2 Digital Twins

The Digital Twin concept originates from a presentation held at the University of Michigan in 2002 by Grieves [Grie02][Grie17, P. 93]. The presentation provides the groundwork of the digital twin concept which consists of:

- **Real space**: the physical system.
- **Virtual space**: a virtual representation of the physical system
- **Information flow link**: bi-directional information flow between the real and virtual space

The presentation slide that defines the digital twin concept is titled *Conceptual Ideal of PLM*. However, according to Grieves, the PLM system, within the context of the digital twin, is not static, instead it is a constantly evolving and interconnected representation of the physical system. This representation spans across the stages of its lifecycle, including creation, production, operation, and disposal [Grie17, P. 93].

Digital Twins for Manufacturing

Currently Digital Twins are considered for a wide range of industries [Da S22, P. 4f.]. When employed in manufacturing, Digital Twins utilize data from information systems to analyze, control, and optimize the virtual factory. It enables real-time simulation and intelligent operations between the physical and virtual spaces. The virtual factory reflects and verifies production information, facilitating communication and feedback, which improves the performance of the physical factory.

Furthermore, with the progress of computing power, it is possible to utilize 3D models of complete systems within the virtual space of the Digital Twin. Leveraging the real-time computational advantages offered by the Digital Twin, potential conflicts and problems can be identified early on in the virtual space, leading to quicker and more cost-effective issue resolution during the manufacturing process [Grie17, P. 96].

Bao et al. propose three types of Digital Twins when applied in manufacturing [Bao19, P. 539–546]:

- **Product Digital Twins**: reflects the physical product state that results from production without detailed information about the manufacturing process.
- **Process Digital Twins**: supports the production processes by linking product design with the required manufacturing processes.
- **Operation Digital Twins**: simulates interactions between production factors and monitors operations such as resource scheduling, production process management, and equipment health management.

According to Kritzinger et al., who conducted an extensive categorical literature review on Digital Twins in the manufacturing context, the development of Digital Twins is still in its early stages. The existing literature primarily revolves around conceptual discussions, lacking concrete case studies [Krit18, P. 1018]. The following section examines works related to utilizing Digital Twins in shipbuilding and commissioning activities.

Digital Twins for Shipbuilding and Commissioning Activities

In the industry of shipbuilding, it is believed that Digital Twins are on the way to becoming a standard technology for designing, commissioning, operating, and maintaining ships, as stated by the head of the Maritime Transport research program at the international classification society DNV GL [Smog17, P. 5]. Several researchers examine and show potentials of Digital Twins in areas such entire ship design and production [Kunk22] [Iwań23], maintenance [Cora19] [Arri20, P. 121], system testing [Dufo18] and simulation [Fons20].

In a report by the Danish Maritime Authority, demand is expressed for employing Digital Twins in shipbuilding as a whole. The report also highlights use cases for Digital Twins in commissioning to support system integration, evaluate performance, ensure system quality, and provide services for monitoring and maintenance [Ludv18, P. 11]. This demand shows the potential of Digital Twins, while also revealing a lack of systematic approaches for digital maritime commissioning.

Ludvigsen et al. suggest the utilization of simulation models implemented on a Digital Twin as a means to improve traditional testing and the documentation of test outcomes. They present a scenario where tests can be conducted virtually to analyze the repercussions of a failure on the digital twin model. While the test inputs are obtained from physical sensors, the actual testing occurs within the virtual space of the Digital Twin. The obtained results are subsequently stored in databases for the purpose of benchmarking. Additionally, they identify the advantages of employing Digital Twins during commissioning as follows [Ludv16, P. 455f.]:

- Early prototyping and testing
- Demonstration of system failures effects
- Early feedback on system design compliance
- Improved quality and efficiency for testing cyber-physical systems
- Central access for information about installation and commissioning
- Models for condition monitoring, allowing event-based inspections
- Live troubleshooting and issue investigation

Consequently, Ayani et al. also suggest including a phase in production called *virtual commissioning*, in which the commissioning of systems is carried out in a virtual space before commencing the real commissioning, as seen in Figure 6.

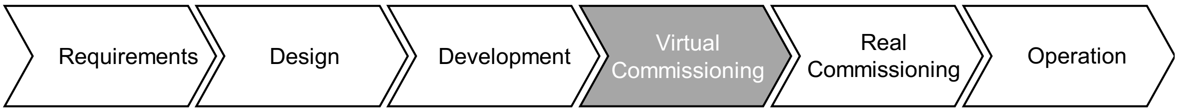


Figure 6: Virtual commissioning as a phase in the production lifecycle [Ayan18, P. 244].

In their paper, the authors present a project that centers around the reconditioning of machinery, utilizing the benefits of a Digital Twin. They highlight the advantages of integrating a Digital Twin during commissioning, resulting in reduced commissioning time and enhanced quality. By integrating the Digital Twin into the commissioning process, the authors note that they could successfully identify and resolve issues promptly, including actuator signal errors and synchronization issues among different machines. Nevertheless, it is important to highlight that the developed Digital Twin primarily emphasizes Factory Acceptance Testing (FAT), referred to as VFAT (Virtual Factory Acceptance Testing) by the authors [Ayan18, P. 247].

Additionally, Leng et al. propose the utilization of Digital Twins for remote commissioning activities. In their paper, they introduce a Digital Twin system specifically designed for remote semi-physical commissioning. To demonstrate the effectiveness of their system, they conduct a case study involving the remote commissioning of a smartphone assembly line. The commissioning process using the Digital Twin system yields several benefits as follows [Leng21, P. 12f.]:

- Significant reduction in the average integrated commissioning cycle, from 21 days to 7 days.
- Lower downtime rate, decreased from 5% to 2%.
- Reduction in equipment failure rate, from 0.5% to 0.3%.
- The capability to execute commissioning tasks in parallel, enhancing efficiency.

While the majority of research on Digital Twins for commissioning focus mainly on the testing phase of automated systems like Factory Acceptance Testing (FAT), it is evident that there is still a requirement for broader implementation of Digital Twin technology in the overall commissioning process, especially within the maritime sector [Ludv18, P. 11]. However, considering the complexity of the commissioning process, it is worth exploring the utilization of other technologies alongside the Digital Twins. Subsequent sections discuss Digital Assistance Systems (DAS) and the Internet of Things (IoT) and their potential application within the maritime industry as a whole.

2.3.3 Digital Assistance Systems

In essence, an assistance system can be considered a form of *Intelligent Decision Support Systems* (IDSS) aiming to improve decision-making by providing accurate information in a timely and appropriate manner, i.e., addressing the questions of *what* information to present*, how, and when* to present it [Holl87, P. 665] [Hinr19, P. 287]. The subsequent section examines more attributes of Digital Assistance Systems (DAS) in the context of production, followed by an exploration of their application in shipbuilding and commissioning contexts.

Attributes of Digital Assistance Systems in Production

With the progress of robotics and information technology, automation has found its place in diverse domains. However, it is important to note that automation is often applicable for repetitive and predictable physical activities [Stra17, P. 356], while manual work remains necessary for activities demanding precision and advanced skills [Many17, P. 2], as in OKP. Nevertheless, manual work in OKP presents several drawbacks, such as the significant effort and time required for preparing and extracting information, which ultimately leads to a decrease in productivity and increase in cost [Tu11, P. 15f.]. Furthermore, relying solely on manual labor in OKP demands a high level of skill, resulting in an increased risk of errors and necessitating comprehensive training programs.

Accordingly, companies are seeking to integrate DAS into their production processes to support their workers and mitigate the disadvantages of pure manual work. These systems utilize multimodal interfaces to guide users interactively through their work, based on their individual qualifications and the prevailing circumstances. The applications of these systems vary from tablets to on-site projection systems, as well as augmented or virtual reality devices [Oest19, P. 14].

Moreover, traditional manufacturing and assembly systems are not adequately equipped to efficiently handle customized productions that involve highly personalized requirements and frequently changing processes. Consequently, there is a growing motivation to develop advanced manufacturing systems that incorporate technologies like Cyber-Physical Systems (CPS), which are anticipated to offer greater flexibility and adaptability to frequent variations in products and processes [Hold17, P. 143f.].

CPS are systems designed with integrated computational units to facilitate the connection between physical systems and intelligent digital infrastructures. Their purpose is to enable more efficient control and enhance human interaction with the physical systems [Bahe11, P. 161]. CPS has various application fields such as process control and automation systems, autonomous driving, and power optimization [N. J14, P. 1]. Enabling human participation in CPS-based processes necessitates the provision of an interface through which inputs can be provided and information can be retrieved for task execution [Stoe08, P. 245]. In the production context, this interface can be achieved through the implementation of DAS [Hold17, P. 144].

As stated by Hold and Sihn [Hold16, P. 1], DAS offer more than just information representation. They can provide real-time support to the human workers in the assembly environment. This allows for automatic synchronization of work instructions and reduction of manual interaction between the worker and the DAS. This type of DAS is referred to as being context-aware.

Context-aware DAS integrate sensory data regarding the progress of the assembly, the production environment, and the condition of the human worker. This integration aims to generate context-sensitive instructions and adjust the information output to suit the worker [Stoe08, P. 245].

Hinrichsen et al. categorize DAS used in assembly processes into three types: stationary, mobile, and hand-held. Stationary DAS refers to devices or screens that are fixed at workstations, while mobile DAS includes devices that can be relocated and attached directly to workpieces. Hand-held DAS encompasses tablets or smartwatches [Hinr16, P. 8]. With a primary focus on hand-held assistance systems, this dissertation proceeds to discuss research works pertaining to DAS for shipbuilding and commissioning activities.

Digital Assistance Systems for Shipbuilding and Commissioning Activities

Within the field of shipbuilding, extensive research has been conducted to enhance the process through the utilization of DAS. Halata's research demonstrates that the implementation of an augmented reality (AR) DAS for information provisioning during intricate assemblies, such as those in shipbuilding, can result in a notable 30% increase in productivity and a significant reduction in errors [Hala18, P. 145].

Halata's developed DAS is a hand-held system that employs 3D and augmented reality to assist workers in assembly tasks. The system utilizes automated calculations to suggest a viable assembly sequence and presents the user with a 3D model representing the components to be assembled in the correct order. Additionally, the DAS offers the worker augmented reality displays that provide various information, including hints, warnings, and measurements. Figure 7 shows the user interface of the DAS developed by Halata [Hala18, P. 82].

The user interface of the Halata system presents the work packages and steps on the right side, allowing the user to mark completed steps or report errors. In the center of the screen, an augmented reality overlay of a 3D model demonstrates the desired final assembly, accompanied by measurements and a toggle button for switching between augmented reality and pure 3D views. On the left side, there are tool options for activating information display, including measurements, showcasing the final state, displaying work step-related information, and more.

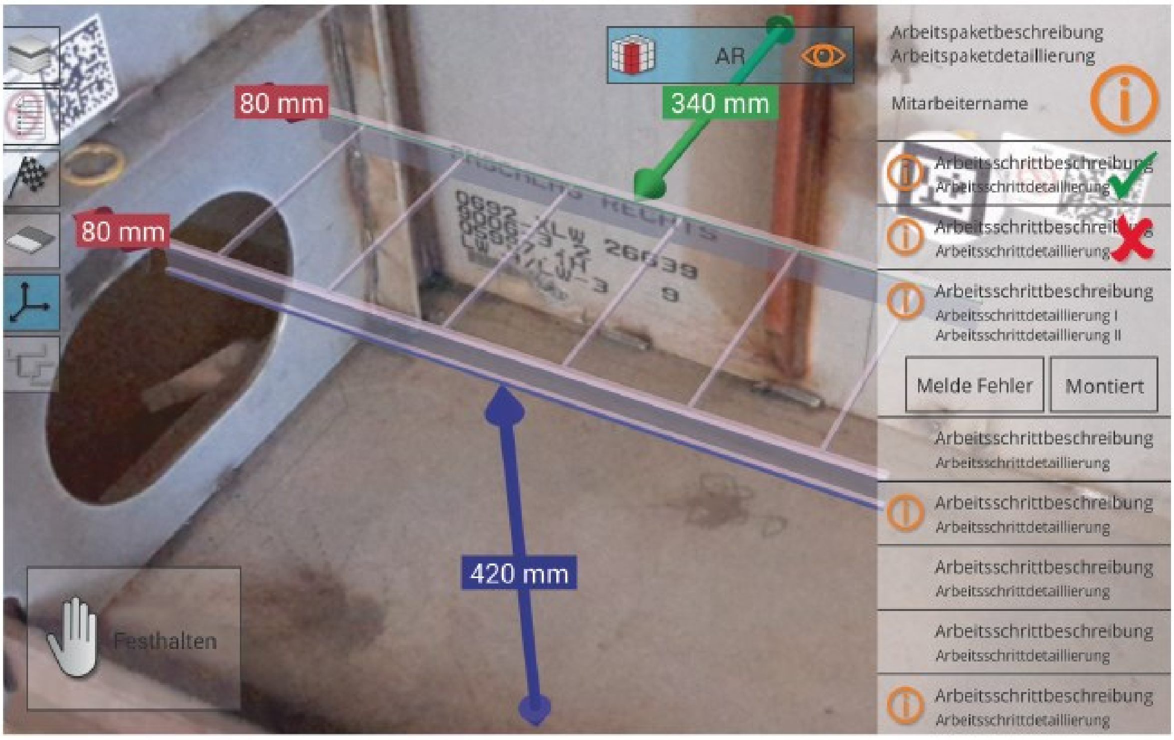


Figure 7: User interface of the DAS developed by Halata [Hala18, P. 82]

Halata's work concludes by proposing the expansion of the DAS to include quality control, thereby establishing a feedback loop that aids in the identification of potential errors and maintenance requirements [Hala18, P. 146].

For maritime maintenance, Meluzov introduces an augmented reality assistance system that aids maintenance workers by presenting relevant information on a display, removing the necessity for manual searches and reliance on paper-based resources. This system is seamlessly integrated with a comprehensive authoring system that streamlines the process of creating step-by-step instructions. Meluzov's experiments demonstrate that the utilization of his DAS results in reduced time and errors compared to the use of a conventional paper-based workflow [Melu22, P. 107]. An overview of the structure of the concept, including the crucial system components for managing, creating, and visualizing digital maintenance information, is illustrated in Figure 8 [Melu22, P. 50].

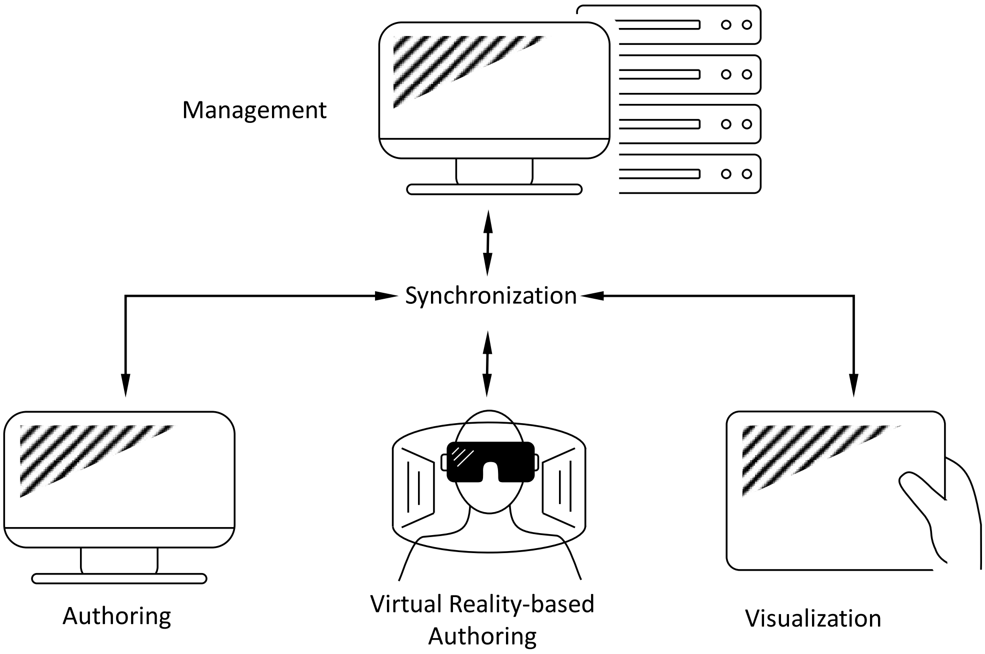


Figure 8: Overview of Meluzov's DAS for maintenance [Melu22, P. 50]

Building upon his research, Meluzov suggests expanding the system to encompass the entirety of the shipbuilding lifecycle. This expansion would allow for the retrieval of relevant information from the commissioning phase. The rationale behind this proposal is that the data obtained during commissioning can be consolidated in a unified database, resulting in enhanced efficiency when planning and executing maintenance tasks. Additionally, Meluzov asserts that the efficiency of authoring digital instructions can be further enhanced by achieving complete automation in their generation, as well as linking with technical information [Melu22, P. 108].

2.3.4 Internet of Things (IoT)

Ashton is commonly acknowledged as the first to mention the term *Internet of Things* or IoT in 1999 during a presentation focused on the utilization of RFID technology in Procter & Gamble's (P&G) supply chain [Asht09]. That being said, a single definition for IoT does not exist, and the meaning of the term changes depending on the field its applied in [Atzo10, P. 2]. In order to provide a more comprehensive understanding of IoT, Giusto et al. elaborate on the concept of IoT [Gius10, P. V]:

> *"In the last few years, a stimulating idea is fast emerging in the wireless scenario: the pervasive presence around us of a variety of things or objects, such as RFID, sensors, actuators, mobile phones, which, through unique addressing schemes, are able to interact with each other*

> *and cooperate with their neighboring smart components to reach common goals. This novel paradigm, named The Internet of Things (IoT) … paves the way to the deployment of numerous applications with a significant impact on many fields of future every-day life."*

According to Giusto et al., in this context, the IoT paradigm consists of two aspects: a *network* that provides the environment of interaction between humans and devices, and *smart objects* that possess contextual awareness, capable of processing information, and independently engaging with their surrounding environments as well as other devices [Gius10, P. 157]

Atzori et al., in their survey, introduce an additional aspect to the IoT paradigm, namely *semantics* [Atzo10, P. 4]. The concept behind semantic technologies is that they are essential for managing the exponential increase in connected objects within the IoT network. They enable efficient and scalable information transfer models and middleware [Toma, P. 142]. Figure 9 shows the three aspects that form the IoT paradigm as illustrated by Atzori et al. [Atzo10, P. 3]:

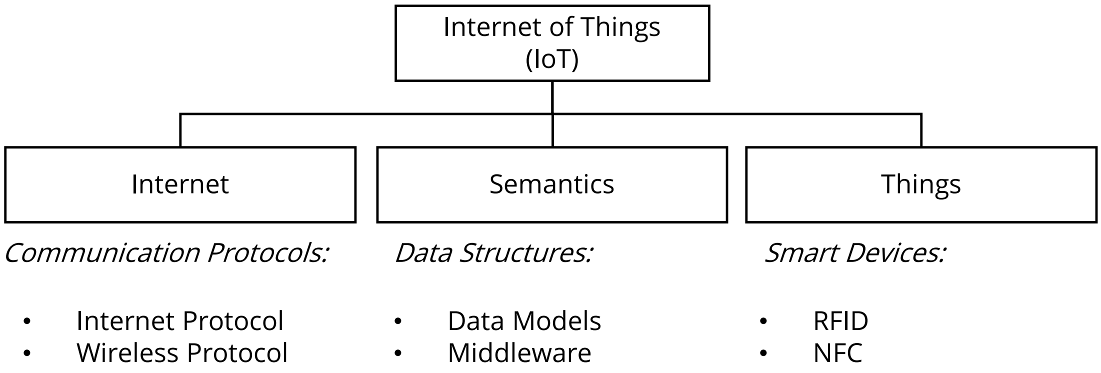


Figure 9: Paradigm of Internet of Things (IOT) according to Atzori et al. [Atzo10, P. 3]

The following subsections examine the utilization of IoT in the context of production, shipbuilding, and commissioning.

Internet of Things for Production

Manufacturing companies are employing IoT technology to monitor and identify products and materials, enabling improved logistics, inventory management, assembly processes, and sales tracking [Fang16, P. 689f.]. Product identification technologies commonly employed include RFID systems and Barcode technology [Kiri11, P. 482f.]. In this context, Dai et al. conducted a case study in which they implement RFID technology in shop-floor manufacturing for an automotive manufacturer. The study reveals that RFID systems offer advantages such as improved material distribution in warehouses, reduced operational errors, and automated real-time scheduling facilitated by computerized data collection from manufacturing shop floors [Dai12, P. 60].

Figure 9 illustrates that an RFID system (being a smart device) represents just one aspect within the scope of the Internet of Things (IoT) paradigm. When considering IoT-based production, it is crucial to also take into account the communication (internet) aspect. In the field of production, the *Open Platform Communications Unified Architecture* (OPC UA) serves as a widely adopted communication standard.

Developed by the OPC Foundation [OPC 23], OPC UA embodies a platform-independent service-oriented architecture that incorporates advanced features for data communication in industrial automation. OPC UA functions through a client-server session mechanism and implements various security profiles. Additionally, OPC UA facilitates interoperability among diverse protocols such as TCP/IP, UDP/IP, WebSockets, and MQTT, rendering it suitable for flexible industrial automation systems [Ye18, P. 544].

To ensure effective utilization of the OPC UA protocol in a manufacturing system, it is important to establish a suitable design that encompasses the *semantics* aspect of the IoT paradigm. This involves implementing proper data structures and models to enable seamless integration. Seilonen et al. provide an approach, demonstrating the aggregation of multiple OPC UA servers to accommodate two distinct manufacturing systems [Seil16]. Furthermore, Ye and Seung propose integrating OPC UA with the *Automation Markup Language* (AML) as a means to facilitate the transition from traditional production systems to the Industry 4.0 architecture [Ye18].

Internet of Things for Shipbuilding and Commissioning Activities

Stanić et al. suggest leveraging IoT technology in the maritime industry to enhance productivity and collaboration across the complete shipbuilding lifecycle. The authors emphasize the importance of establishing a smooth integration of IoT by connecting shipbuilders with suppliers through an effective digital infrastructure. This infrastructure enables shipbuilders to gain advantages through real-time access to relevant data throughout the entire lifecycle of shipbuilding [Stan18, P. 116].

In their paper, Fraga-Lamas et al. introduce a smart system for supporting shipbuilders. The proposed system utilizes IoT technology to track and locate pipes used in ship construction. The authors outline the necessary requirements for establishing a *smart pipe* system capable of transmitting spatial signals. The paper includes an implementation example and explores the supporting architecture. Spatial diversity techniques are suggested to enhance the stability of Received Signal Strength (RSS) values in active RFID systems. However, the authors note that additional research is needed to enhance positioning algorithms and mitigate interferences caused by physical obstacles [Frag16, P. 34–38].

In addition to the concept proposed by Fraga-Lamas et al. in their paper, the authors highlight the potential of utilizing IoT sensors to gather precise operational data and enable effective monitoring [Frag16, P. 2]. This data can be valuable for ship commissioning purposes. Moreover, it is advisable to incorporate the IoT paradigm throughout the entire shipbuilding process, starting from the design phase and extending to ship decommissioning. This integration enables the monitoring of pertinent data by all stakeholders involved at each stage of ship construction, ultimately leading to the optimization of IoT-driven shipbuilding processes [J. H16, P. 5306].

Within the commissioning domain, research often centers around incorporating IoT in the commissioning of control systems, as demonstrated by the works of [Rose23] and [Kozi19]. This is because the conventional approach for commissioning such devices involves often utilizing technologies like Hardware-in-the-Loop [VDE 16, P. 6–9], which could provide digital interfaces facilitating the implementation of IoT solutions.

According to the findings of Koziolek et al., the utilization of IoT in commissioning control systems leads to a significant reduction in configuration and integration time. The system they propose demonstrates reduction of commissioning time from 5-23 minutes to 0.5-1 minute, translating in a reduction of over 90%. When commissioning 10,000 devices, this time-saving equates to approximately 1500 hours. The authors highlight the following advantages of employing IoT in the commissioning process [Kozi19, P. 137]:

- Automated transfer of device parameters
- Automated identification of affected devices
- Automated signal matching between devices and controllers

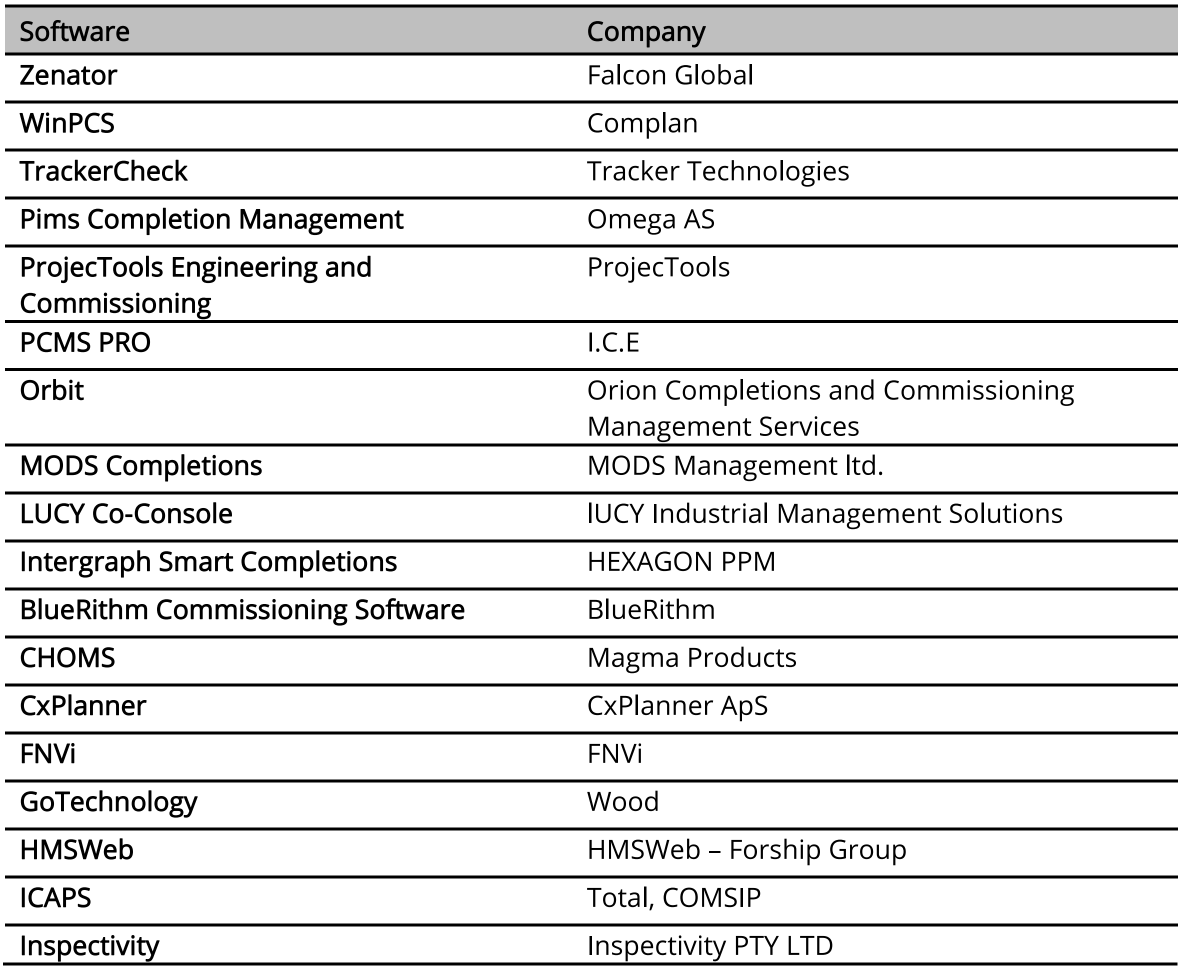
Although manufacturing companies are embracing IoT, there are obstacles that need to be addressed in order to facilitate the transition to IoT-based processes. Badarinath and Prabhu summarize these challenges as follows [Bada17, P. 117]:

- **High computational burden:** the increasing number of sensors and smart devices leads to large data that must be analyzed and processed in real-time, requiring significant computational resources.
- **Concerns regarding security and privacy:** the presence of a network of smart devices introduces the potential for cyber-attacks and privacy issues.
- **Migration considerations**: traditional equipment may not always be compatible with the IoT paradigm and may require adaptations for integration. Additionally, more widely adopted open standards are required to speed up the migration process.

Furthermore, there is a lack of research that quantitatively investigates the advantages of utilizing IoT specifically for maritime commissioning. Most existing works primarily concentrate on the commissioning of control systems, overlooking the comprehensive maritime commissioning process.

2.3.5 Commercial Solutions for Commissioning

This section presents selected commercial digital solutions for commissioning. However, it is worth noting that not all of these solutions could be thoroughly tested due to their proprietary nature. Consequently, the analysis of these solutions primarily relies on the descriptions provided by their developers. It is important to acknowledge that companies often prioritize enhancing their image and promoting product sales, which may impact the objectivity of the analysis. Nevertheless, exploring these solutions offers valuable inspiration for the later stages of this work in terms of design and implementation. In Figure 10, Thomas Stünkel, the CEO of Swiss Commissioning GmbH and a commissioning manager, provides an overview of globally available software options for commissioning [Stün21]. Stünkel identifies and lists 18 software solutions that he deems pertinent to the field.



Software	Company
Zenator	Falcon Global
WinPCS	Complan
TrackerCheck	Tracker Technologies
Pims Completion Management	Omega AS
ProjecTools Engineering and Commissioning	ProjecTools
PCMS PRO	I.C.E
Orbit	Orion Completions and Commissioning Management Services
MODS Completions	MODS Management ltd.
LUCY Co-Console	lUCY Industrial Management Solutions
Intergraph Smart Completions	HEXAGON PPM
BlueRithm Commissioning Software	BlueRithm
CHOMS	Magma Products
CxPlanner	CxPlanner ApS
FNVi	FNVi
GoTechnology	Wood
HMSWeb	HMSWeb – Forship Group
ICAPS	Total, COMSIP
Inspectivity	Inspectivity PTY LTD

Figure 10: Overview of commercial software for commissioning [Stün21]

It is important to note that the existing commissioning software is not specifically designed for the maritime industry. Instead, it typically caters to various industries that involve commissioning, such as construction or process engineering. However, it is still valuable to explore these solutions because of the similarities in the commissioning process across these different fields.

Among the software solutions listed by Stünkel [Stün21], the ones considered most relevant are CxPlanner, Pims Completion Management, and BlueRithm. These selected solutions are noteworthy as they encompass the entire commissioning process. The remaining solutions in the list either lack comprehensive process coverage or offer functionalities that are very similar to the chosen software. Consequently, these solutions are not discussed further in this dissertation.

CxPlanner

CxPlanner is a software platform developed by construction industry experts [CxPl23]. According to the company, this software adheres to ASHRAE requirements and encompasses the commissioning process from pre-design to operation. It offers various functionalities for equipment testing, issue tracking, and documenting the entire commissioning process in a format that aligns with client specifications.

To facilitate the creation of commissioning tests, the software provides predefined testing templates that users can customize to suit their specific commissioning projects. Within the template, there is a *test items* field where users can enter text descriptions for tests or include scripted descriptions that help define the test type.

For effective organization of created tests, each test can be assigned a type, such as mechanical check, pre-functional test, or system test. Tests can also be categorized based on location or system type (cooling, heating, ventilation). Moreover, the software includes a 3D viewer that allows users to import 3D models and toggle between wireframe view or selectively show/hide specific elements in the model. That being said, it seems that the software does not provide functionalities for technical dependency management and complex documentation capabilities.

Pims Completion Management

Pims Completion Management, created by Omega 365 [Omeg23], is a software designed to include the entire commissioning lifecycle, ranging from *configuration* to *operation*. This software provides commissioning capabilities through pre-defined checklists, which users can manually customize to suit the specific needs of their projects. These checklists can be printed for offline use or accessed on-site through a smartphone. Monitoring activities are facilitated by a web-based dashboard, accessible via both smartphones and desktop computers. Similar to CxPlanner, Pims Completion Manager also does not consider technical dependencies between equipment and focuses on providing simple binary checklists instead of comprehensive documentation.

BlueRithm

In addition to its core functionalities of creating and managing commissioning tests, BlueRithm, a commissioning software, offers integration with various systems throughout the design-to-operation phase [Blue23]. This interface capability enables the connection of a Digital Twin to the software. Additionally, BlueRithm allows the inclusion of equipment templates to streamline the configuration process of commissioning projects, reducing time and effort. BlueRithm enables the creation of commissioning tests that incorporate validation rules, offering more than basic binary checks. BlueRithm provides an extensive dashboard viewer and an issue management system, fostering efficient collaboration among team members responsible for addressing issues and problems identified during commissioning. Moreover, BlueRithm facilitates the export of a traditional final commissioning report that stakeholders can review, sign, and accept as the final product.

Also similar to the previously mentioned solutions, BlueRithm does not contain functionalities for effective management of technical dependencies.

3 Commissioning Processes and Deficits

Achieving a proficient commissioning process necessitates a carefully planned workflow to systematically minimize delays, avoid unnecessary costs, and reduce errors. Consequently, to enhance the commissioning workflow, it is necessary to analyze the conventional processes of commissioning and identify their deficits.

This chapter provides a detailed analysis of commissioning processes (Section 3.1) and highlights the deficits of the processes (Section 3.2). The information is gathered through literature reviews, interviews, and workshops involving field experts from the shipbuilding industry. Notably, there is limited literature specifically dedicated to maritime commissioning, therefore, insights from building commissioning literature are incorporated and compared against the experts' input to achieve a comprehensive analysis of the commissioning processes and their deficits.

It is important to highlight that Chapter 3 predominantly centers on the outcome of the analysis of commissioning processes. However, in order to comprehend the specific data types utilized for the analysis and the methods applied for analyzing and modeling the commissioning processes, the reader should consult Chapter 5.

3.1 Processes of Commissioning

Killcross categorizes all commissioning activities into three stages (or processes): *preparation*, *implementation*, and *closure*, as outlined in his book [Kill12]. During preparation, the emphasis is on defining project requirements and developing a commissioning plan. Commissioning implementation is concerned with conducting testing procedures and ensuring that the requirements are met. Finally, the closure process entails finalizing documentation and delivering the completed product.

As stated in Section 1.3, this dissertation is an outcome of the research project *smart.START*. The analysis conducted within the scope of the research project reveals that maritime commissioning can be broken down into three primary processes analogous to those defined by Killcross, i.e., *preparation*, *implementation*, and *documentation*. Figure 11 depicts the three primary commissioning processes along with the corresponding activities for each process. It also emphasizes the specific areas of focus explored in this dissertation.

It is worth noting that this dissertation places emphasis on the technical details of the activities involved in commissioning processes, rather than the scheduling or timing of these activities. Consequently, *scheduling* is not addressed in this dissertation (see Figure 11). However, the current research in this particular domain is presented in the publication by Köster [Köst23].

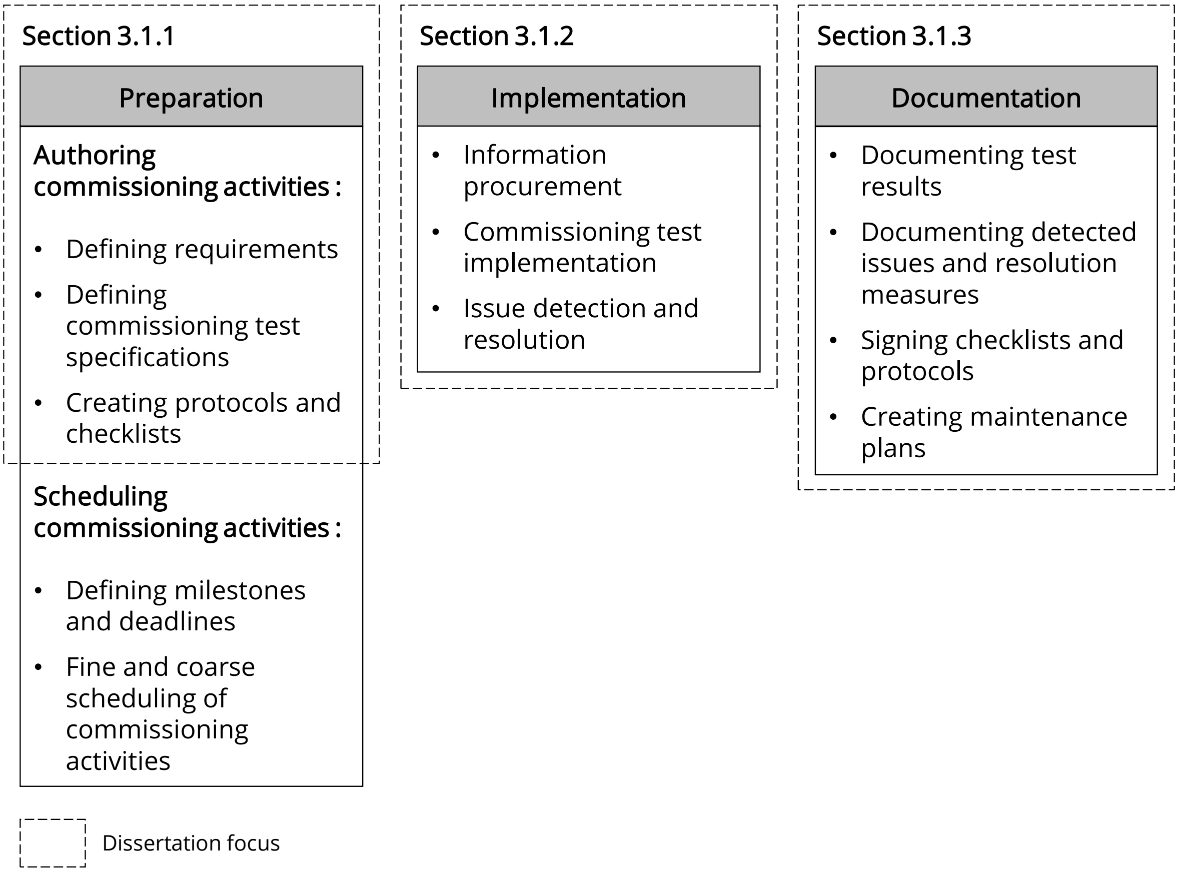


Figure 11: Overview of the commissioning processes

3.1.1 Preparation

Commissioning preparation takes place during the phases of pre-design and design. The main deliverable of the preparation process is the *commissioning plan* required for initiating commissioning. The entity responsible for commissioning preparation is the commissioning authority. In coordination with all project stakeholders, the commissioning authority gathers requirements and develops the commissioning plan.

Typically, the owner initiates the requirements, which are then discussed and refined by the commissioning authority and the commissioning team. Each requirement item is carefully defined to include acceptance criteria and measurement benchmarks. These requirements provide the commissioning authority with all the necessary information to develop a comprehensive and feasible commissioning plan. The commissioning plan outlines the necessary procedures to ensure successful commissioning and incorporates schedules for these procedures. The commissioning plan undergoes continuous updates throughout the project's lifecycle to accommodate design, construction, and operation changes. It also adapts to any issues that arise during the implementation of the commissioning process.

As discussed in Section 3.1, this dissertation focuses explicitly on the technical non-temporal aspects of commissioning. In this context, the commissioning plan is regarded as a collection of technical documents that provide instructions for implementing commissioning, excluding the scheduling aspect. Consequently, this section focuses on the preparation and management of *construction checklists* and the *systems manual*, as they encompass the necessary information required to initiate the implementation of commissioning.

Construction Checklists

The commissioning team needs a document called the *construction checklist* to begin implementing commissioning tests. The checklist ensures that the installed components and systems conform to the project requirements and specifications. The checklist comprises two types: component-based and system-based checklists. The former is employed for an individual component that is installed and started up, mostly by the subcontractor, while the latter is used for systems and assemblies that cannot be assessed with separate checklists for their subcomponents [ASHR05, P. 45].

A construction checklist includes basic information about the equipment/system to be inspected as well as fields for reporting installation status. The checklist also contains forms for submitting test measurements and data to verify proper functionality if required. Additionally, the checklist has a field for reporting any corrective actions taken to fix a problem detected during commissioning. This section is referred to as the *negative responses section* [ASHR05, P. 11].

It is clear that construction checklists are created for every equipment and system, and therefore different members within the commissioning authority collaborate on creating the checklists. Design professionals create or review checklists that are within the scope of their expertise, while the commissioning authority collaborates with contractors and suppliers to complete the checklists for the equipment supplied by their companies.

Systems Manual

The systems manual is valuable for individuals who were not involved in the design phase as it helps them understand, operate, and maintain the equipment and systems in the facility. It also contains information gathered during commissioning and information about correction work. Therefore, the commissioning team must have a partially complete systems manual before implementing the commissioning process. The complete systems manual will be finalized once the commissioning process is finished [ASHR05, P. 11].

Managing the development of the systems manual and reviewing the outcome lies with the commissioning authority. The manual is primarily developed through collaboration among the owner, contractor, and design professionals. They gather all relevant information about the systems and assemblies, along with the owner's project requirements and technical drawings and organize them in an indexed manual with cross-references [ASHR05, P. 54].

Process Model of Commissioning Preparation

This subsection provides a concise illustration of the preparation process using the Business Process Modeling Notation (BPMN) model [Whit04, P. 1], as depicted in Figure 12. The BPMN model presents the commissioning personnel or process actors as *lanes*. One lane, called *commissioning authority*, includes three sub-lanes representing project management, technical bureau, and engineering management. In practice, there are additional departments and personnel involved in the process. However, for simplicity, only three main actors are presented. The purpose of displaying the process actors is to illustrate the participation of various personnel in the preparation of the commissioning plan.

The technical bureau is responsible for conducting the primary and most comprehensive tasks involved in developing the commissioning plan. The authoring process begins by reviewing documents, including the initial contract, norms and standards, and technical design sheets and data, in order to define commissioning tests. The commissioning plan is subsequently sent to project and engineering management personnel for final adjustments and refinement.

The BPMN model indicates that the technical bureau is the primary beneficiary of an efficient commissioning preparation workflow. Therefore, the analysis involved close collaboration with professionals from the technical bureau to develop the process model presented in Figure 12.

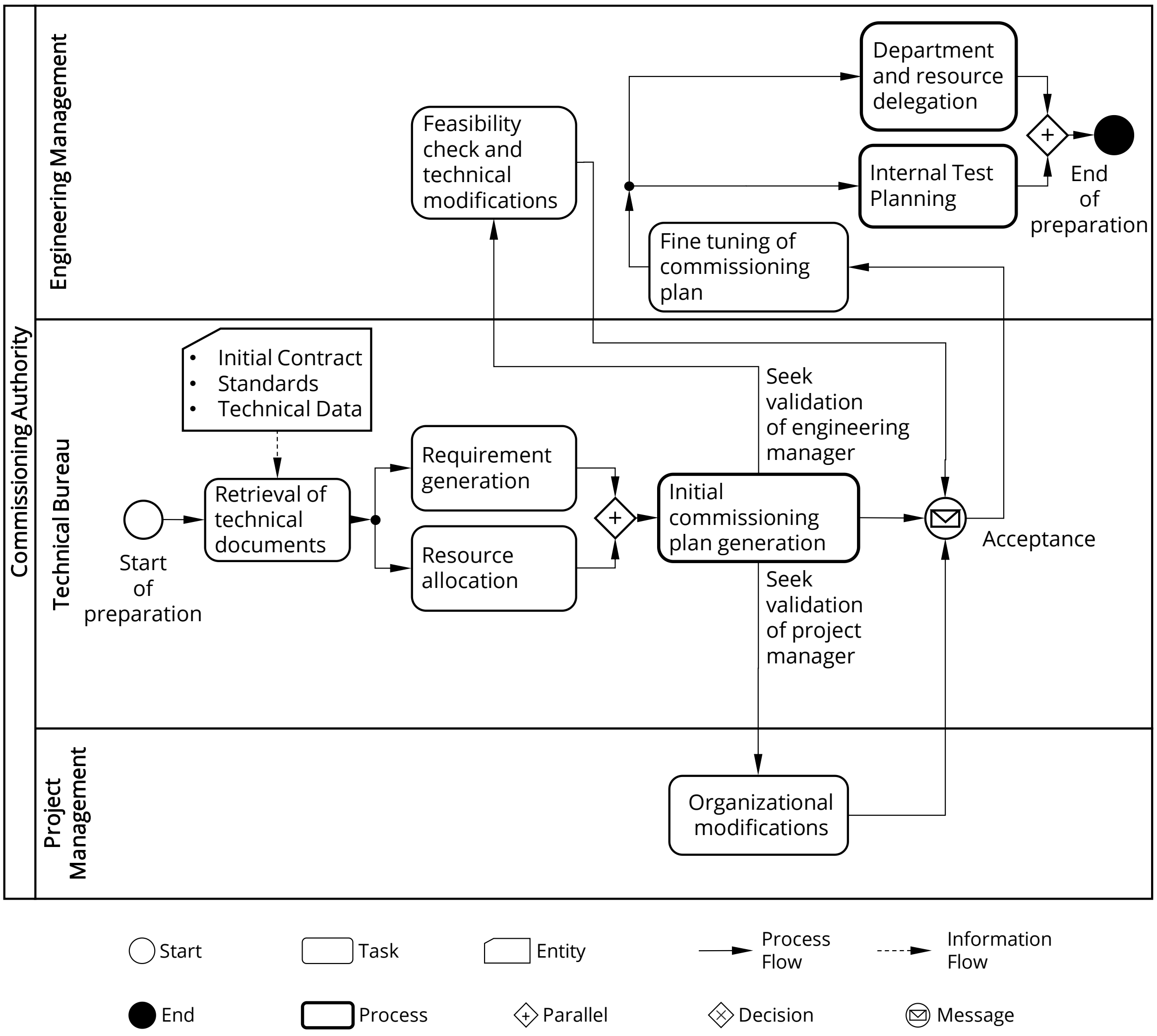


Figure 12: Simplified BPMN model for commissioning preparation

3.1.2 Implementation

Commissioning implementation takes place during the construction phase. The main objective of implementation is to verify that the owner’s project requirements are fulfilled. The entity responsible for commissioning implementation is referred to as the *commissioning team*.

The work of the commissioning team can be categorized into two primary areas: organizational and technical tasks. Organizational tasks involve activities related to planning the testing procedure, including setting a schedule and coordinating the participation of external personnel, such as owner's representatives, classification society members, and subcontractors. On the other hand, technical tasks include all the activities specified in the construction checklists.

Organizational Tasks

In shipbuilding, it is common to conduct weekly meetings to report unexpected issues during system installation [Rose17, P. 3]. Correspondingly, to effectively manage commissioning implementation, the commissioning team holds regular meetings where members from various disciplines participate. These meetings provide a platform for reporting updates on construction progress, schedule reviews, unresolved issues, and emerging concerns. During the initial stages of construction, the owner's representatives and the commissioning authority may also join these meetings to discuss and evaluate requirement changes. Additionally, subcontractors are also involved in the meetings.

Furthermore, organizational work includes other preparatory tasks before commencing on-site testing. For example, members from the commissioning team may conduct a site visit to ensure that the equipment to be tested is properly installed and that the testing area is free from any obstructions caused by ongoing construction activities. Once it is established that testing can proceed, the team members proceed to gather the necessary documents for conducting the tests and make arrangements to secure the tools and instruments required for the testing procedure.

Technical Tasks

As previously mentioned, equipment/system testing is the technical aspect of commissioning implementation. Even though testing mostly takes place on-site, it is typical to execute tests prior to the installation of the equipment. This particular form of testing is carried out by the manufacturer and is known as *Factory Acceptance Testing* (FAT) [IEC 06, P. 9]. FAT verifies that the equipment adheres to the design requirements before it leaves the factory by employing simulation and modeling techniques, such as Hardware-in-the-Loop [Baci05, P. 3194]. Figure 13 summarizes the technical activities performed during FAT [IEC 06, P. 14–16].

Once the manufacturer completes the FAT, the equipment can be shipped and installed. Following the installation, on-site testing can commence. This testing procedure involves verifying correct installation and functionality of individual equipment and systems, as well as conducting tests to assess the performance of multiple independent systems when combined, to achieve the functionality specified in the requirements [IEC 06, P. 16f.]. The testing conducted while a ship docked is commonly known as *Harbor Acceptance Testing* (HAT). Upon commencement of sea trials, the ship undergoes on-site testing while it is in motion, which is known as *Sea Acceptance Testing* (SAT) (refer to *Phases of Maritime Commissioning* in Section 2.2.3).

Category	Activity	Description	Detailed Tasks
System Features	**Start-up test**	Test to verify that the system starts correctly	Testing of switches Powerup testing
	General functionality tests	Basic system features are verified in this test	Recovery from failure Redundancy checks Log functionalities Alarm processing Performance tests (refresh rate, speed, etc.)
Scope of Application	**Human-machine interface (HMI) tests**	This test is concerned with verifying functionality of HMI devices (such as displays)	Correct display of symbols Correct display of colors Correct display of dynamic information (process flow, hierarchies, etc.)
	Communication links test	This test is concerned with testing communication links to subsystems	Simulation of signal messages Verifying correct behavior according to signals
Rework	**Error Rectification**	Activities performed when an error is encountered	Identification of rework Action planning Action execution Test repeating

Figure 13: Summary of technical activities in Factory Acceptance Testing (FAT) [IEC 06, P. 14–16]

3.1.3 Documentation

Shipbuilding is an industry that falls under strict regulation by the EU. According to Directive 2014/90/EU of the European Parliament and of the Council of 23 July 2014 on marine equipment and repealing Council Directive 96/98/EC, manufacturers in the field of shipbuilding must provide and keep technical documentation for safe installation on board and safe use of the product. The directive also obliges the manufacturer to archive the documentation for at least ten years. Further obligations and a more precise formulation of the obligations for documentation are listed in the directive [Euro14, P. 156].

The documents generated following the completion of commissioning implementation are primarily technical. The term *technical documentation* refers to all essential documents regarding technical products and processes. These documents encompass information covering the product life cycle from the product idea to its operation, disposal, and recycling. Technical documentation presents information in a well-organized and coherent manner and includes various forms such as product descriptions, user manuals, maintenance manuals, parts catalogs, and programming [VDI 06, P. 5–7].

The Association of German Engineers (VDI) categorizes technical documentation into internal and external documentation. Internal documentation is used within the enterprise and encompasses all the information necessary for product planning, development, commissioning, and maintenance. On the other hand, external documentation is shared with the client and includes information such as operating instructions, testing certificates, diagnostic results, and disposal instructions. [VDI 06, P. 5–11]. In commissioning, technical documentation serves both internal and external purposes. The commissioning team utilizes internal documentation for executing commissioning tests and reporting errors. On the other hand, external documentation is used during the acceptance phase to verify compliance with the requirements.

Technical documentation in maritime commissioning varies in format depending on the specific test type (FAT, HAT, SAT) and the equipment or system being evaluated. For instance, the International Organization for Standardization (ISO) provides twelve templates for recording outcomes achieved during sea trials [DIN 05, P. 25–38]. These templates consist of paper-based documents featuring tables and text sections where the commissioning agent can record data gathered from tests like anchor-handling tests, noise tests, steering gear trials, and others. The documents represented by the following sources provide more examples of technical documentation templates for commissioning [ISO 20] [DIN 02] [ASHR05].

Section 2.2.3 discusses two examples of documents generated during commissioning preparation: construction checklists and the systems manual. Additionally, more documents are created throughout the commissioning process. These documents may vary depending on the project type and the owner's requirements [ASHR05, P. 4]. Typically, all commissioning documents are included as appendices in a report known as the *final commissioning report* which is handed out at the end of commissioning. This report encompasses the project deliverables generalized in Figure 14 [PIER01, P. 41] [Haas99, P. 60] [ASHR05, P. 17f.].

Deliverable	Description
Construction checklists completion and verification summary	Documents that verify construction and correct installation of equipment, systems, and assemblies.
Test procedures and results	All tests conducted to confirm the functionality of the system, along with the corresponding test results.
Contractors' test reports	FAT reports by manufacturers and system suppliers.
Blank test reports	Blank forms for future testing and verification.
Issue log	Issues discovered during commissioning as well as the measures taken to correct such issues.
Requirement deviations	Lists of systems or assemblies that deviate from the owner's requirements but are still approved by the owner due to budget limitations or other factors.
Systems manual	Document for understanding and operating the equipment and systems in the facility.
Training documents	Sign-in sheets that verify training delivery to intended personnel and users.
Maintenance plans	Maintenance and troubleshooting documentation.

Figure 14: Final commissioning report deliverables [PIER01, P. 41] [Haas99, P. 60] [ASHR05, P. 17f.]

Process Model of Commissioning Implementation and Documentation

The model presented in this subsection (see Figure 15) summarizes the workflow of both the implementation and documentation processes. The model shows that the commissioning team lane (which includes all the engineers and technicians responsible for testing) contains most of the implementation and documentation tasks, and therefore, the solution presented in this dissertation seeks to optimize the workflow of the commissioning team by reducing the effort required for initial preparation, testing, and measurement capturing.

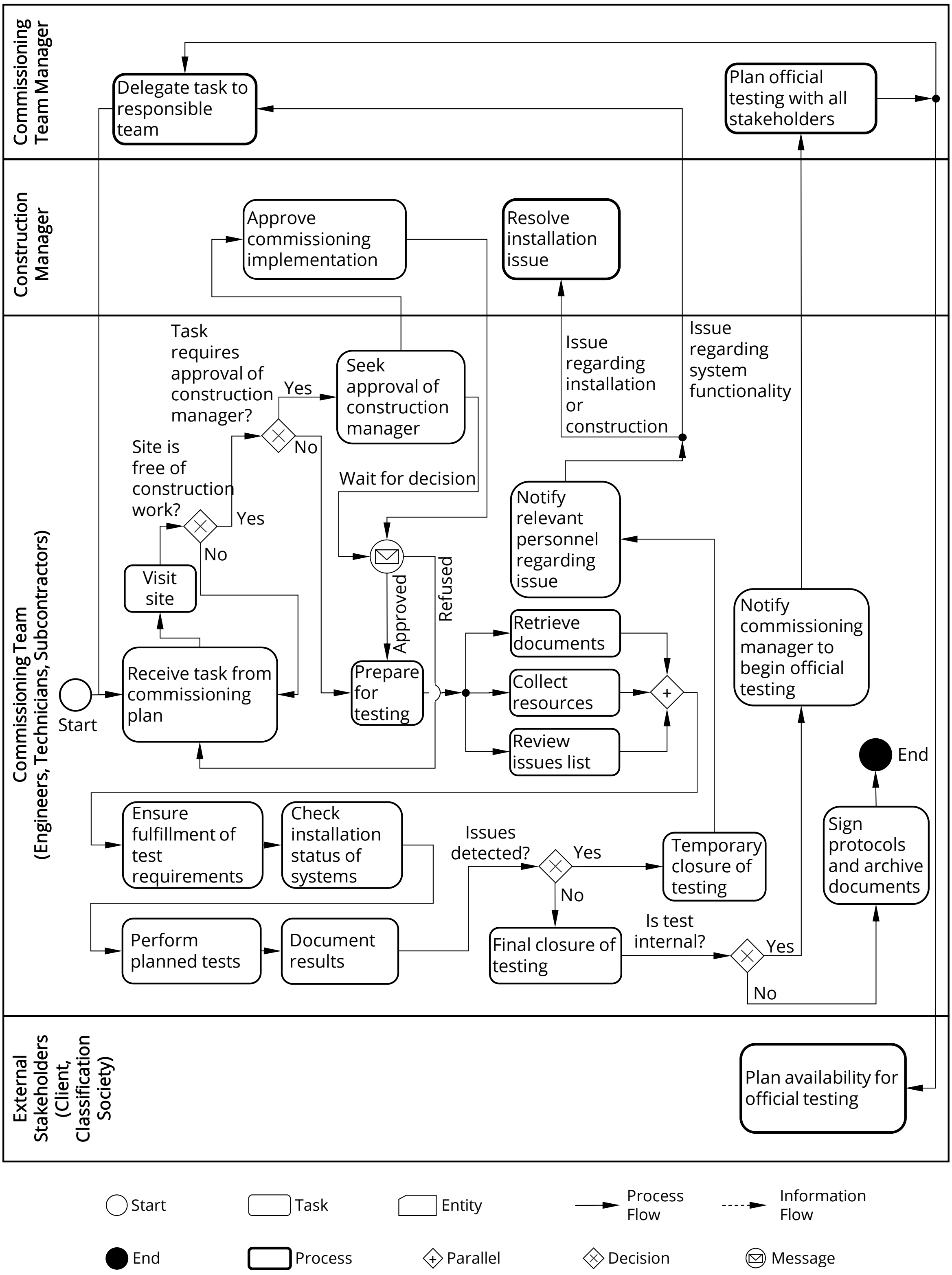


Figure 15: Simplified BPMN model for commissioning implementation and documentation

3.2 Deficits of the Conventional Process

The analysis conducted within the scope of this dissertation reveals that due to the complexity of the ship, it is normal to conduct over *ten thousand* tests during the commissioning, and depending on the ship to be commissioned, the process may take up to twelve months to complete. Accordingly, Südekum, leader of the Industry Sector Management Process & Marine Department at WAGO GmbH & Co. KG [WAGO23a], a German company that performs integration tests for ship commissioning, emphasizes that "*mastering complex processes and systems poses a significant challenge for shipbuilders*" [Muzy18].

In such a complex process, it is expected to face numerous challenges and deficits. Consequently, Section 3.2 discusses the most significant deficits of the conventional process of commissioning. These deficits are analyzed and discussed in the following sections with regard to the processes of preparation, implementation, and documentation.

It is important to highlight that the deficits in the conventional commissioning process can differ from one shipyard to another. This implies that certain shipyards integrate varying levels of automation into their workflow to reduce time and effort in specific isolated use cases, while others entirely depend on conventional tools for commissioning preparation, implementation, and documentation. The deficits discussed in this dissertation are specifically those arising from a reliance on traditional, non-specialized tools for conducting maritime commissioning.

To facilitate the identification of these deficits in the upcoming chapters, each deficit is assigned a unique identifier that starts with a letter denoting the specific commissioning process that suffers from the deficit. For example, "P" stands for preparation deficit, "I" is implementation, and "D" for documentation. Finally, a numerical value is added after the deficit identifier. Figure 16 lists all the deficits to obtain an overview before discussing each deficit in detail.

Process	Identifier	Deficit
Preparation (Section 3.2.1)	P1	High effort of commissioning plan authoring
	P2	Suboptimal commissioning plans due to lack of consideration of technical dependencies
Implementation (Section 3.2.2)	I1	High effort for initial preparation and information procurement
	I2	Inefficient workflow when dealing with disturbances and errors
Documentation (Section 3.2.3)	D1	Inefficient documentation of commissioning test results
	D2	Inefficient issue logging and information retrieval
	D3	Lack of a dynamic overview of documentation progress

Figure 16: Overview of the commissioning processes deficits

3.2.1 Preparation Deficits

The complexity of commissioning arises from dealing with a highly intricate product like a ship. As mentioned in Section 2.1, a cruise ship contains more than 10 million components [Seew15], all of which would require testing and verification for the ship to be successfully commissioned. Hence, it is necessary for the commissioning authority to develop a comprehensive commissioning plan that contains the testing procedures for all components and systems within the ship. Nevertheless, the extensive number of components and systems in the ship results in significant effort and time for preparation. Furthermore, the current conventional methods and tools used by the shipyards for commissioning preparation lack the efficiency to develop a commissioning plan that takes into account the technical dependencies between all the ship's components.

Deficit P1: High Effort of Commissioning Plan Authoring

A commissioning plan contains all the documents for testing and verifying the components and systems in the ship as mentioned in Section 3.1.1. The authoring of such checklists is assigned to personnel based on their specializations. For instance, experts from the electrical engineering department are responsible for creating checklists related to electrical components and systems. As a result, to create a commissioning plan, access to a list encompassing all ship components and systems, arranged according to different departments, becomes essential. Such access is provided via systems such as PLM and ERP.

That being said, it is worth noting that the data concerning the components within these systems may not always be complete, necessitating those in charge of creating the commissioning plan to seek out the missing data from design sheets and manufacturers' manuals. Particularly when dealing with components of considerable quantity, like sensors, the information retrieval process can be time-consuming. Once the necessary data is obtained, the creation of the commissioning plan can begin.

A testing procedure within the commissioning plan must encompass information regarding the specific component or system to be tested. This includes the identification and location of the component, the type of test to be conducted, the anticipated values resulting from the test, the tools and equipment required for performing the test, and other relevant meta information. If necessary, technical drawings can also be included to aid with performing the commissioning test.

The process of authoring a comprehensive testing procedure requires substantial time and effort, as it entails obtaining essential data from a source (e.g., a PLM system, design sheets, or manufacturers’ manuals) and transferring it to a dedicated document, often using generic software like Microsoft Word. To facilitate the creation of commissioning plan documents, commissioning authority personnel employ templates that already contain the fundamental structure of a testing procedure. They then insert information about the component to be tested and their attributes into these templates. Despite using templates, this approach still necessitates considerable effort because the document editing software (e.g., Microsoft Word) does not automate the retrieval of component details from the PLM system or the copying of these details into the Word template. The effort intensifies significantly when dealing with a large number of components.

It is important to note that the commissioning plans created in their current form cannot be readily applied to different ships and commissioning projects. The limitation arises from the use of generic software for developing these plans, as it does not facilitate reusability. For true reusability, structured and modular data models are required, enabling seamless adaptation to various projects through automated application.

Deficit P2: Suboptimal Commissioning Plans due to Lack of Consideration of Technical Dependencies

The scope of the commissioning plan varies based on the size and complexity of the ship under commissioning, and it may comprise hundreds of documents detailing the components to be tested and the specific testing procedures for each. These documents are typically printed and utilized by the commissioning team in physical form. In a project thesis supervised as part of the doctoral research, Depperschmidt conducted a questionnaire among maritime commissioning experts. The findings of this questionnaire indicate that the commissioning plan lacks clear instructions regarding the optimal sequence for conducting the commissioning tests [Depp22, P. 108].

Using the conventional methods of authoring the commissioning plan, determining the execution sequence of commissioning tests becomes impractical, as it necessitates the commissioning authority personnel to have a comprehensive overview of all the commissioning tests and manually identify interdependencies among them. In cases where the plan encompasses an extensive number of commissioning tests, surpassing ten thousand, this process becomes exceedingly laborious and time-consuming. Consequently, the tests are defined without a specific execution sequence, leaving the commissioning team members to rely solely on their prior experiences to identify a viable sequence for conducting the tests.

The necessity for a precise execution sequence arises from the technical interdependencies among the components. For instance, if an electrical equipment fault occurs, it might be linked to faulty cables. Consequently, it becomes advantageous to verify the cables before proceeding with the testing of the equipment. It is important to state that an incorrect sequence in carrying out the commissioning tests can result in various issues, including the overlooking of faulty equipment and systems on the ship. Such oversights could lead to negative consequences, especially when dealing with safety equipment. Moreover, an incorrect testing sequence might lead to prolonged identification of failure causes and the inability to fully meet the client requirements.

3.2.2 Implementation Deficits

As stated in Section 3.2, the entire commissioning process can extend beyond twelve months for completion. To speed up the process, commissioning tests are conducted during the ship's construction stage. However, this concurrent implementation of commissioning tests during construction gives rise to conflicts and disruptions. Furthermore, the extensive work involved in commissioning implementation demands significant time and effort for initial preparation and information procurement.

Deficit I1: High Effort for Initial Preparation and Information Procurement

As previously mentioned, the commissioning plan documents are utilized in physical form by the commissioning team to carry out the testing procedures. However, before commencing the implementation work, a member of the commissioning team must visit the commissioning site to ensure that it is clear of obstacles caused by ongoing construction activities. This scouting process incurs unnecessary time and effort, as the person conducting the site visit may spend over an hour walking to and from the location before they can resume their initial preparation tasks at their desk. The prolonged duration is attributed to possible blockages along the usual route to the commissioning site due to construction work, necessitating the person to find an alternative path to reach their destination. This long time mainly affects larger projects such as the commissioning of a cruise ship. If the location is found to be unsuitable for conducting the necessary testing, the commissioning team personnel seek another location to conduct different tests.

It is evident that personal visits to the testing location are unnecessary but become inevitable in the conventional workflow due to communication challenges. This situation arises from the absence of a dynamic system that automatically updates the construction status. Additionally, traditional communication methods like E-Mails and phone calls are suboptimal during ongoing construction work, making personal site visits the only feasible option.

Once the scouting step is completed, and the site is confirmed obstacle-free, the commissioning team proceeds with the preparation of necessary testing documents and tools. To collect the required documents for testing, the commissioning team conducts searches through directories to access checklists, manuals, and supporting documents related to the components and systems slated for testing. The search process should not be underestimated, given the large number of components present on the ship. Furthermore, the documents are subject to updates due to design modifications and evolving requirements. As a result, the commissioning team must be aware about such changes while collecting the documents for testing. Moreover, it also happens that the commissioning plan documents are not fully authored, resulting in a waste of time during the site scouting and document search processes. Furthermore, preparing the tools required for testing, such as setpoint generators, requires the commissioning team to view the documents for testing and decide on the tools relevant for the testing procedure. If the commissioning team member is planning to conduct a large number of tests, it is not optimal to manually search the documents for the required tools. After the tools are identified, it often happens that the tool is currently in use by other commissioning team members.

The deficits of documentation and resource gathering arise from the absence of a centralized system that automatically prioritizes commissioning test implementation based on resource availability.

Deficit I2: Inefficient Workflow when Dealing with Disturbances and Errors

Commissioning is necessary for early detection and rectification of errors and deviations from design requirements. In the best-case scenario, when an error is encountered, the commissioning team can quickly identify its cause, address it on-site, and continue with the implementation of other commissioning tests. Nonetheless, achieving a quick error resolution is not always feasible, as errors may sometimes stem from issues beyond the specialization of the commissioning team members. Such cases demand the involvement of specific individuals with different expertise who might not be present at the time of error detection. Consequently, the testing procedure comes to a halt until the responsible personnel arrive, leading to idle time, especially if subsequent tests depend on the equipment where the error was identified.

Furthermore, there are instances where reaching the responsible individual becomes impractical due to challenges with on-site communication. In such cases, the commissioning team cannot proceed with the planned tests and would need to implement alternative commissioning tests. This situation results in a loss of time invested in preparing for the initial testing, compelling the commissioning team to restart the preparation process for other commissioning tests.

3.2.3 Documentation Deficits

Upon completing a commissioning test, the results are recorded in dedicated documents like checklists, punch lists, and logs. The documentation process holds significant importance, as mentioned in Section 3.1.3, and therefore, it must be executed efficiently and clearly. Nevertheless, several shortcomings emerge due to the diversity of components and the varying complexity of corresponding testing procedures. Some tests may be straightforward, like visual checks (e.g., installation tests), where documentation involves simple check marks to indicate component installation status. On the other hand, other tests demand more time and effort for documentation, especially when it is required to capture measurement values over a period of time.

Despite the diverse complexities of commissioning tests, the prevalent method for documenting commissioning test results typically involves physical paper documents. This approach introduces deficits, such as difficulties in accurately recording measurement values, a lack of real-time overviews of commissioning progress, and inefficiencies in the storage and retrieval of commissioning test results.

Deficit D1: Inefficient Documentation of Commissioning Test Results

Commissioning tests are performed to validate the client's requirements and ensure compliance with the established regulations and standards defined by classification societies. These tests encompass various types, each with distinct documentation requirements. As previously mentioned, installation tests are straightforward to document. However, when it comes to functional tests, more comprehensive documentation efforts are necessary.

Functional tests aim to confirm the proper functioning of systems and components installed on the ship. To document the result of testing, checklists are prepared by the commissioning authority containing several *commissioning steps* that provide guidance on verifying the functionality of each component. These steps come with designated fields where the commissioning team can record the results obtained during testing. The results documented in these fields can take two primary forms. Firstly, a binary check used to indicate whether the component is operating correctly or not. Secondly, a text field for submitting values that correspond to the readings obtained from the conducted test.

The measured values in commissioning tests can be categorized as either discrete or continuous. To illustrate, when sensor-based alarms are being tested, the commissioning team may seek to obtain a specific reading that would trigger the alarm. In such cases, a single discrete value is recorded, representing a distinct point in time. On the other hand, some tests require capturing continuous readings over a duration of time. For instance, monitoring temperature or observing the speed of pressure drop. In these scenarios, a series of continuous data points are documented, showing the changing values over the specified period. Additionally, it is not uncommon for commissioning tests to involve the simultaneous recording of values from various components over an extended time frame. This necessitates the presence of multiple individuals who can collect these data points in parallel to ensure synchronous documentation of readings.

Documentation of such comprehensive tests is not efficient due to using paper-based checklists. The process of recording data over an extended period on paper requires unnecessarily high resources, involving multiple individuals from the commissioning team. Moreover, manual documentation of continuous values leads to idle time, where the team's productivity suffers as the team members must wait and write down measurement values on paper.

Moreover, this workflow has the potential to introduce inaccuracies and errors, since individuals may accidentally overlook measurement values during the comprehensive documentation process. In certain instances, measurement values may be inaccurately perceived from the source or incorrectly recorded on paper. Furthermore, the potential for misinterpretation of measurement values exists as a result of imprecise handwriting, given that the measurements are recorded on paper.

Deficit D2: Inefficient Issue Logging and Information Retrieval

Commissioning is crucial for identifying construction and installation errors, and these errors are tracked using *issue logs*. Such issue logs are used for documenting the identified errors, deviations from requirements, and the corrective actions taken to address them. The final commissioning report must encompass the complete history of such issues. Different methods are currently employed by the commissioning team to log and communicate these issues while documenting test results. The choice of the logging method depends on the type of the issue. For instance, functional errors are logged using textual descriptions, while visible quality errors can be documented through photographs or videos taken using cameras or smartphones.

To report the issues identified during the testing procedure, the commissioning team scans paper-based logs and sends them, along with relevant photographs, via email to the responsible individuals. Additionally, copies of these logs are stored in a centralized folder accessible to both the commissioning team and the commissioning authority. Moreover, shipyards may utilize task management systems to assign responsibility to individuals specialized in addressing specific issues. Lastly, issues may be verbally reported either via telephone calls or during weekly meetings.

The current issue logging workflow suffers from various drawbacks arising from the use of multiple media and methods. Paper-based logging, in particular, presents certain limitations, including reduced clarity and challenges in efficiently tracking detected errors. For instance, when the issue log is scanned and stored in a network folder, responsible personnel face the task of manually searching for issues relevant to their specialization and extracting the necessary information pertaining to each problem. This process can be time-consuming and prone to errors. In cases where the issue log entries lack clarity due to incomplete information or unclear handwriting, the responsible personnel must personally reach out to the individual who logged the issues to seek further clarification, which induces delays and productivity loss.

Furthermore, the use of photographs or videos to log issues without a multimodal dedicated infrastructure for issue tracking is unproductive. Currently, the commissioning team captures such media and shares them with responsible personnel through emails and enterprise messaging services. However, this approach has its limitations, as it necessitates manual searches through emails and messages to access relevant photographs and videos when tracking issue history. In the case of complex issues, relying solely on photographs and videos may only display the symptoms of the detected errors, and a textual description becomes crucial for explaining the problem comprehensively. As a result, the commissioning team faces more effort for logging the issue. They need to record the problem on paper, including a detailed textual description, and also capture relevant photographs or videos. This information is then shared with the responsible individual who must interpret the issue using both textual and visual sources.

Consequently, the absence of a dedicated issue logging system adversely impacts productivity, mainly due to the substantial effort needed for logging and retrieving information. Furthermore, this workflow introduces potential errors and deviations from requirements, as there is a risk of misinterpreting issue logs.

Deficit D3: Lack of a Dynamic Overview of Documentation Progress

The current documentation workflow, heavily reliant on paper-based methods, also poses challenges in efficiently maintaining a comprehensive overview of the commissioning work progress. Accessing information about the testing status of a specific component on the ship requires individuals to navigate through the latest versions of scanned checklists and logs, manually searching for the relevant component within these documents. Alternatively, interested parties may have to directly contact the responsible commissioning team to inquire about such information. By establishing a dynamic overview of the construction and commissioning progress, potential disturbances arising from conflicts between these two processes, as discussed in Deficit P2 in Section 3.2.1, can be effectively mitigated.

Finally, the bilateral communication approach for information retrieval, and the lack of centralized information organization prevent the development of a valuable repository of *lessons learned*. Such a repository could be used for guiding future projects of the shipyard.

4 Problem Statement and Solution Requirements

Section 4.1 of this chapter concisely summarizes the shortcomings of the conventional process of maritime commissioning. These shortcomings are presented as a problem statement, which includes the problem context, significance, and the research objectives and goals. Finally, Section 4.2 outlines the requirements for developing a potential solution to address the identified problem.

4.1 Problem Statement

The problem that this dissertation addresses is the inefficiency of the current conventional methods employed by shipyards for maritime commissioning, which lead to productivity loss, errors, and unnecessary costs. This section summarizes the problem including research deficits, consequences, and research aims and objectives.

Problem Context

Maritime commissioning is a crucial process where a newly constructed ship undergoes extensive testing and verification procedures before becoming fully operational. When conducted efficiently by the shipyard, this process effectively contributes to delivering ships in the shortest possible time, avoiding rework or unnecessary costs, while ensuring compliance with client requirements, regulations, and safety standards. Thus, efficient commissioning not only benefits the shipyard's business but also promotes high quality, safety, and energy-efficient operations. However, the current workflow typically employed by shipyards lacks the desired efficiency, resulting in delays, increased costs, and suboptimal allocation of resources. Although efforts have been made to improve the process, they have not been entirely effective, necessitating further enhancements due to intense global competition among shipyards. As a result, there is a growing demand for research and innovation to optimize the commissioning process and maintain a competitive edge in the maritime industry.

Digitalization has proven to be a beneficial factor in enhancing the shipbuilding industry as a whole, prompting extensive research on applying digital technologies to shipbuilding processes. However, there is still a notable research gap in the digitalization of commissioning. Current research primarily focuses on optimizing specific aspects of the commissioning process, such as improving the testing procedures for automation systems. Yet, these concepts do not provide a comprehensive solution that covers enhancements for the entire process, including commissioning preparation, implementation, and documentation. Moreover, the existing research does not prioritize developing solutions for the seamless integration of digital commissioning into the overall production process. This lack of comprehensive solutions can demotivate shipyards from adopting such technologies, as uncertainties and high efforts associated with integration remain significant hurdles. Further research is needed to address these challenges and provide comprehensive approaches to digitally optimize the commissioning process in shipbuilding.

Problem Significance

As discussed in Chapter 3, the commissioning workflow suffers from several limitations in the preparation, implementation, and documentation processes. These shortcomings arise from factors such as heavy reliance on paper-based documents, inefficient information management, and the absence of dedicated centralized systems for commissioning. Consequently, the preparation of testing procedures imposes unnecessary effort and time on the responsible employees, while performing tests and submitting results using paper-based documents leads to errors, delays, and suboptimal resource allocation. Moreover, the conventional documentation systems fail to establish a repository of *lessons-learned* due to the lack of structured information systems and difficulties in information retrieval and transfer. All these deficits have a negative impact on shipyards, affecting their productivity and competitiveness.

Research Aims and Objectives

This dissertation aims to overcome the deficits of the conventional commissioning workflow by implementing digitalization. Enhancing a process involves elevating its *quality*, minimizing *costs*, and reducing the overall *time* of the process [Lödd14, P. 23]. To achieve this, the dissertation involves an analysis of the current commissioning processes (Section 3.1), identifying key deficits (Section 3.2) and necessary requirements (Section 4.2). Subsequently, the process is modeled in terms of data and behavior (Chapter 5).

The suggested solution is a *Digital Assistance System* (DAS) that seamlessly integrates into the shipyard's infrastructure and connects with existing Information Technology (IT) systems. This DAS aims to enhance the efficiency of commissioning by facilitating more streamlined preparation, implementation, and documentation processes (Chapter 6). To assess the effectiveness of the developed DAS, a series of comprehensive tests are conducted by professionals in the shipbuilding industry. Additionally, feedback from the intended users is gathered, hence serving as a qualitative evaluation. The evaluation focuses on examining the DAS's integration capabilities, qualitative benefits, and potential productivity improvements it offers to the commissioning processes (Chapter 7).

4.2 Solution Requirements

To design a DAS that provides a solution for the problem stated in Section 4.1, it is important to first define the necessary requirements of the solution. The requirements are derived from the deficits identified in Section 3.2 and are categorized as follows:

1. Requirements for *organization* of commissioning information (O)
2. Requirements for productive *preparation* of commissioning plan (P)
3. Requirements for efficient *implementation* of commissioning tests (I)
4. Requirements for systematic *documentation* of commissioning results (D)
5. Requirements for integration and *acceptance* (A)

Figure 17 lists all the requirements to obtain an overview before discussing each requirement in detail.

Category	Identifier	Requirement
Organization (Section 4.2.1)	O1	Centralized system for project organization
	O2	Integrating assembly information with commissioning
Preparation (Section 4.2.2)	P1	Improving the authoring of testing procedures
	P2	Considering technical dependencies in the commissioning plan
Implementation (Section 4.2.3)	I1	Reducing effort for initial preparation via context-awareness
	I2	Efficient information procurement and visualization
Documentation (Section 4.2.4)	D1	Productive documentation of functional test results
	D2	Systematic documentation of issues
Acceptance (Section 4.2.5)	A1	Easy integration with existing infrastructure
	A2	User satisfaction

Figure 17: Overview of the solution requirements

4.2.1 Organization of Commissioning Information

A comprehensive process like maritime commissioning involves complex data and information exchange among various departments and individuals, therefore, efficient organization of project information becomes essential. Consequently, a centralized system that forms the infrastructure of the DAS and integrates with the existing infrastructure of the shipyard is required to effectively manage the storage, processing, and retrieval of information.

Requirement O1: Centralized System for Project Organization

To provide efficient information procurement and enhance communication between different departments, a centralized system is required. This system should incorporate various modules, such as a database, interfaces compatible with the existing infrastructure of the shipyard, intelligent data processing services, as well as communication and security services. By effectively integrating such a system, the dependence on paper-based workflows is expected to significantly diminish.

Requirement O2: Integrating Assembly Information with Commissioning

As highlighted in Section 2.1.2, shipbuilding processes overlap to minimize idle time and maximize productivity. However, this overlapping of processes leads to conflicts. Consequently, commissioning work occurs concurrently while the ship is being built, necessitating a system that offers the commissioning team real-time and precise information on the ongoing assembly status. This system should intelligently integrate with the shipyard production systems, allowing for automatic and dynamic updates on the assembly progress, thereby eliminating the need for manual inquiries and saving time and effort.

It is worth noting that the DAS for commissioning to be developed within the scope of this dissertation can be used to its fullest extent when a DAS for assembly is already present in the shipyard’s infrastructure. An example for such a system is the one developed by Halata [Hala18] (see Section 2.3.3) or the DAS by Rost [Rost23]. An interface to a DAS for assembly plays a crucial role in facilitating effective communication and coordination between the commissioning team and the current assembly operations. Having such an interface minimizes interruptions and disputes that may arise due to overlapping activities between the commissioning and assembly processes. Nevertheless, it is still necessary for the commissioning DAS to include conflict-avoidance capabilities, even in the absence of an assembly DAS inside the shipyard's infrastructure.

4.2.2 Productive Preparation of Commissioning Plan

The commissioning team requires a well-defined commissioning plan encompassing all the necessary details for conducting the testing procedures. Efficient and low-effort preparation of this commissioning plan is essential to fully leverage the advantages of employing a DAS for commissioning processes. Additionally, the preparation process should incorporate the ability to account for technical dependencies, and the resulting plan should be reusable across different commissioning projects.

Requirement P1: Improving the Authoring of Testing Procedures

Improving the preparation process entails minimizing the time and effort invested in extensive information retrieval and manual authoring of testing procedures. To achieve this improvement, a dedicated authoring system must be developed to overcome the limitations associated with the current generic tools employed by shipyards for commissioning planning. The developed system should have the capability to extract and interpret data from the shipyard's PLM systems. Subsequently, it should automatically identify and select the relevant data required for commissioning planning. Additionally, the system should automatically generate initial testing procedures, which can be further modified and approved by the commissioning authority, which would reduce the manual work.

Requirement P2: Considering Technical Dependencies in the Commissioning

Plan

The conventional paper-based workflow induces several limitations including the inability to maintain a clear overview of all the testing procedures and their interdependencies. With the development of a dedicated authoring system, this limitation should be mitigated. In other words, establishing a well-defined structure and information models should facilitate the inclusion of supplementary details, such as technical dependencies. The proposed authoring system should offer the commissioning authority the ability to visualize these dependencies. Moreover, it should enable the automatic generation of an execution sequence for the commissioning tests based on their technical dependencies.

Requirement P3: Achieving Cross-project Reusability of Commissioning Plans

In many shipyards and in the majority of commissioning software, the reusability of commissioning plans among various ships is currently restricted due to the utilization of generic tools, such as Microsoft Office, for commissioning planning. To address this limitation effectively, a dedicated authoring system must be developed (as stated in Requirement P1). The new system should adopt a template-based approach for authoring, thereby eliminating the need to create testing procedures from scratch. By employing a template-based workflow, the commissioning plans generated by the new system should become reusable across different projects, to achieve enhanced productivity and efficiency.

4.2.3 Efficient Implementation of Commissioning Tests

To achieve efficient implementation of commissioning tests defined in the commissioning plan, it is essential to facilitate the initial preparation of documents and resources while also reducing the likelihood of encountering disruptions and conflicts. In this regard, integrating a DAS into the process should offer support to the commissioning team by providing clear steps and well-structured information, thus facilitating their tasks and reducing errors and delays.

Requirement I1: Reducing Effort for Initial Preparation via Context-Awareness

To enhance the efficiency of the implementation process, it is essential for the commissioning team to minimize manual efforts in searching for suitable work packages and instead focus on the technical tasks at hand. To achieve this, a context-aware system, which has access to the assembly status (as described in Section 4.2.1), should be made available to the commissioning team members. This system should intelligently recommend suitable work packages based on each team member's specialization and the current status of assembly work. Additionally, it would be advantageous to draw the commissioning team's attention to potential disturbances in specific ship locations that could hinder their progress. This awareness should allow for better navigation and quicker access to target locations.

Requirement I2: Efficient Information Procurement and Visualization

By employing a DAS, the commissioning team should be able to efficiently locate the components and systems that require testing, eliminating the need for extensive search efforts. The DAS should leverage information from the commissioning plan regarding technical dependencies and the execution sequence. It should then guide the commissioning team through an optimal testing sequence, thereby reducing the likelihood of errors and failures. Furthermore, the DAS should be equipped with 2D and 3D visualization capabilities, facilitating easy navigation for the commissioning team. This visualization enables the commissioning team to easily reach designated locations and validate the structure indicated in the CAD models.

4.2.4 Systematic Documentation of Commissioning Results

To achieve effective and productive documentation of commissioning activities, the DAS should be utilized. It should support the commissioning team in documenting the results obtained from functional tests efficiently. Additionally, the DAS should enable the commissioning team to capture and document issues and mistakes detected during the commissioning process according to a systematic process. Furthermore, the DAS should have the capability to submit the documentation to the centralized project organization system. This ensures that real-time updates on the commissioning progress are readily available, offering a comprehensive overview of the ongoing activities.

Requirement D1: Productive Documentation of Functional Test Results

The DAS should incorporate automation technologies to automatically capture measurement values. This automation process should yield significant time and resource savings, which are currently expended on extensive measurement capturing through paper-based protocols. Moreover, in situations where an equipment lacks interfaces with automation devices, the DAS should offer a systematic and easy workflow for submitting test results, i.e., via templates or photographs.

Requirement D2: Systematic Documentation of Issues

To comprehensively and efficiently document issues and errors identified during testing, the DAS should encompass multimodal documentation functionalities. Furthermore, the system should serve as the exclusive medium for documenting such issues. By centralizing documentation within a single system, the risk of information loss is mitigated, and the effort and time invested in searching for relevant information across various platforms are reduced. In alignment with this, the DAS should allow the commissioning team to document issues using a variety of modes, including textual descriptions, photographs, and videos. It is also important that the detected issues be submitted through the same DAS.

Moreover, the system should be equipped with intelligence to automatically prioritize and propose work packages for which issues have been submitted. Also, the system should have the capability to assign responsibility of issue resolving to the relevant individuals based on the type of the reported issue.

Requirement D3: Maintaining Realtime Overview of Commissioning Progress

The transition from traditional paper-based documentation to a DAS linked with a centralized project organization system should yield several advantages. The new documentation workflow should enable a real-time overview of the commissioning progress. Additionally, the documentation data should be systematically organized, facilitating information filtering and searching. This systematic arrangement of information should contribute to the establishment of a repository of *lessons learned* which can provide benefits to the shipyard by offering know-how from past experiences, not only for the optimization of future commissioning projects but also for the authoring of effective maintenance plans.

4.2.5 Integration and Acceptance

To adopt a novel system for maritime commissioning, the system should easily integrate into the existing infrastructure of the shipyard. Moreover, the system should be intuitive and user-friendly to minimize the time and effort needed for learning. As a result, the following requirements should be fulfilled:

Requirement A1: Easy Integration with Existing Infrastructure

For the shipyard to begin using the DAS for commissioning, it is essential that the DAS encompasses interfaces to integrate with the shipyard's existing systems, such as MES, ERP, and PLM systems. Furthermore, the DAS should have the capability to handle legacy data, automatically converting it into a format compatible with the DAS data models. This data conversion capability is crucial for a successful migration process.

Requirement A2: User Satisfaction

To facilitate the transition of potential users from conventional paper-based commissioning practices to the adoption of the DAS, it is important that the DAS attains high levels of user satisfaction. Consequently, the DAS should encompass attributes including an intuitive workflow, structured information, a clear graphical user interface, and minimal learning effort.

5 Groundwork for Digitalizing the Processes of Commissioning

The initial stage of the development process for a *Digital Assistance System* (DAS) in the context of maritime commissioning entails the construction of models that accurately depict the system's fundamental structure and its operational behavior. The formulation of these models is achieved through an analysis of commissioning plans, checklists, and other relevant materials acquired from previous ship commissioning projects. The primary aim of this analysis is to extract and systematically interpret data and variables related to the commissioning processes, while illustrating the flow of information throughout the different commissioning activities.

As an introduction, Section 5.1 discusses the analysis methods applied on the data collected from the shipyards to extract the relevant information. The interpretation of the analysis is represented in the form of structural models (Section 5.1) and behavioral models (Section 5.2). These models serve as the fundamental groundwork upon which the digital transformation of commissioning processes can be realized.

5.1 Pre-modeling of Commissioning Data

To systematically model the structure and behavior of the DAS for commissioning, real data from past commissioning projects was collected and analyzed. The data was collected within the scope of the research project smart.START funded by the German Federal Ministry for Economic Affairs and Climate Action [Wirt23]. Due to the extensive amounts of data involved in maritime commissioning projects, systematic preparation of data is required. Section 5.1 describes the data used for modeling and the methods applied for data collection, preparation, and modeling.

5.1.1 Data Types and Preparation Strategy

Prior to describing the strategy utilized in the preparation and modeling of maritime commissioning data, it is necessary to establish a clear understanding of the types of data employed in the process, and how the data was collected.

Data Types

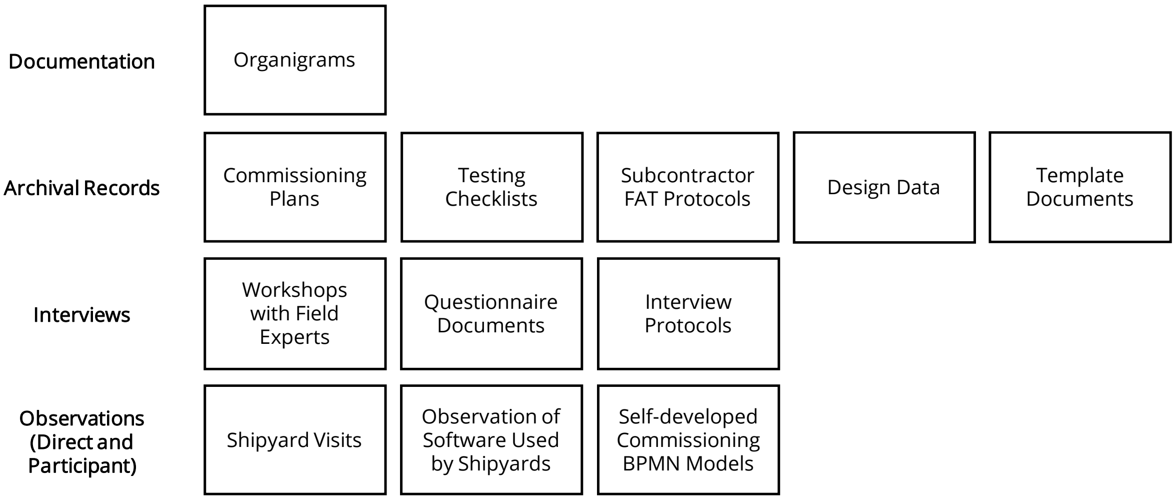
According to Yin, there are six types of data sources for gaining evidence in empirical research, these sources are: *documentation, archival records, interviews, direct observation, participant observation, and physical artifacts* [Yin14, P. 166]. In his book, Yin explains each source in detail and provides characteristic of each data source as demonstrated in Figure 18 [Yin14, P. 168–187].

Source	Description	Examples	Characteristics
Documentation	Written information which can be publicly available	• Reports • Announcements • Formal studies	• Repeatable access • Can be specific or broad
Archival Records	Written information which is only privately available	• Budget records • Personal records	• Subject to access difficulties due to privacy
Interviews	Guided conversations with field experts and personnel	• Open-ended Interviews • Focus interviews	• Provides explanations and personal opinions • Subject to biases • Subject to inaccuracies due to poor recall
Direct Observation	Passive observation of real-life situations and processes	• Meeting Observations • Fieldwork observations	• Contextual • Real-time covering of actions • Time-consuming • Costly
Participant Observation	Active observation of real-life situation and processes in which the observer assumes a role in the observed process	• Assuming the role of a staff member of an organization	• *[same as direct observation]* • Subject to biases
Physical Artifacts	Observation of a physical artifact such as a product, tool, or instrument	• Observing status of a machine being technically evaluated	• Useful for achieving insight into technical operations • Subject to availability difficulties

Figure 18: Data sources for gaining evidence in empirical research [Yin14, P. 168–187]

The categories depicted in Figure 18, as presented by Yin, are utilized in this dissertation to categorize the data provided within the context of the research project smart.START. Accordingly, Figure 19 depicts the data used for the modeling of maritime commissioning information and processes. Prior to discussing the data, it is important to acknowledge that certain data provided by the shipyards have been omitted from the appendix of this dissertation as a result of non-disclosure agreements.

As shown in Figure 19, archival records obtained from the shipyards encompass a range of data pertaining to past ship commissioning projects. These records include commissioning plans and schedules, signed checklists that provide history of the tests carried out by the commissioning team, FAT protocols submitted by subcontractors, which display the technical measurements obtained through factory testing of equipment. Additionally, design sheets containing illustrations and 3D CAD models for various parts of the ship are included, along with template documents that signify the initial stages of authoring testing procedures and commissioning plans.



Documentation	Organigrams				
Archival Records	Commissioning Plans	Testing Checklists	Subcontractor FAT Protocols	Design Data	Template Documents
Interviews	Workshops with Field Experts	Questionnaire Documents	Interview Protocols		
Observations (Direct and Participant)	Shipyard Visits	Observation of Software Used by Shipyards	Self-developed Commissioning BPMN Models		

Figure 19: Input data for modeling maritime commissioning information and processes

Moreover, a series of interviews and workshops have been conducted with industry professionals in the field of maritime commissioning. The purpose of these interactions was to gather insights and acquire knowledge pertaining to the flow of information and the specific requirements necessary for the effective development of a DAS for maritime commissioning. During the conducted interviews and workshops, data was gathered using questionnaires and protocols (see Appendix B, C, D).

Furthermore, visits to ongoing shipbuilding projects allowed for direct observations, while meetings with members of the commissioning authority of the shipyard were organized to examine the process of commissioning planning using current tools and software within the shipyard. Consequently, preliminary BPMN models have been generated and provided to industry specialists for assessment and enhancement to ensure accurate understanding of information flow across the different commissioning activities.

Data Preparation Strategy

Given the variety of data types provided by shipyards, it is necessary to implement a data preparation strategy in order to achieve a uniform structure for the data. This uniform structure can later simplify the modeling process.

Generally speaking, the process of data preparation involves systematic breakdown of unstructured or raw data into smaller components, facilitating the interpretation of data and ultimately leading to the generation of structured knowledge [Sand95, P. 372]. There are various strategies for data preparation, and the choice of a particular strategy depends on the research problem being addressed and the attributes of the data being examined.

Figure 19 illustrates that certain data sources have qualitative attributes, such as interviews and observations. Even archival records often include qualitative data in the form of unstructured textual descriptions such as these written by the commissioning team to document issues and mistakes encountered during the implementation of commissioning tests. In these instances, employing strategies such as *coding* can be beneficial for the preparation and analysis of the data [Byrn01, P. 904]. According to LeCompte and Schensul coding is a process that "*involves organizing data into categories related to the framework and questions guiding the research so that they can be used to support analysis and interpretation*" [LeCo99, P. 45]. Baralt provides a concise overview of the qualitative coding process, outlining the steps involved as follows [Bara11, P. 223]:

1. **Theme extraction**: involves the categorization of data into distinct thematic groups called *themes*.
2. **Theme comparison**: a step in which the extracted themes are compared across different types of data sources (e.g., interviews and observations), and among different participants.
3. **Recursive interaction with data**: a step in which the researcher reflects on coding decisions, and reviews the extracted themes.

The coding process was used to analyze the commissioning data obtained from shipyards and extract themes. Moreover, the themes were further subdivided into sub-themes in order to achieve a comprehensive representation of the data, which in turn facilitates the modeling process. The extracted themes describe the structure of commissioning data and the interactions between these themes illustrate the flow of information during commissioning activities. The following section describes the objectives of modeling and outlines the methods utilized to model the data.

5.1.2 Objectives and Methods of Data Modeling

To model the data resulting from the coding process, it is necessary to employ different methods based on the modeling objectives and data types. The modeling objectives are derived from the problem statement (see Section 4.1) and the solution requirements (see Section 4.2) and can be summarized as follows:

- **Organization of commissioning information**: achieving a comprehensive overview of the information and interactions involved in the conventional process of maritime commissioning.
- **Design of the DAS**: architectural design of the building blocks of the system including its components and modules.

- **Design of database**: organization and structuring of data for efficient storage, retrieval, and management.
- **Information flow design**: identification of communication patterns, functionalities, and systematic planning of interactions within the DAS.

Methods of Data Modeling

To facilitate the decision-making process for selecting appropriate modeling methods, the objectives of modeling can be broadly classified into two primary categories: structural modeling and behavioral modeling, as depicted in Figure 20.

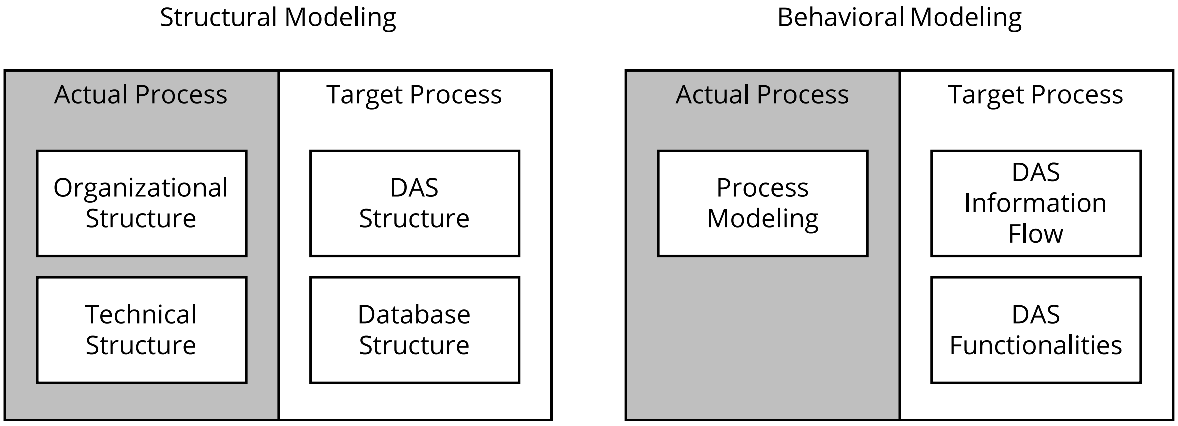


Figure 20: Data modeling categories for actual and target processes

As indicated in Figure 20, each modeling category comprises two sub-categories, namely the *actual process* and the *target process*. The sub-category of the actual process encompasses the structural and behavioral models that have been established for the conventional commissioning process. On the other hand, the sub-category of the target process refers to the models that are necessary for the development of the DAS for marine commissioning.

The structural and behavioral models pertaining to the actual process have been covered in Section 3.1, rendering them redundant and unnecessary to include in this chapter.

For modeling the target process, signified by the DAS, the Unified Modeling Language (UML) has been selected for its capability of being a comprehensive language that includes several tools for designing a software system. Moreover, the UML covers both static and dynamic behavior of the system, and can be used for code generation and documentation of the developed system as stated by Rumbaugh et al. [Rumb99, P. 3f.].

5.1.3 Summary of the Pre-modeling Process

Before presenting the developed models, Figure 21 summarizes the process and the steps taken to acquire and prepare the data.

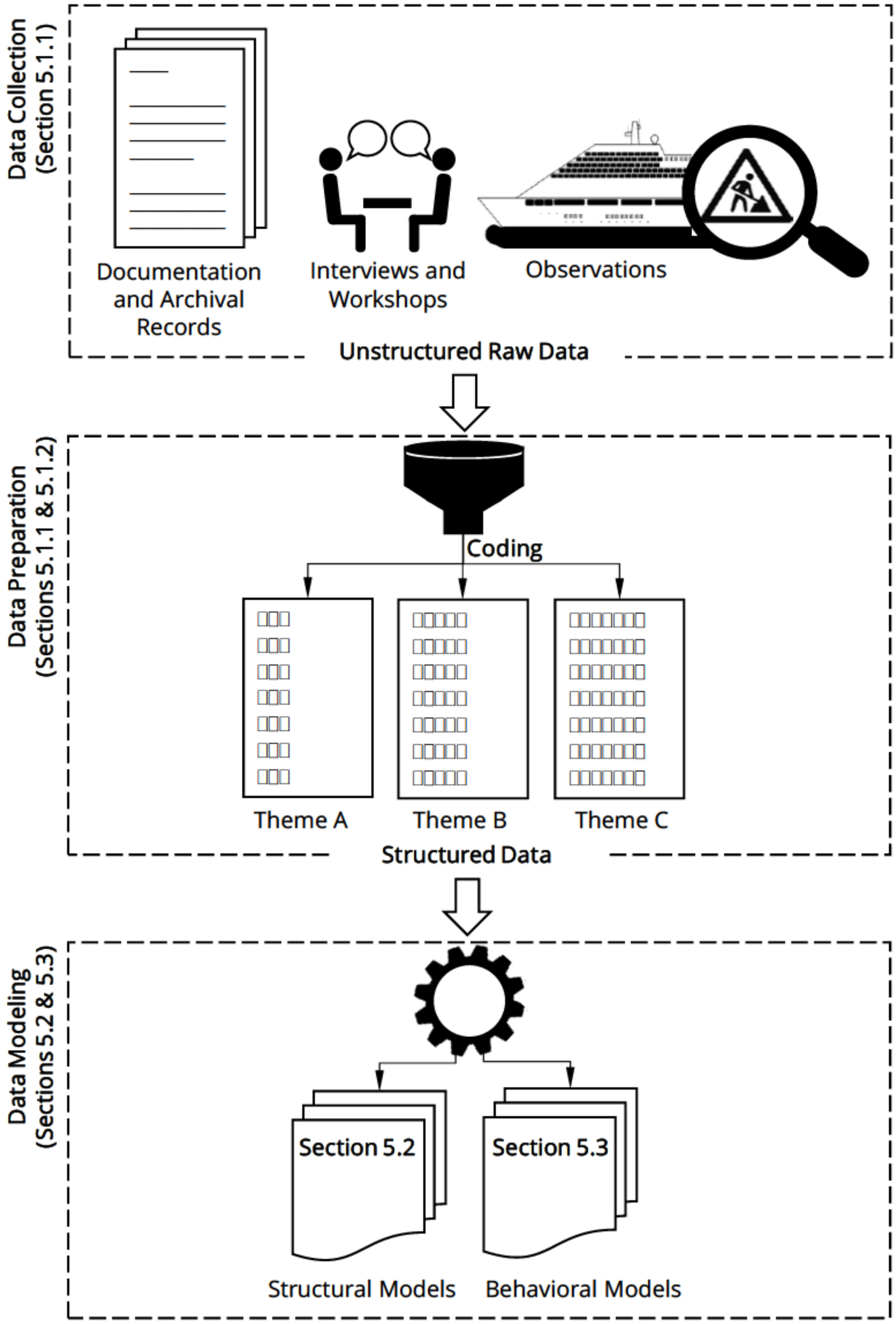


Figure 21: Summary of the pre-modeling process

Data Collection

During this stage, data is gathered from various sources including documentation, archival records of past ship commissioning projects, interviews with field experts, and direct observations of ongoing shipbuilding projects. The outcome is a collection of unorganized data that needs to be prepared for modeling. Refer to Section 5.1.1.

Data Preparation

The data is prepared using the coding method, which involves extracting themes from raw data to enhance understanding and facilitate data modeling. The recursive nature of this stage involves comparing themes against various sources and validating the result via close collaboration with field experts. Furthermore, modeling methods are defined in this stage. Refer to Sections 5.1.1 and 5.1.2.

Data Modeling

The extracted themes and the solution requirements (Section 4.2) are utilized to develop final models that describe the structure and behavior of the proposed DAS for maritime commissioning. Refer to Sections 5.2 and 5.3.

5.2 Structural Modeling of the Digital Assistance System

To develop a DAS for maritime commissioning processes, it is necessary to create models of the system's structure and the data that will be managed by the DAS. Section 5.2.1 presents the static structure of the system using the UML deployment diagram. This diagram visually represents the components and modules that are integral to the system. Section 5.2.2 presents the primary data models utilized in the DAS, represented as UML class diagrams.

5.2.1 System Structure

The UML deployment diagram is chosen to depict the topology or static structure of the DAS. The deployment diagram includes various notation objects. A *node* is represented by a three-dimensional box and signifies a physical device or a processing unit. While a two-dimensional rectangle represents a software artifact that can be deployed on the node. Nodes and artifacts can be combined into a single entity referred to as a *component*, which is visually represented as a rectangle with a tab in the upper left corner. Figure 22 depicts the deployment diagram of the DAS.

The figure illustrates the three primary components, namely the commissioning clients, commissioning server, and production system. The DAS for maritime commissioning comprises the first two components outlined with dotted lines in Figure 22. The interconnection between each component is established by a communication interface, which is visually represented by a solid line in the figure. The interface plays a crucial role in facilitating the exchange of data across the different components.

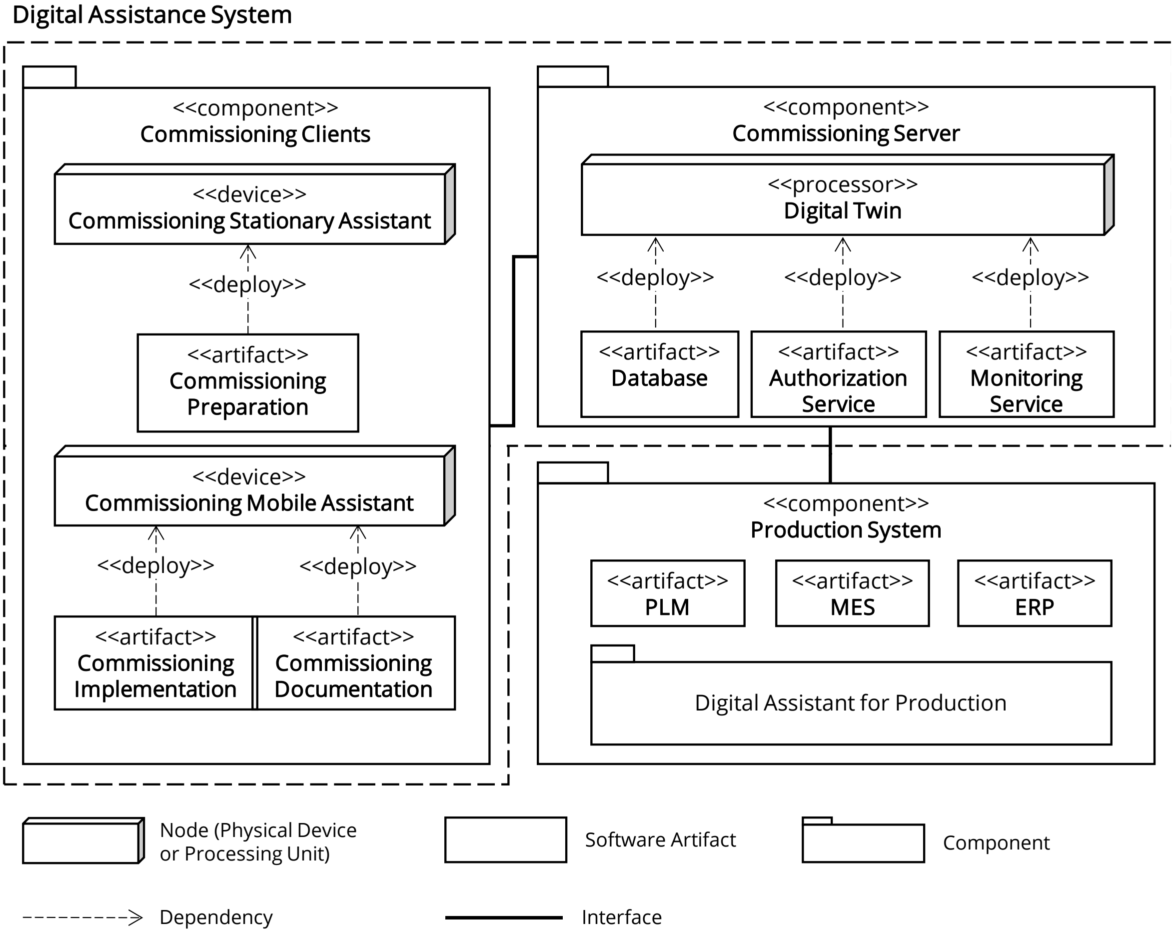


Figure 22: Deployment diagram of the DAS

The commissioning clients’ component represents the end-users of the DAS. The clients utilize the system for commissioning preparation, implementation, and documentation. The commissioning preparation node is represented by a stationary device. This is because commissioning authority personnel typically carry out their work in regular office settings and do not need to be physically present at the site for commissioning preparation. On the contrary, the commissioning team would require a mobile assistant that replaces paper-based checklists and protocols while implementing tests on site, hence the *commissioning mobile assistant* node. The mobile assistant includes both implementation and documentation artifacts.

The commissioning server component includes a node called *Digital Twin* that is responsible for intelligent processing operations, such as database management, authorization, and monitoring services. Chapter 6 provides a detailed explanation of the primary tasks performed by the Digital Twin.

The production system component serves as an abstraction for existing shipyard infrastructure systems, including PLM, MES, and ERP systems. Additionally, it incorporates a Digital Assistant for production to synchronize assembly work, as specified in requirement

O2 (refer to Section 4.2.1).

5.2.2 Models of Data Managed by the System

The DAS is responsible for managing and processing data obtained from the production system and produced throughout the different processes of commissioning. This processed data is then exchanged among the users of the DAS according to specific rules as later discussed in Section 5.3. In the current section, the data is classified into two main categories: organizational and technical data.

Organizational Data Models

Maritime commissioning is a complex process that involves various types of metadata to ensure a structured workflow. The models of *organizational data* in this section exclude any technical attributes regarding the ship's equipment or systems and include only the data for organizing the commissioning workflow.

Starting from the commissioning plan, a top-down modeling approach is utilized to model the organizational data, however the temporal aspects are excluded from the data as mentioned in Section 3.1.1. Figure 23 shows a simplified UML class diagram for organizational data in commissioning.

It was identified from the data preparation stage that organizational data can be hierarchically organized. To model the hierarchy of organizational data in commissioning, the aggregation notation in the UML class diagram is used, indicated by the black diamond symbol. Aggregation notation in UML class diagrams denotes a hierarchical relationship between data classes, where one class acts as the parent and another as the child. This implies that objects of the child class are unable to exist without the parent.

Figure 23 illustrates that the commissioning plan occupies the highest position in the aggregation hierarchy of organizational data. The commissioning plan includes multiple testing procedures, referred to from now on as *commissioning tests*. Each commissioning test consists of several testing steps, as shown in Figure 23.

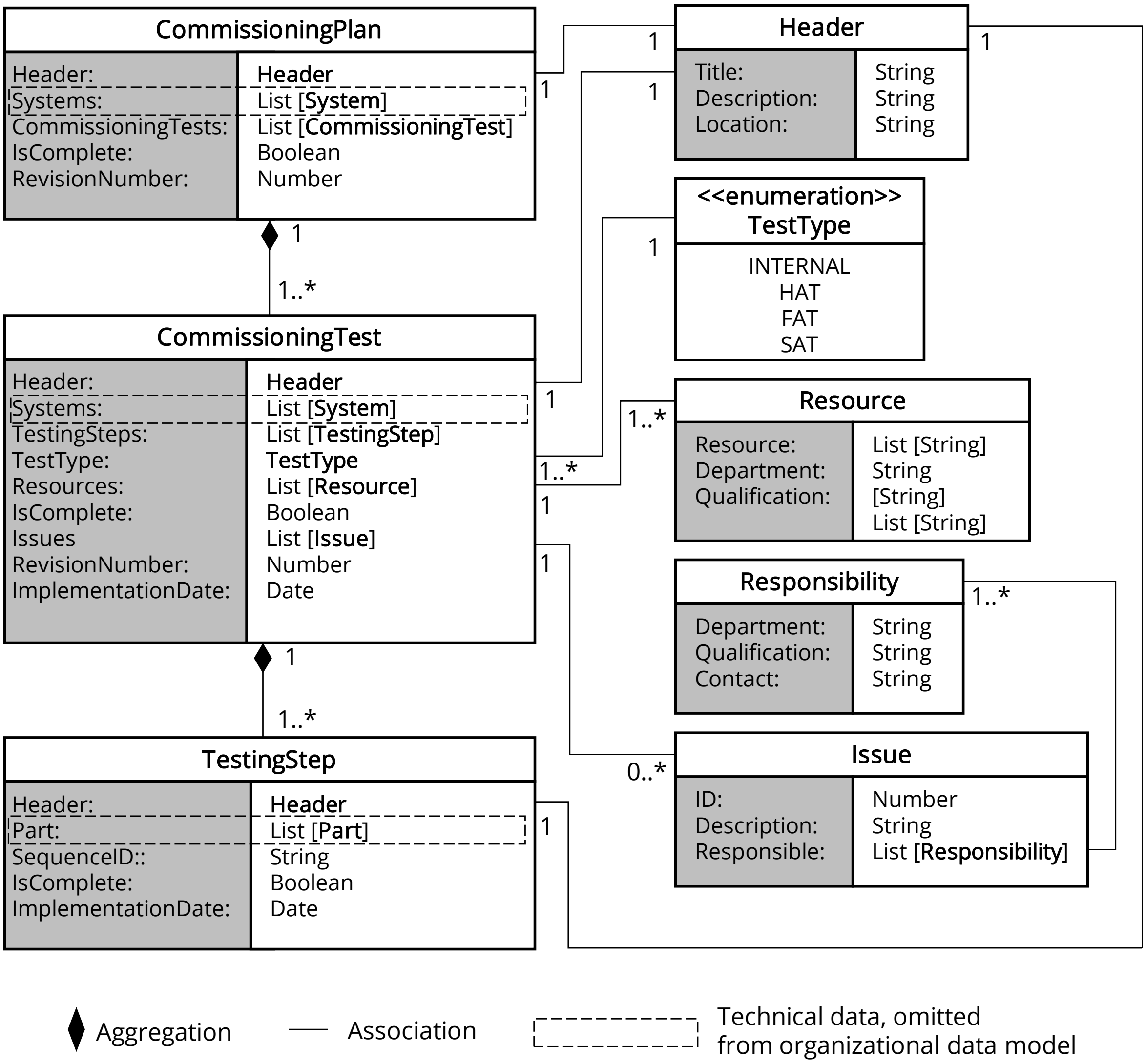


Figure 23: Simplified class diagram for organizational data in maritime commissioning

The right-hand side of the class diagram presents other data models such as *header, test type, resource, and responsibility*. These models provide supplemental information for the commissioning plan, test, and step. For example, the title, description, and location of the commissioning test or testing step are all stored in the *header* class. The type of the commissioning test is identified by the *test type* class. Sections 2.2.3 and 3.1.1 provide more detail on different commissioning test types. The commissioning team's qualifications, the department in charge of carrying out the commissioning tests, and any tools that might be necessary for testing are all stored in the *resource* class. Furthermore, the *issues* class depicts the data structure of the issues that the commissioning team might encounter during commissioning implementation, and the *responsibility* class stores information about the staff members who are in charge of handling such issues.

Technical Data Models

In this dissertation, the term *technical data* denotes the technical characteristics of assemblies, components, and ship parts that undergo testing and verification during the commissioning process. Technical data also encompasses the measurements obtained during the commissioning implementation process. Modeling this data facilitates the development of efficient and reusable commissioning plans and testing procedures. Figure 24 shows a simplified UML class diagram of the technical data in maritime commissioning.

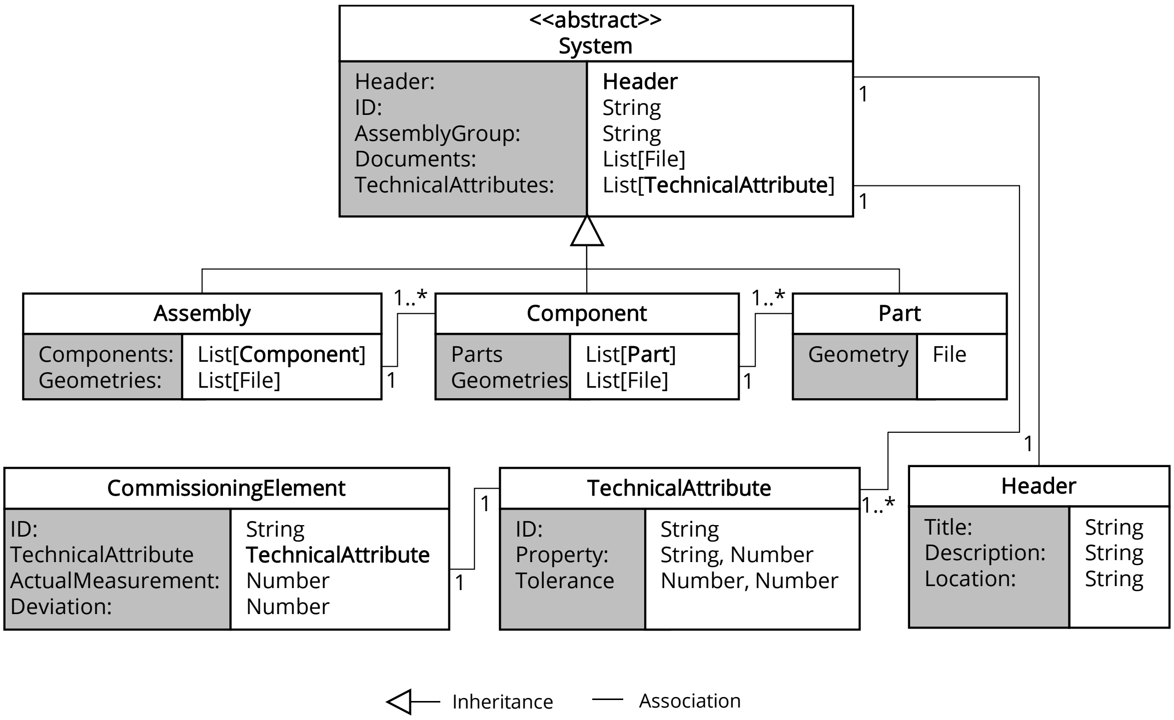


Figure 24: Simplified class diagram for technical data in maritime commissioning

In the technical data model, the term *system* refers to any entity that undergoes testing during the commissioning process. The class diagram represents the system entity as an abstract class that acts as the base class for assemblies, components, and parts. Each subclass inherits the system's properties, including a header (containing basic details such as title, description, and location), an ID, an assembly group (for hierarchical identification), documents (such as specification sheets), and technical attributes.

The class of *technical attribute* stores system attributes that are relevant for commissioning work. This class is also useful for enabling the functionality on the Digital Twin that facilitates direct retrieval of commissioning-related technical data from the digital BOM. The technical attributes are obtained from the PLM and ERP systems, as described in Section 5.3.1.

Furthermore, the *commissioning element* class stores the actual measurements obtained during the implementation of commissioning tests. Moreover, this class incorporates values from the technical attribute class and includes an attribute that represents measurement deviations, which is beneficial for detecting requirement deviations or issues.

5.3 Behavioral Modeling of the Digital Assistance System

This section presents behavioral models for comprehending the information flow in the novel process using the DAS. Modeling the information flow is primarily useful before developing the software solution and therefore, the standard UML sequence diagram was used.

The communication and information exchange within the conventional process takes place via traditional channels, e.g., emails, telephone, and weekly meetings. The DAS should enhance the communication and information exchange during the processes of commissioning preparation, implementation, and documentation. The models in this section describe the workflow and communication using the DAS.

5.3.1 Model of Commissioning Preparation

Figure 25 depicts a simplified UML sequence diagram for the commissioning preparation workflow using the DAS. The sequence diagram illustrates the involvement of the commissioning authority as the primary actor in the preparation process using the DAS. The process incorporates a stationary assistance system and a Digital Twin, both of which are utilized as follows:

- **Stationary assistance system:** the system is primarily used by the commissioning authority to initiate the commissioning project and to create the commissioning plan. Figure 25 shows that the stationary assistant does not directly engage in complex computational tasks, but rather functions as an intermediary between the commissioning authority and the Digital Twin. The commissioning authority uses the stationary assistant to submit requests for retrieving relevant information from the shipyard production systems, generating commissioning tests, and starting computational activity and data storage services through the Digital Twin.
- **Digital Twin (for commissioning preparation):** functions as a centralized system responsible for executing various computational operations, storing data, and facilitating information procurement and processing activities. In Figure 25, it is shown that the Digital Twin responds to the requests of the stationary assistance system for retrieving data from the ship production systems and processing this data to generate commissioning tests and viable testing sequences.

To comprehend the information flow depicted by the sequence diagram illustrated in Figure 25, the reader should start the examination of the diagram from the upper left corner, where the commissioning authority is portrayed as a stick figure. The commissioning authority begins the preparation process by generating an empty commissioning project using the *stationary assistant*.

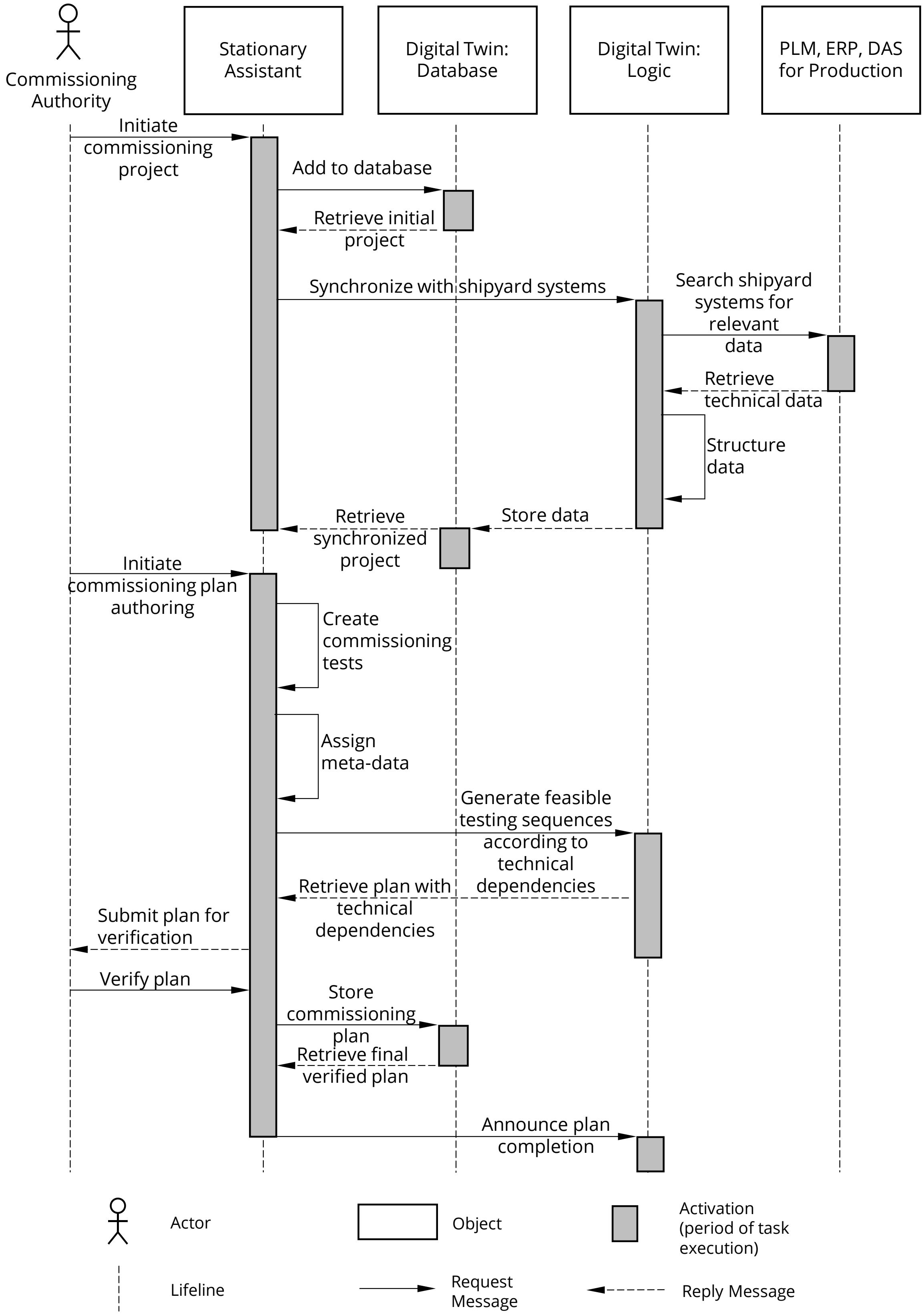


Figure 25: Simplified UML sequence diagram for commissioning preparation using the DAS

The stationary assistant initiates communication with the Digital Twin to formally declare the initiation of a new commissioning project. This enables the Digital Twin to generate a database entry and establish contact with the shipyard systems, namely PLR, ERP, and DAS, in order to retrieve pertinent data required for the commissioning process. The dataset encompasses the Bill of Materials (BOM), 3D models, 2D plans, and other technical attributes. After the retrieval of the necessary data from the shipyard systems, the data is further processed to align it with the data models utilized in the commissioning project. As an illustration, the BOM is organized hierarchically into assemblies, components, and parts and assigned relevant technical attributes according to the data model depicted in Figure 24. After processing the data, the Digital Twin proceeds to save it and then sends a response message to the stationary assistant system, notifying it that the user is now able to begin the creation of the commissioning plan.

Consequently, the user initiates the process of creating the specifications for commissioning tests across all systems within the ship, while also allocating the necessary metadata and organizational resources. After the creation of the commissioning tests, the user proceeds to send a request to the logic entity of the Digital Twin in order to organize the tests into a viable sequence for execution. In response, the Digital Twin analyzes the request and creates an automatically generates a sequence based on the technical dependencies information obtained from the shipyard systems. Subsequently, the Digital Twin presents the execution sequence to the user for the purpose of verification.

After the user confirms the viability of the execution sequence, the commissioning plan is then stored in the central database managed by the Digital Twin. The commissioning plan is then officially declared as ready for implementation by the commissioning team.

5.3.2 Model of Commissioning Implementation and Documentation

Figure 26 shows a simplified UML sequence diagram for commissioning implementation and documentation using the DAS. For simplicity, the model shows three actors: the commissioning team, construction manager, and external stakeholders. The systems presented in the model are as follows:

- **Mobile assistance system:** the mobile assistant is primarily utilized by the commissioning team for task retrieval, execution, and result documentation. In Figure 26, the commissioning team utilizes the mobile assistant to request the Digital Twin for the retrieval of appropriate tasks. The commissioning team carries out the commissioning implementation by conducting installation and functional tests, and recording the outcomes on the mobile assistant. Documentation can be either manual or automated using the Digital Twin. The commissioning team reports issues on the mobile assistant and generates an issue alert to be handled by the Digital Twin. Finally, all stakeholders

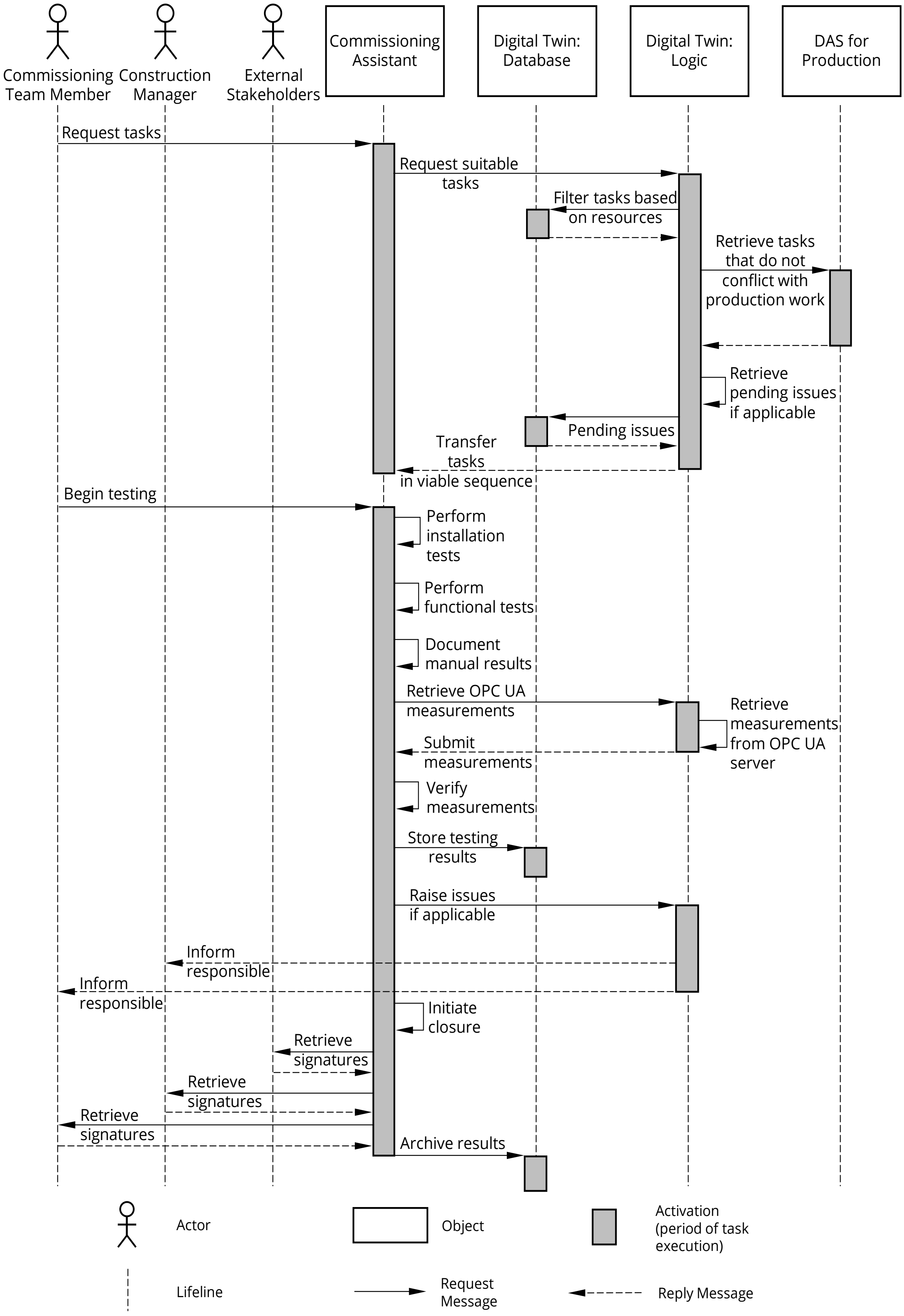


Figure 26: Simplified UML sequence diagram for commissioning implementation and documentation using the DAS

can digitally sign the completed tests using the mobile assistant to mark successful closure.

> **Digital Twin (for commissioning implementation and documentation):** acts as a computational unit for processing requests made by the mobile assistant. Figure 26 illustrates the interception of requests made by the mobile assistant for retrieving appropriate tasks by the Digital Twin for the commissioning team. The Digital Twin can access shipyard systems to identify ongoing assembly work and retrieve non-colliding tasks. Moreover, the Digital Twin retrieves the tasks in a viable execution sequence based on the technical dependencies between commissioning tests. Furthermore, the Digital Twin stores and automatically forwards issues to the responsible personnel.

To comprehend the information flow depicted by the sequence diagram illustrated in Figure 26, the reader should start the examination of the diagram from the upper left corner, where the *commissioning team member* is portrayed as a stick figure. The commissioning team begins the implementation process by requesting commissioning tasks using the *mobile assistant*.

The mobile assistant establishes connection with the Digital Twin in order to request tasks that align with the expertise of the commissioning team member, and the resources that are available at the time of the request. Moreover, the Digital Twin guarantees that the tasks obtained do not present any conflicts with the assembly work. This may be achieved through the utilization of automated communication with the DAS for production. The Digital Twin also retrieves tasks that encompass unsolved issues. The Digital Twin thereafter generates structured work packages and transfers them to the mobile assistant, enabling the user to begin the testing process.

Consequently, the user commences the testing process by conducting installation and functional tests and records the outcomes immediately using the mobile assistant. When it comes to the automated documenting of measurement values through IoT, the mobile assistant initiates a request to the Digital Twin. This request includes pertinent information on the equipment that is presently being tested by the user. Subsequently, the Digital Twin establishes a reliable connection between the mobile assistant and the equipment intended for testing via the IoT server. Consequently, the user is able to observe the measurement values in real-time and electronically document the results. When encountering flaws or problems, the user proceeds to submit issues to the Digital Twin. The Digital Twin stores these issues with the purpose of subsequently submitting them to the responsible personnel.

Upon the completion of the implementation and technical documentation processes, a closure procedure is launched via the mobile assistant, enabling all stakeholders to digitally sign the documentation, hence marking the work package as complete.

6 A Digital Assistance System for Maritime Commissioning

The *Digital Assistance System* (DAS) for maritime commissioning is a software system developed within the *smart.START* research project [Wirt23]. The system has been set up in three major shipyards in Germany and has undergone testing by industry experts for a duration of over one and a half years. Moreover, the concept of the DAS has been introduced and discussed in the following publications: [Elza22b], [Elza22a], and [Jans23a]. This chapter starts with an introduction (Section 6.1) so that the reader can have a basic understanding of the DAS before getting into the technical details of the system. Sections 6.2, 6.3, and 6.4 examine each primary component of the DAS and provide comprehensive explanations and technical details of the system.

6.1 Introduction

This introduction offers a concise summary of the approach utilized in the search for solutions and the design of the DAS's technical features. Additionally, the introduction presents a brief overview of the DAS and its primary components.

6.1.1 Solution Seeking Approach

Design Science Research (DSR) (see Section 1.3) is the research methodology used in this dissertation to develop an *artifact*, i.e., a DAS, which addresses the shortcomings of the conventional maritime commissioning workflow. According to the DSR methodology, the design cycle for the artifact should include end-users to gather requirements and verify the solution's relevance and acceptance. Therefore, interviews and workshops were conducted, including experts from the shipbuilding industry and researchers with specialized knowledge in information technology. Involving end-users in the design of a software system is often known in the field of *Human Computer Interaction* (HCI) as *User-centered Design* (UCD). According to Abras et al., UCD is a term used to "*describe design processes in which end-users influence how a design takes shape*" [Abra04, P. 445]. Although, the design process included interviews and workshops with end-users and researchers, it was crucial to ensure that the process adhered to scientific principles. Hence, systematic methods for designing the DAS functionalities were necessary.

A DAS that offers a visual and interactive representation of information can be regarded as an *information seeking* system from the standpoint of HCI. As a result, the widely recognized *Visual Information Seeking Mantra* in the field of HCI by Shneiderman [Shne96], is chosen as a primary method that directs the design of information visualization functionalities of the DAS. In summary, Shneiderman proposes three key elements to enhancing information seeking in a software system as follows:

1. **Overview**: users should be presented with a comprehensive overview of the complete dataset prior to delving into specific details. This overview enables users to gain a broad understanding of the overall structures and patterns inherent in the data.
2. **Zoom and filter:** users can actively engage with the data by zooming in on points of interest and applying filtering. This allows the users to uncover details and patterns within the selected data points.
3. **Details-on-demand:** this element highlights the importance of offering users detailed information only when the users specifically request the information through queries or interactions. This approach promotes user-centered and interactive data visualization.

When discussing information visualization features of the DAS, this chapter consistently refers to the three elements proposed by Shneiderman in order to clarify the solution-seeking process and the underlying rationale for developing each feature. That being said, when it comes to designing complex interactions and communication patterns for the DAS, the *Visual Information Seeking Mantra* is not sufficient as it tends to *oversimplify* the design problem. Different approaches from the domains of HCI and software engineering are taken into account in such situations and are elaborated upon as necessary.

6.1.2 Overview of the Digital Assistance System

The DAS consists of three primary applications: an *authoring assistant*, a *commissioning assistant*, and a *Digital Twin* as previously mentioned in Section 5.2.1. A short summary of each application is presented by the following subsections. The section concludes with Figure 27, which shows an overview of the DAS and references the corresponding sections in this chapter that provide detailed explanations of each element of the DAS.

Stationary/Authoring Assistant

The stationary assistant is a software application designed to run on a desktop computer, providing support to the commissioning authority in the process of authoring the commissioning plan (*Requirements P1 – P3*). The system was referred to as the *stationary assistant* to signify its applicability within the commissioning authority's stationary work environment. From now on, and for clarity, the system will be referred to as the *authoring assistant* since its primary function is to *assist* the user with creating or *authoring* the final commissioning plan, which includes all the commissioning tests, checklists, and protocol templates utilized by the commissioning team during commissioning implementation and documentation. Sections 6.2 and 6.3 provide details of the *authoring assistant* utilized for commissioning preparation.

Mobile/Commissioning Assistant

This tool is designed to facilitate the retrieval of tasks from the commissioning plan, as well as the execution of these tasks and the documentation of the corresponding outcomes. The team responsible for commissioning operates at the project site, thereby necessitating the use of a mobile device (such as a smartphone or tablet) for the assistance system (*Requirements I1, I2, D1, D2*). For clarity, the mobile assistant will be referred to from now on as the *commissioning assistant.* Section 6.4 discusses the *commissioning assistant* in detail.

Digital Twin

The Digital Twin functions as a centralized hub, facilitating the connection between various ship systems and the DAS. Additionally, the system offers the functionality of real-time monitoring, data storage, and computing capabilities (*Requirements O1, O2, D3, A1*). The developed *Digital Twin* is frequently discussed in various sections of Chapter 6 since it is closely linked with all elements of the DAS.

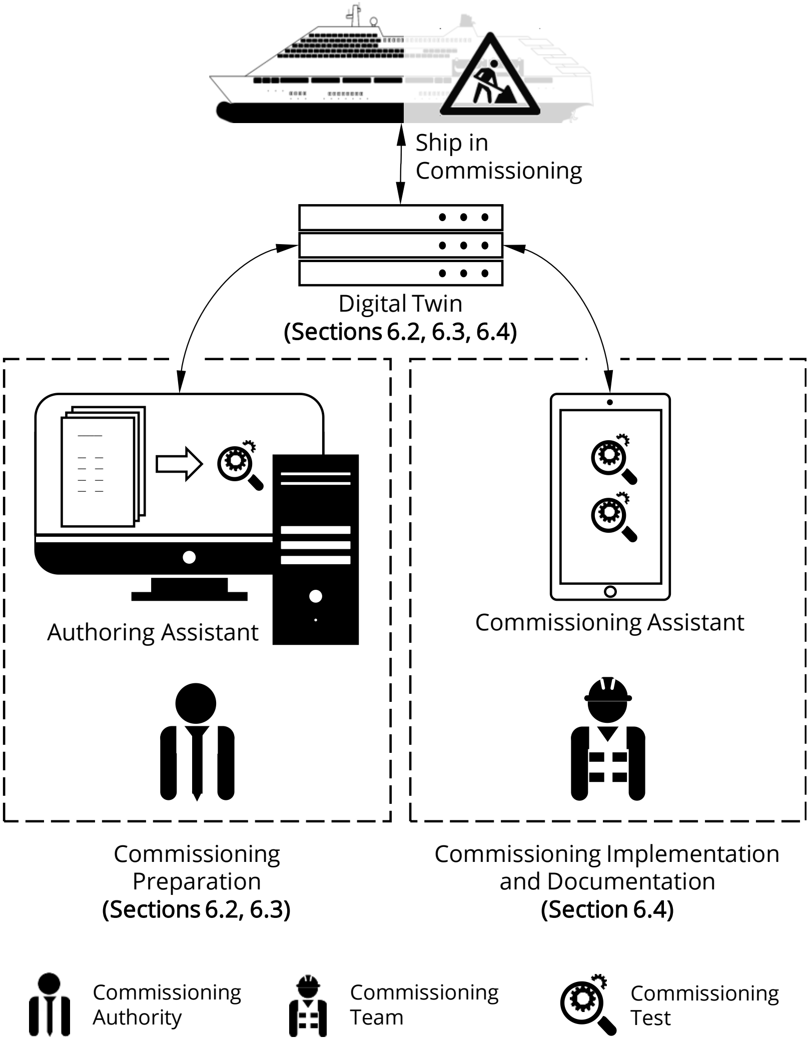


Figure 27: Overview of the Digital Assistance System

6.2 Authoring Assistant for Commissioning Preparation

According to requirements *P1* and *P3*, it is necessary for the DAS to improve the preparation process. In other words, reducing the effort and time for the initial preparation of technical data. The objective can be accomplished by employing an automated workflow to minimize the time spent on authoring commissioning tests from scratch. The section begins with an overview of the *authoring assistant* for commissioning preparation and subsequently examines the primary functionalities and tools developed within the system to meet the requirements for productive preparation of the commissioning plan.

6.2.1 Technology and Features of the Authoring Assistant

This section presents the method employed to determine the technology used in developing the authoring assistant. Subsequently, the section concludes with a brief summary of the general features incorporated in the authoring assistant.

Choice of Technology for Developing the Authoring Assistant

Since that commissioning preparation requires collaboration between personnel from various departments in the shipyard as well as subcontractors, the authoring assistant must be accessible via a network and should be compatible with a variety of operating systems. In addition, the system must be able to easily integrate with the shipyard's infrastructure and import and process various forms of data, including text, 2D, and 3D files.

Different technologies exist for developing such a software system; therefore, it is common practice to use a multiple-criteria decision analysis, such as the method developed by Dittmer [Ditt95, P. 43], to determine the development technology. The decision-making process involved researchers and experts qualified to provide an objective assessment of the advantages and disadvantages of the technologies for developing the authoring assistant. On the basis of the previously mentioned requirements of the authoring assistant, the choices were between developing a *native software application*, a *web application*, or a *mobile application*. The analysis results are depicted in Figure 28.

Figure 28 indicates that a web application is the best option due to its independence of the hosting operating system and native network connectivity. It is important to note that, as a result of recent advancements in web development, web applications are now able to process data more efficiently, enabling them to load and display complex files such as 3D CAD models. In contrast, web application technology receives low marks for its capability of *integration with shipyard systems*. This is due to the fact that a web application would require an additional backend layer that can communicate to the shipyard system. However, this limitation is resolved by using a Digital Twin.

Authoring Assistant			
Functionality	**Technology**		
	Native Software Application	Web Application	Mobile Application
Independence of operating system	0	+3	0
Data processing capabilities	+3	+2	+1
Integration with shipyard systems	+2	+1	+1
Network availability	+1	+3	+3
Average result	**1.5**	**2.25**	**1.25**

Figure 28: Development technology of authoring assistant

General Features of the Authoring Assistant

The authoring assistant serves as the primary tool for the commissioning authority which includes the required functionalities for the creation, editing, and submission of the commissioning plan. To create the commissioning plan, the user requires input data relevant to commissioning the ship in production. The input data comprises the Bill of Materials (BOM), lists of technical attributes of the parts listed in the BOM, 2D illustrations, and 3D models.

Once the input data is available for the authoring assistant, the user can initiate the process of creating the commissioning plan. As seen in the UML class diagram illustrated in Figure 23, the commissioning plan is regarded as a *container* for a set of testing procedures known as *commissioning tests*. Hence, the objective of the authoring assistant can be characterized as the creation of commissioning tests for the systems installed in the ship. The commissioning plan is then referred to as the *commissioning project* within the DAS. Using the DAS, a single project is created and maintained through to the entire process of commissioning. As stated in *Requirement P3*, the authoring assistant adopts a *template-based* approach for automatic generation of commissioning tests.

Figure 29 illustrates the general features of the authoring assistant and references the corresponding sections in this chapter that provide detailed explanations of each feature of the authoring assistant.

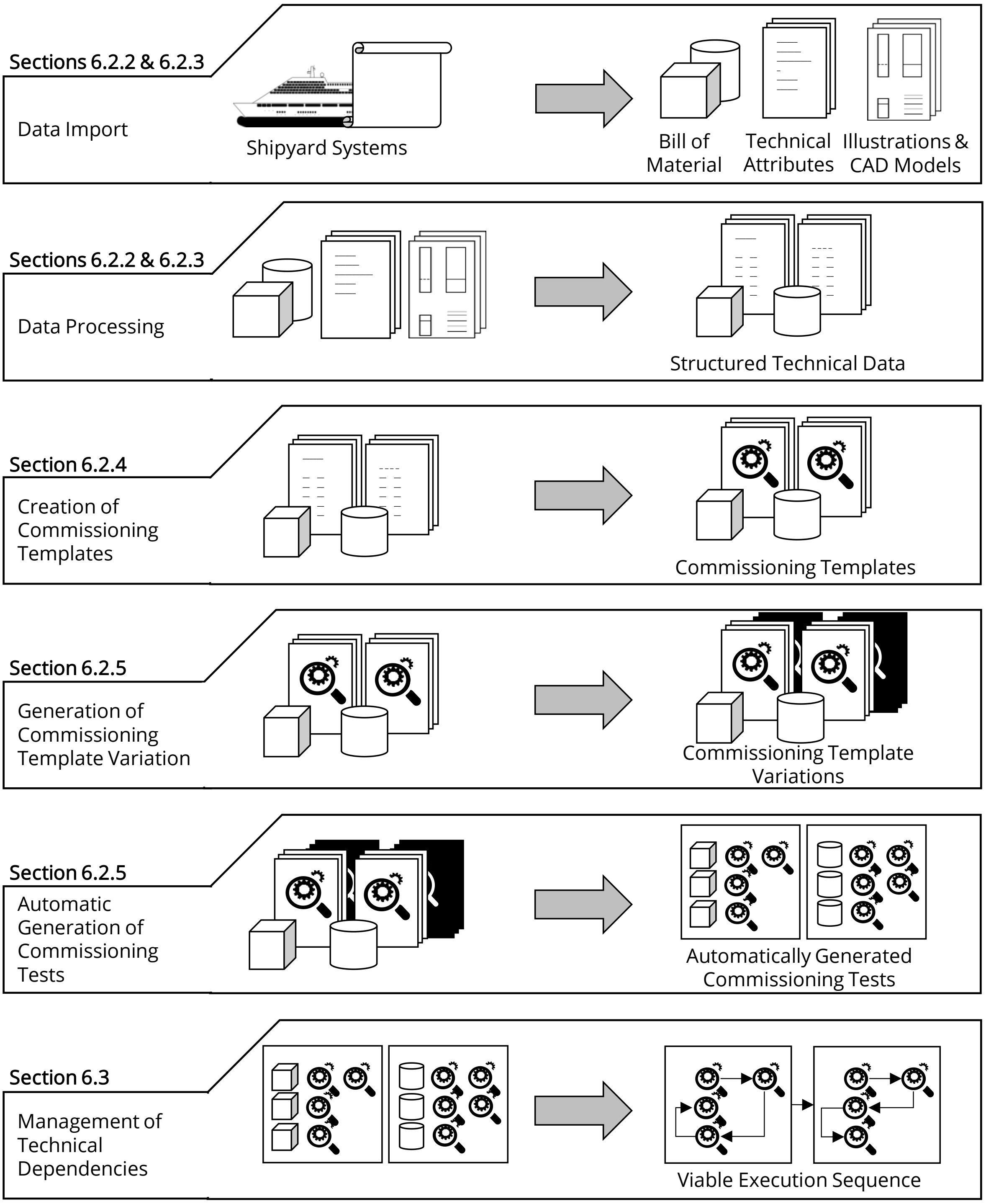


Figure 29: General features of the authoring assistant

6.2.2 Preparation of BOM and Technical Attributes

To initiate the creation of commissioning tests for all ship systems and equipment, the authoring assistant requires data from the shipyard production systems concerning the ship in production. As depicted in Figure 25 of the UML sequence diagram, the user of the authoring assistant begins by creating an empty project for commissioning and imports the data from the shipyard systems via the Digital Twin. The data initially imported by the authoring assistant includes the BOM and all the technical attributes and 3D CAD models associated with the BOM.

BOM and Corresponding Technical Attributes and 3D CAD models

The BOM encompasses a comprehensive hierarchical list of all assemblies, components, and parts that are necessary for the construction of the ship. The BOM, which is sent to the authoring assistant, is initially presented in a tabular format. In this format, each row represents an individual item, such as a part, component, or assembly, while each column represents a specific attribute associated with the related item. Moreover, technical attributes of the items in the BOM are sent to the authoring assistant alongside the CAD models of the items. Figure 30 shows an example of a BOM list which contains technical attributes. Additionally, a schematic representation of the authoring assistant user interface for BOM visualization is depicted in the figure.

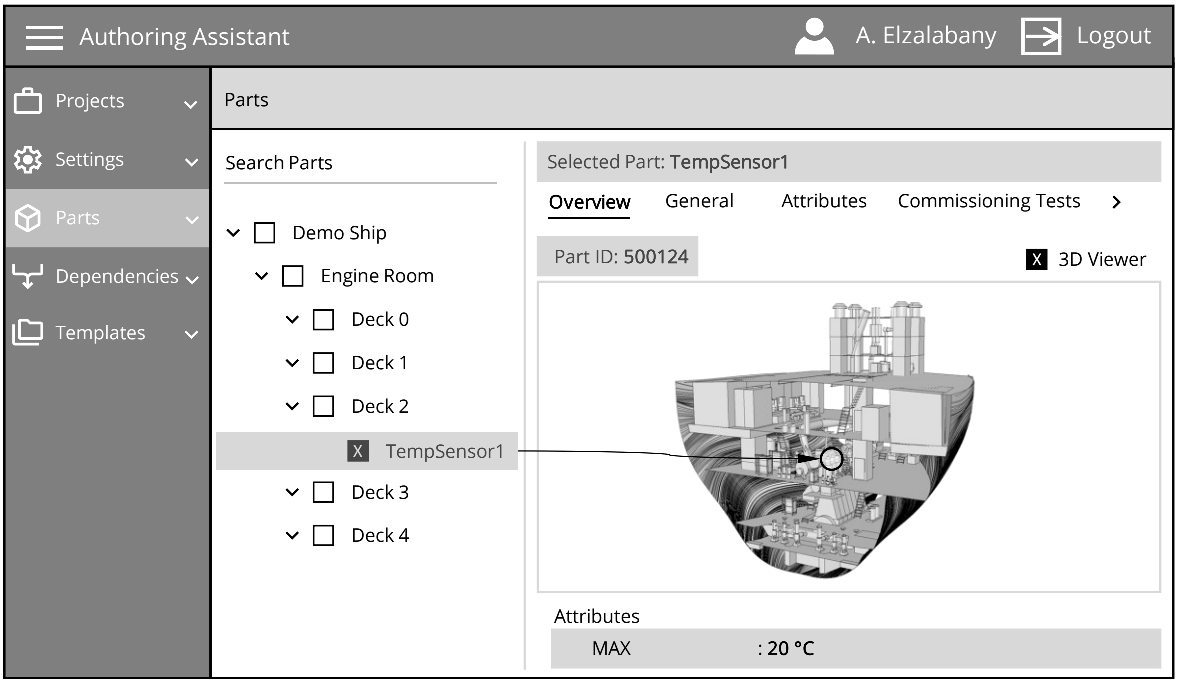
The table at the top section of Figure 30 represents the BOM list in its initial form prior to processing. The table columns represent identification information and technical attributes of the corresponding part. To simplify, only the following attributes are included in the identification information:

- **Assembly Group:** a numeric value corresponding to the assembly group to which a part or a component belongs.
- **Part ID:** a unique number consisting of the assembly group number of the part and a numeric value.
- **Parent ID:** identifies the part's parent in the BOM for the purpose of constructing hierarchies.
- **Name:** stores a text identifier that represents the part name.

As an example, the BOM in Figure 30 includes a part with the name *TempSensor1* that has the ID value *500124* and the parent ID *500123,* indicating that the part is a child of the *Engine Room*.

Furthermore, the table contains technical attributes specific to each part in the BOM. The technical attributes constitute the technical information that must be validated during testing. The table in Figure 30 indicates, for instance, that the first temperature sensor in the engine room should not register a temperature higher than 20 degrees Celsius. A temperature above this level indicates a problem with the engine. Such information is required by the commissioning authority to be able to define commissioning tests for the engine.

Identification				*Technical Attributes*		
Assembly Group	Part ID	Parent ID	Name	Attribute 1	. . .	Attribute n
500	500123	-	EngineRoom	-	-	-
500	500124	500123	TempSensor1	MAX	20 °C	-
500	500125	500123	TempSensor2	MAX	25 °C	-



Selected Part: **TempSensor1**

Part ID: **500124**

☒ 3D Viewer

MAX : **20 °C**

Figure 30: BOM before (top) and after import and processing by the authoring assistant (bottom [1])

Figure 30's lower section displays a schematic representation of the authoring assistant user interface. In accordance with Shneiderman's principles (see Section 6.1.1), the user interface of the BOM in the authoring assistant is structured to deliver specific information regarding each part of the BOM at the user's request, i.e., *details-on-demand*. For data containing parent-child and sibling relationships, Shneiderman recommends employing a tree visualization [Shne96, P. 339]. Accordingly, the user of the authoring assistant imports the BOM, the technical attributes, and the corresponding 3D CAD models, then the authoring assistant builds a hierarchy tree based on the parent IDs in the BOM. As shown in the figure, the authoring assistant assigns technical attributes and corresponding 3D CAD models to each part in the BOM. For example, the part *TempSensor1* is shown in the attributes section to have an attribute of key *MAX* and value *20 °C*. This *virtual BOM* is then stored in the Digital Twin database for maintaining a real-time virtual representation of the ship in commissioning.

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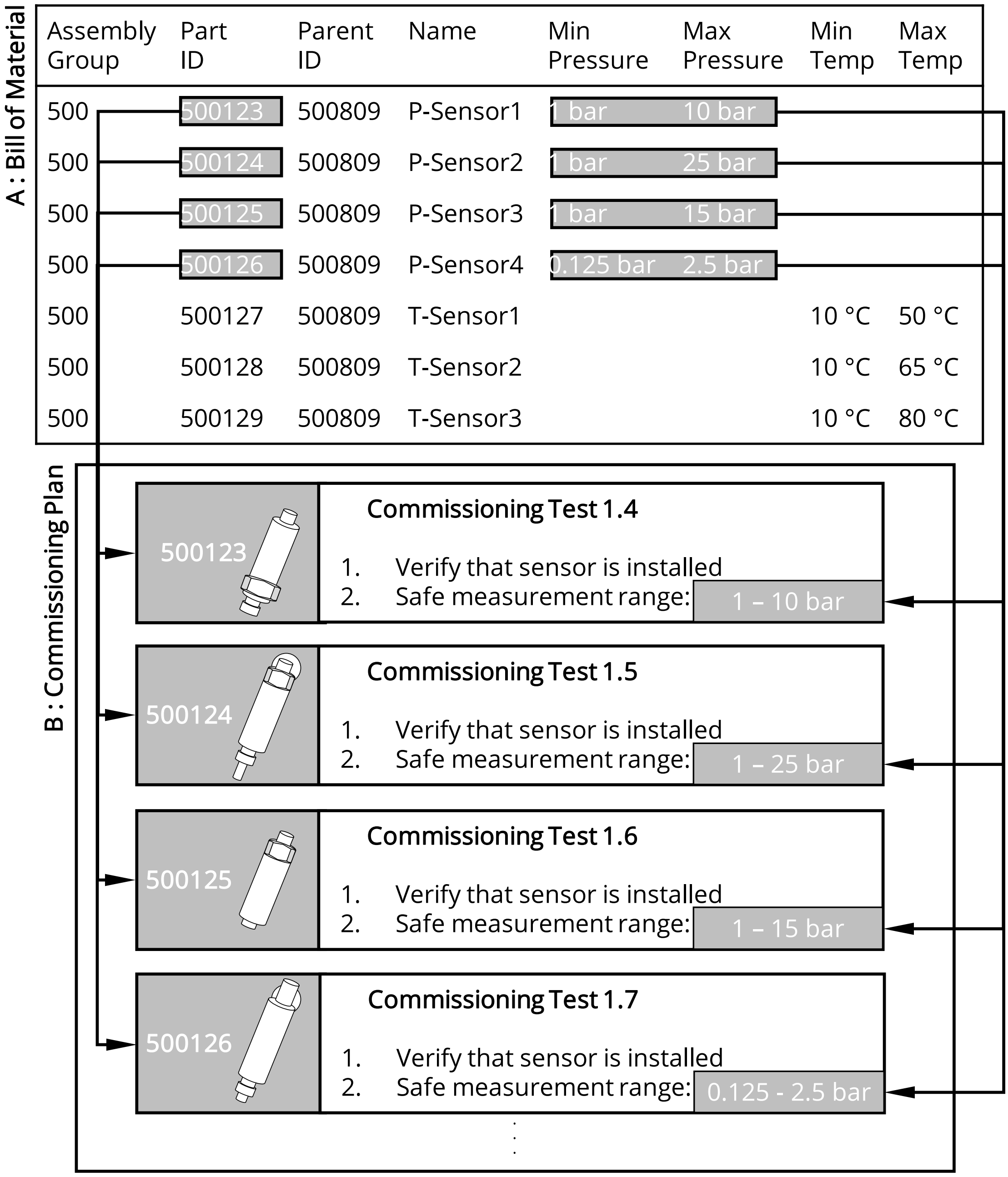
[1] The 3D model of the ship engine room used in Figure 30 is designed by Stefanidis and Tsitsilonis [Stef16].

Clustering of Items in the BOM

The analysis of the conventional process indicates that the commissioning authority expends excessive effort and time in authoring commissioning tests with minimal variations. This deficit can be further elaborated by considering the example of authoring commissioning tests for a group of pressure sensors (see Figure 31).



Assembly Group	Part ID	Parent ID	Name	Min Pressure	Max Pressure	Min Temp	Max Temp
500	500123	500809	P-Sensor1	1 bar	10 bar		
500	500124	500809	P-Sensor2	1 bar	25 bar		
500	500125	500809	P-Sensor3	1 bar	15 bar		
500	500126	500809	P-Sensor4	0.125 bar	2.5 bar		
500	500127	500809	T-Sensor1			10 °C	50 °C
500	500128	500809	T-Sensor2			10 °C	65 °C
500	500129	500809	T-Sensor3			10 °C	80 °C

Commissioning Test 1.4

1. Verify that sensor is installed
2. Safe measurement range: 1 – 10 bar

Commissioning Test 1.5

1. Verify that sensor is installed
2. Safe measurement range: 1 – 25 bar

Commissioning Test 1.6

1. Verify that sensor is installed
2. Safe measurement range: 1 – 15 bar

Commissioning Test 1.7

1. Verify that sensor is installed
2. Safe measurement range: 0.125 - 2.5 bar

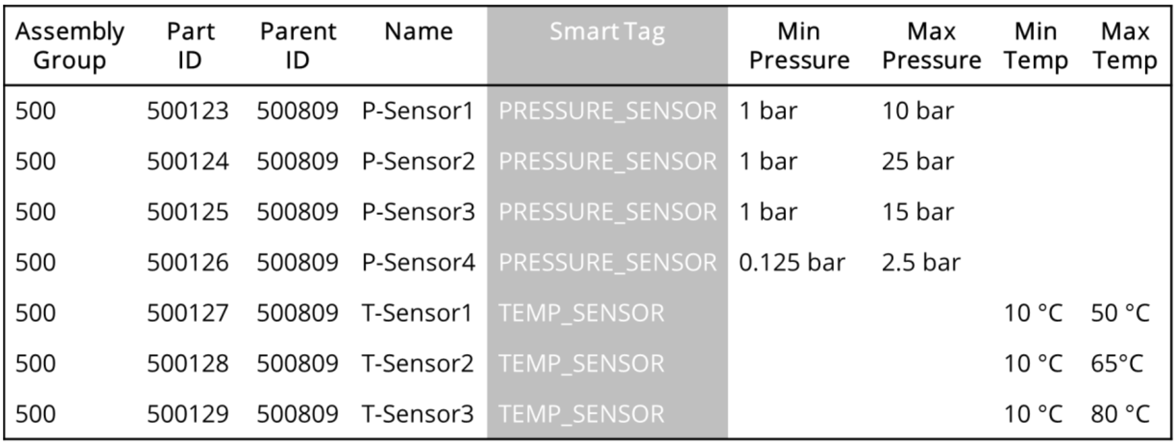
Figure 31: Authoring commissioning tests for pressure sensors

It is common for ships to contain thousands of sensors, and the commissioning authority must create at least one test per sensor. The authoring of such tests requires high effort and time which is manifested in manually copying the relevant technical attribute values of each sensor from the BOM to the corresponding commissioning test document as shown in Figure 31.

That being said, the procedure for testing pressure sensors is identical, but the expected readings vary from one sensor to another. This means that the commissioning tests for components within the same class follow the same steps and require the same resources and tools but vary only in specific attributes. By utilizing the concept of *classes* within the *object-oriented programming* (OOP) paradigm, the process of authoring commissioning tests for components of the same type can be optimized.

In the context of OOP, a *class* is a *blueprint* or a *template* that represents objects which possess identical variables and exhibit identical behavior [Stef85, P. 43]. Applying the approach of *templating* to the authoring assistant workflow, the user needs to create only one *template* of commissioning tests for each class of components. The template acts as a blueprint which automatically generates commissioning tests for components of the same type. This concept is discussed in detail in Section 6.2.4.

However, the first step to applying the concept of *commissioning templates* is to cluster parts and equipment in classes, where each class of components requires the same steps, tools, and resources for carrying out the commissioning test. To achieve clustering of parts in the BOM, a classifier attribute has been added to each part. This attribute is referred to as the *Smart Tag*. Figure 32 shows an extended BOM which contains the Smart Tag attribute for identifying parts that belong to the same class.



Assembly Group	Part ID	Parent ID	Name	Smart Tag	Min Pressure	Max Pressure	Min Temp	Max Temp
500	500123	500809	P-Sensor1	PRESSURE_SENSOR	1 bar	10 bar		
500	500124	500809	P-Sensor2	PRESSURE_SENSOR	1 bar	25 bar		
500	500125	500809	P-Sensor3	PRESSURE_SENSOR	1 bar	15 bar		
500	500126	500809	P-Sensor4	PRESSURE_SENSOR	0.125 bar	2.5 bar		
500	500127	500809	T-Sensor1	TEMP_SENSOR			10 °C	50 °C
500	500128	500809	T-Sensor2	TEMP_SENSOR			10 °C	65°C
500	500129	500809	T-Sensor3	TEMP_SENSOR			10 °C	80 °C

Figure 32: Smart Tag attribute in the BOM

The process of adding a new attribute to the BOM should not induce additional effort and should be carried out automatically. Fortunately, the shipyard's PLM system usually includes attributes that can be utilized for part classification. The authoring assistant is, therefore, initially configured to recognize the attribute transferred from the PLM system as the classifier attribute. In the case where the PLM system does not contain unique classifier attributes for all parts in the system, an algorithm has been developed to visually classify parts according to their 3D models. This approach relies on machine learning and can be summarized in the following steps [Elza22a]:

1. **Construction of 2D projection images from 3D models of parts:** the classification of parts utilizes view-based image recognition. Therefore, the 3D models of the parts are processed by the Digital Twin to create 2D images.
2. **Feature extraction from 2D images:** in case of a large dataset, it is important to optimize the images to reduce computational effort. Therefore, the images constructed from the 3D models are converted into monochromatic images through the method of Histogram of Oriented Gradients (HOG). The method of HOG was developed by Dalal and Triggs [Dala05] and is widely used in computer vision applications for feature extraction.
3. **Clustering of components using unsupervised learning:** in this step, the resulting HOG images are clustered using the DBSCAN algorithm since that this algorithm does not require pre-knowledge of the number of clusters, i.e., utilizes unsupervised learning.

Figure 33 shows the steps and the results of applying the clustering algorithm [Elza22a]. The algorithm underwent validation and shown efficacy in clustering different components by leveraging their visual attributes, as depicted in Figure 33 (step 3). Nevertheless, the algorithm exhibited difficulty in distinguishing between components, for example pressure and temperature sensors, as a result of their visual resemblances. However, the system's effectiveness can be enhanced by introducing additional attributes into the clustering procedure to allow clustering based on different criteria instead of relying only on the visual attributes of the components.

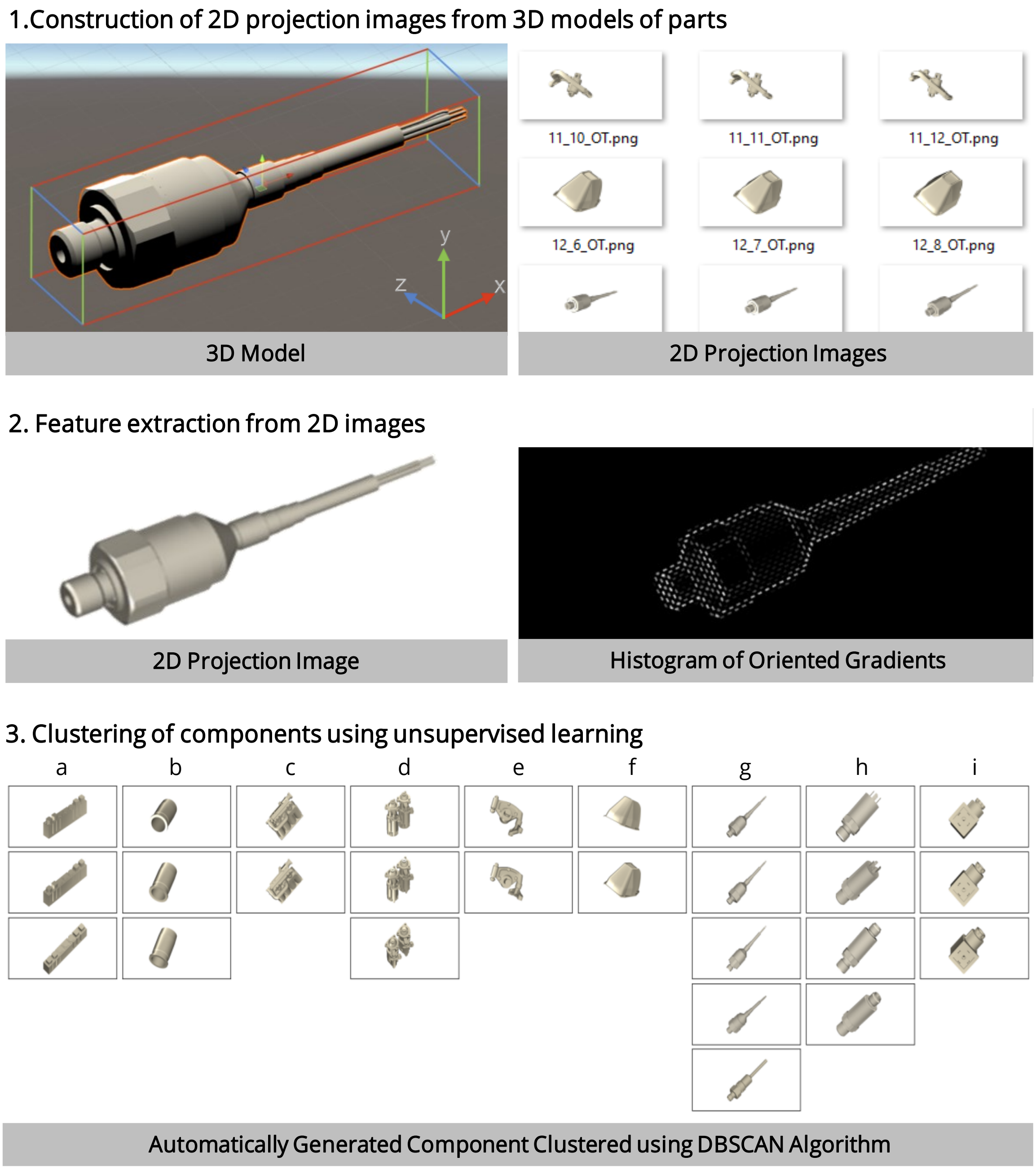


Figure 33: Automatic generation of component clusters [Elza22a] [2]

6.2.3 Preparation of Localization Data

According to Requirement I2, the DAS should include localization capabilities to help improve the workflow of the commissioning team. These capabilities will assist in reducing the time and effort necessary to locate the parts and assemblies in the ship for the purposes of testing. Because of this, it is essential for the authoring assistant to have access to the

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[2] The 3D model of the sensor shown in Figure 33 is for the TM4511 temperature sensor manufactured by IFM Electronic GmbH [IFM 23].

ship's location data. Consequently, the user of the authoring assistant imports both 3D ship models that contain all of the parts included in the BOM. Moreover, the user also imports 2D deck plans of the ship in production (see Figure 34).

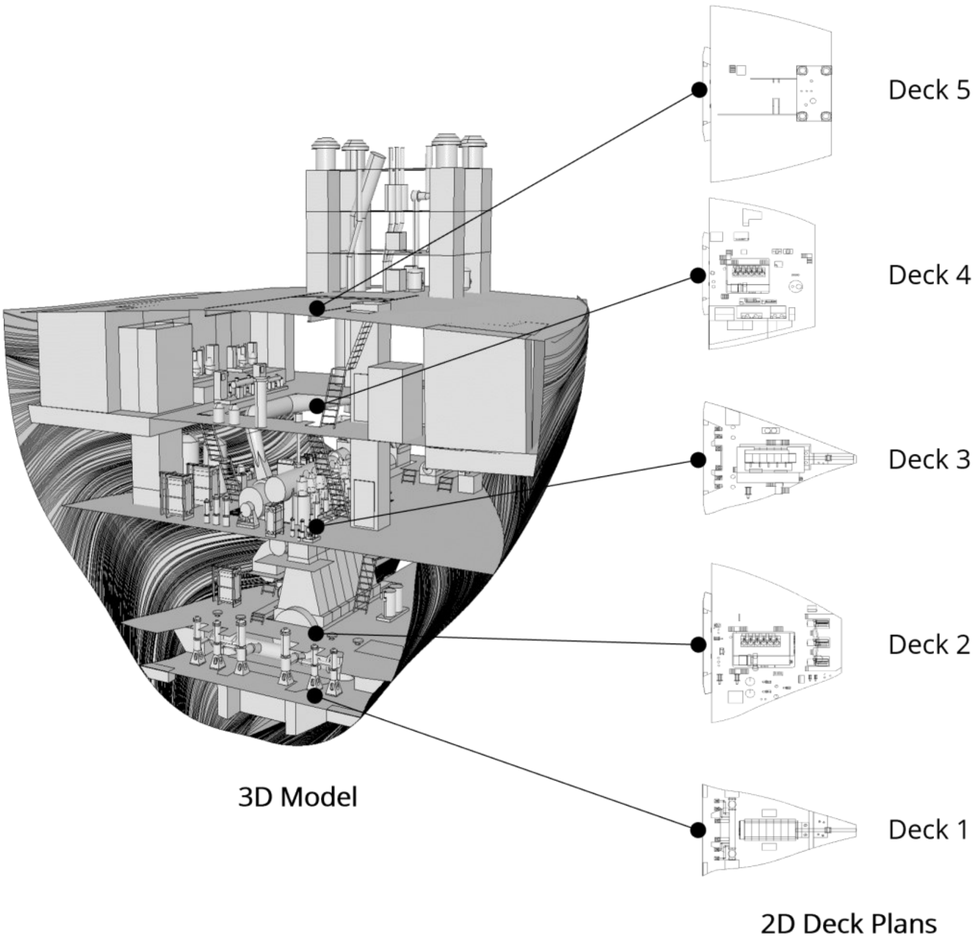
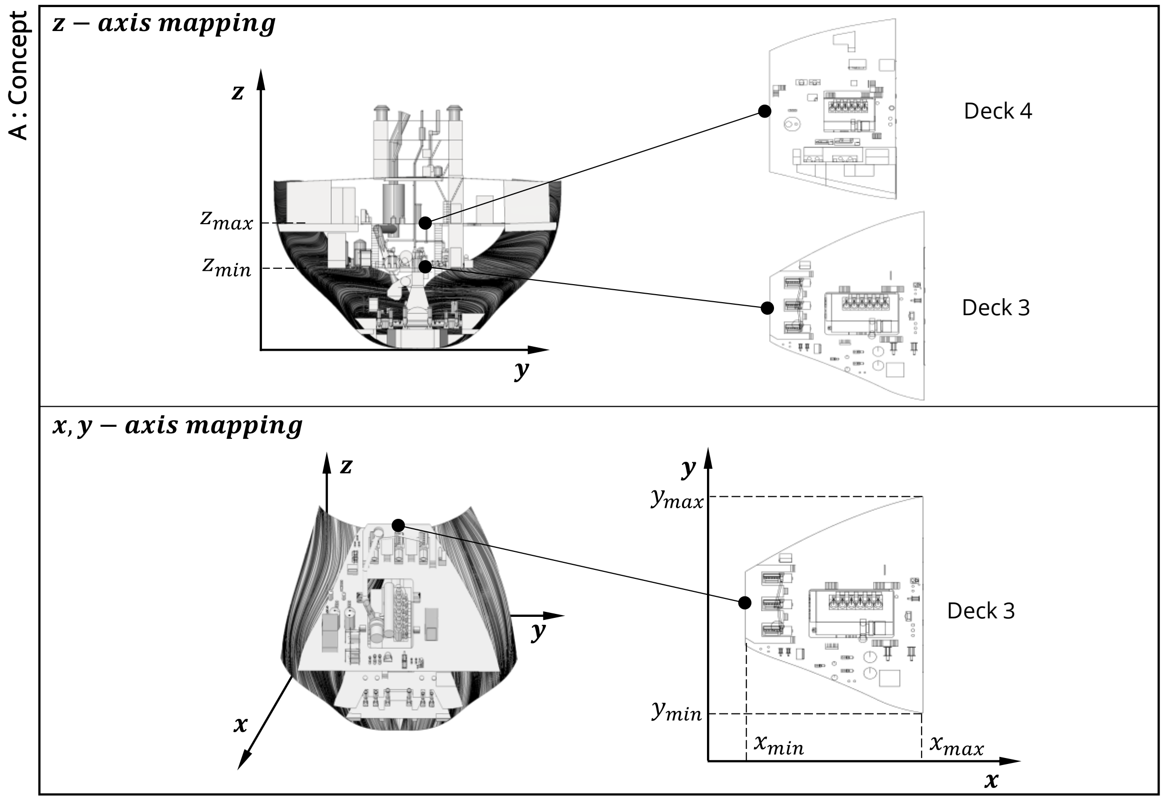
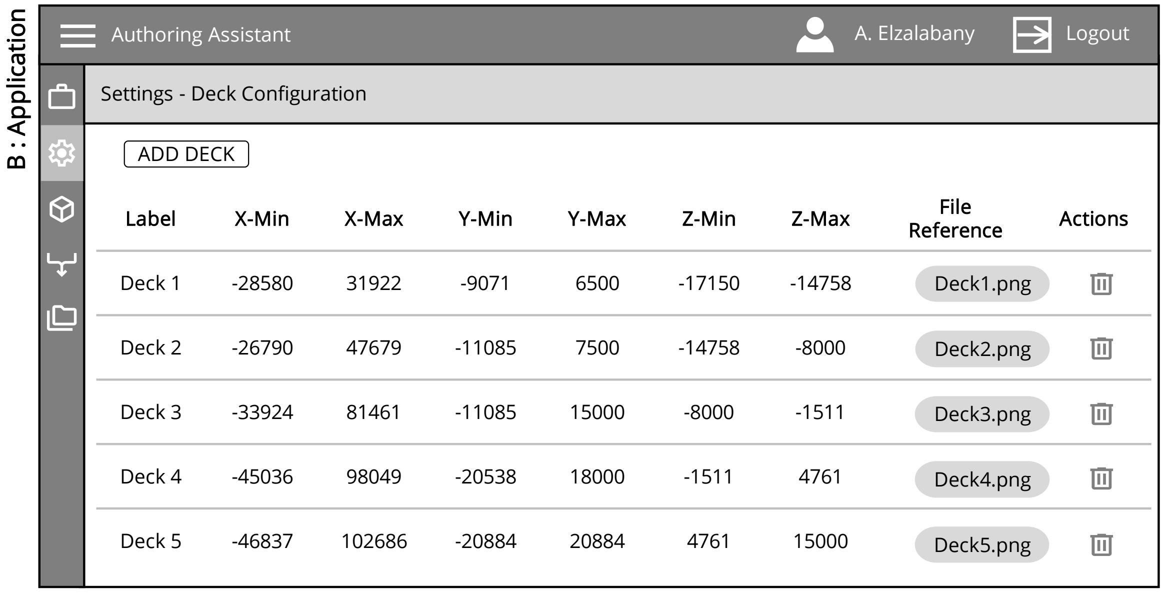


Figure 34: 3D models and 2D deck plans imported by the authoring assistant

The imported 3D models are utilized to pinpoint the location of the ship's assembly groups as well as the various parts that have been fitted aboard (fine localization). When the commissioning team arrives at the site, having this information on hand will be helpful for locating the parts and assemblies. On the other hand, the 2D deck drawings are helpful for navigating the commissioning team towards the location where the assemblies and parts are installed. These 2D plans are imported from the shipyard systems as image files.

The 3D models contain all of the coordinate information, and it is possible to transfer them automatically to the BOM parts. However, the 2D deck plans are just image files; as a result, the image files need to be *mapped* to the 3D model of the ship. Following the import of project data from the shipyard systems, the commissioning authority will carry out this phase manually on a single occasion. As illustrated in Figure 35(B), the user of the authoring assistant is required to configure every 2D picture that represents the deck by supplying the distances between the decks (along the Z-axis) as well as the areas of the decks (along the X-axis and the Y-axis).





Settings - Deck Configuration

Label	X-Min	X-Max	Y-Min	Y-Max	Z-Min	Z-Max	File Reference	Actions
Deck 1	-28580	31922	-9071	6500	-17150	-14758	Deck1.png	🗑
Deck 2	-26790	47679	-11085	7500	-14758	-8000	Deck2.png	🗑
Deck 3	-33924	81461	-11085	15000	-8000	-1511	Deck3.png	🗑
Deck 4	-45036	98049	-20538	18000	-1511	4761	Deck4.png	🗑
Deck 5	-46837	102686	-20884	20884	4761	15000	Deck5.png	🗑

Figure 35: Coordinate mapping of 2D deck plans

6.2.4 Creation of Reusable Commissioning Templates

The concept of *commissioning templates* was developed to satisfy requirements P1 and P3 for the efficient creation and reuse of commissioning plans. The notion of creating a template, instead of creating commissioning tests from scratch, originates from the concept of *classes* within the *object-oriented programming* (OOP) paradigm (see Section 6.2.2). This section presents the concept of the commissioning templates and the information structure of the template.

Concept of Commissioning Templates

The analysis of the conventional process of commissioning demonstrates that manually authoring commissioning tests for each component in the ship wastes time and effort. Rather than manually authoring each and every commissioning test from scratch, it is more efficient to create a reusable template for generating the commissioning tests automatically as shown in Figure 36.

Figure 36 demonstrates that commissioning tests for components of the same class (e.g., PRESSURE_SENSOR) have minor differences, with the only distinctions being specific technical values. Using the Smart Tag attribute described in Section 6.2.2, the authoring assistant user can group components into classes, where one component class corresponds to a commissioning template.

The figure explains the process wherein the user of the authoring assistant creates a commissioning template without including any numerical values in the template. Instead, the template incorporates variables such as the Smart Tag (PRESSURE_SENSOR) and the column IDs inside the BOM list that encompass the technical attributes required for test authoring. As depicted in the figure, it is no longer necessary for the user to manually create four entries for the commissioning tests. Instead, the user creates a single entry, specifically the commissioning template, which can be utilized by a matching algorithm to replace the variables within the template with concrete numerical values from the BOM.

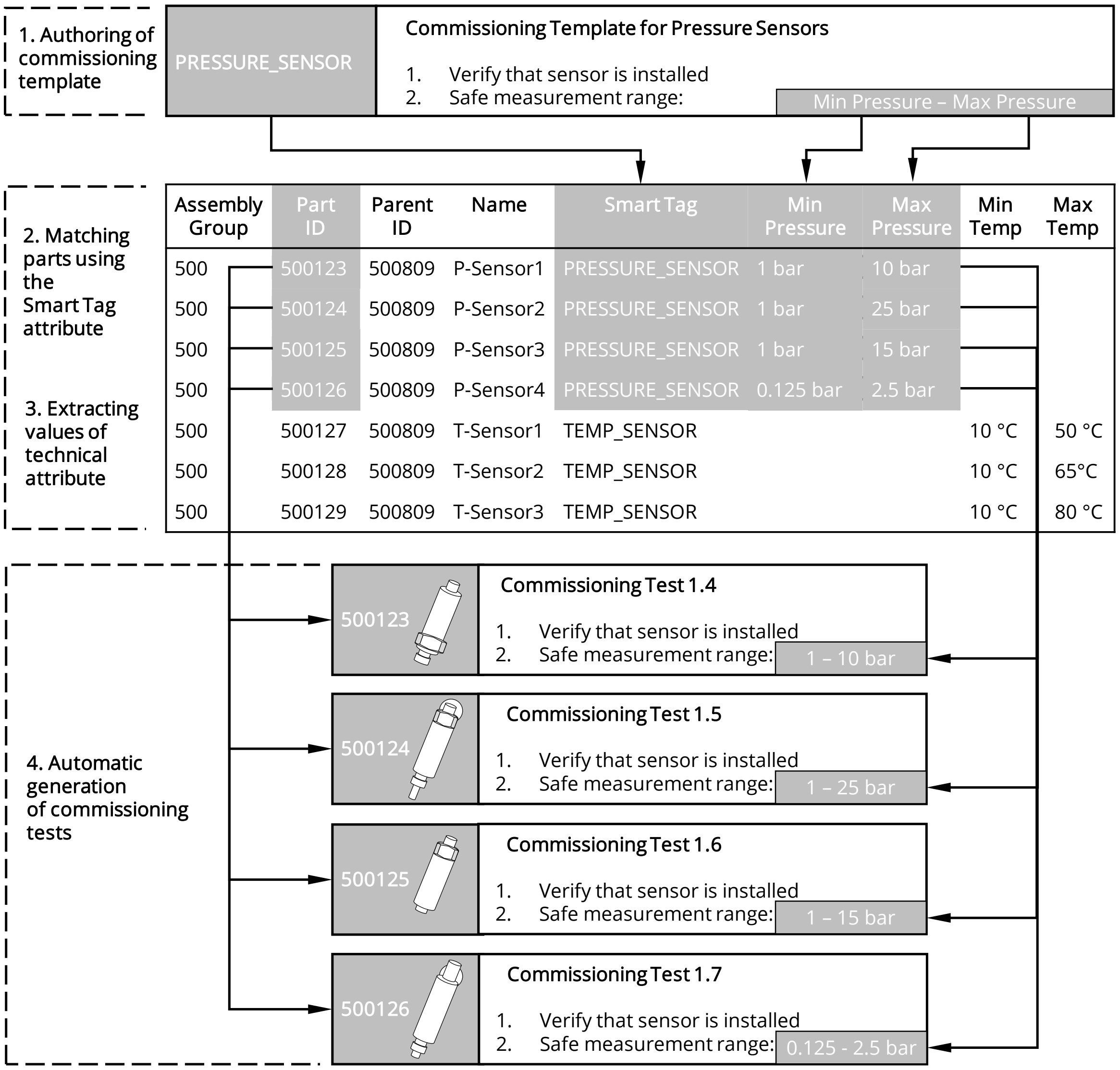
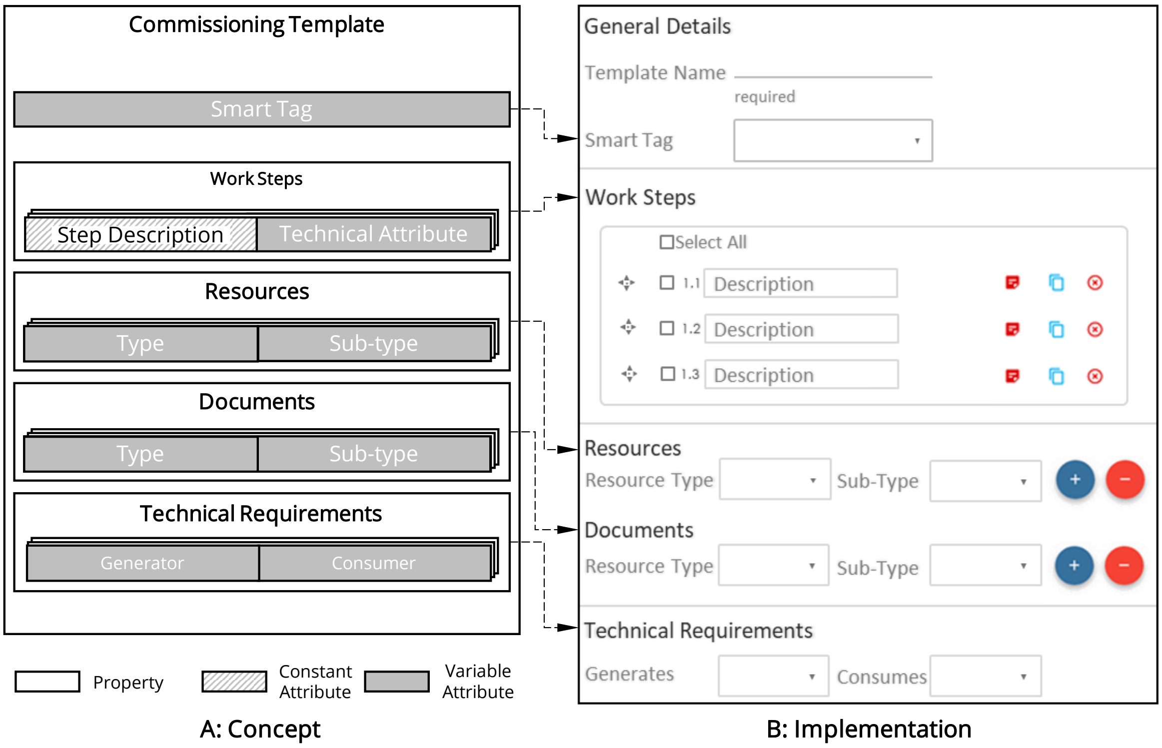


Figure 36: Automatic generation of commissioning tests using the concept of commissioning templates

Template Structure

In addition to including technical attributes in the commissioning templates as variables, the template should also include constants and variables representing information such as work steps, resources, documents, and technical requirements. This information is required for supporting the commissioning team during the testing procedure. Figure 37 shows the developed information structure within the commissioning template and the user interface for authoring a commissioning template. The information structure of the commissioning template is designed based on the model of the commissioning test (see Figure 23).



A: Concept

B: Implementation

Figure 37: Information structure of commissioning template and graphical user interface

As shown in Figure 37, the commissioning template is created for a class of components represented by the *Smart Tag* variable. A variable is an entity which gets assigned a concrete value using a matching algorithm (as described by Figure 36). A commissioning template includes four primary properties which are:

- **Work Steps**: this property includes the steps that describe how to conduct the commissioning test and which technical attributes are relevant to the test. The description is defined as a *constant attribute* in the work step property, indicating that the description is identical for all tests of the same component class. The *technical attribute* value, on the other hand, varies from component to another, hence the variable attribute (see Figure 36).
- **Resources**: this property is essential for assigning personnel, tools, and materials to each commissioning test. Using this property, the user can define templates for the resources required to perform commissioning tests on the corresponding components. For example, the user can define a resource of type *Staff* and a sub-type of *Electrical*. This definition indicates that the commissioning team responsible for conducting the test must be from the *electrical department*. When the system is linked to a resource management system via the Digital Twin, the authoring assistant can automatically assign tasks to the correct personnel of the commissioning team according to their qualification. The resource property also includes tools and materials required for conducting the tests.
- **Documents**: this property is analogous to the resource property, with the exception

that the algorithm matches concrete documents (such as PDF files) with the generated commissioning tests, rather than personnel or tools. To retrieve concrete documents, the matching algorithm on the Digital Twin requires access to a document management system on the shipyard.

- **Technical Requirements**: this property is required to assign execution restrictions and conditions to the commissioning tests. Using this property, the user can specify, for instance, that a test requires electricity to be supplied to the component before the testing can start. The technical requirements property includes the *generator and consumer* attributes. To clarify, the user can designate a template as a generator for a resource, such as *electricity*, indicating that, upon completion of the commissioning test, the corresponding component is guaranteed to provide electricity to other connected components. When the user designates the template as a consumer, it indicates that the test requires electricity to be started. This property is relevant for technical dependency management, and will be described in detail in Section 6.3.

To use the functionality of templates, all variable attributes must be predefined and centrally stored in the Digital Twin database after the user initiates the commissioning project. Section 6.2.2 describes the procedure for automatically defining the Smart Tag attribute. The remaining attributes for resources, documents, and technical requirements are manually defined once and can be reused for all future commissioning projects.

6.2.5 Creation of Commissioning Template Variations

The commissioning implementation process is performed over different phases (see Section 2.2.3). Each phase determines the conditions and timing for conducting the commissioning tests. Moreover, commissioning tests vary in type according to the task to be performed. This section complements Section 6.2.4, which introduces the concept of commissioning templates, by extending the templates to account for the different phases of testing and the types of commissioning tests.

Phases of Testing

According to the analysis, there are three principal phases for maritime commissioning implementation: FAT (Factory Acceptance Testing), HAT (Harbor Acceptance Testing), and SAT (Sea Acceptance Testing). In addition, the shipyard may also organize the tests in sub-phases, such as *internal* and *official testing* as described in Section 5.3.1. It is common practice to conduct the same commissioning test in multiple phases. For instance, a functional test may be performed during the HAT phase and then repeated during the SAT phase to ensure safety during the actual sea trial. That being said, there is a logical sequence for executing the same test in multiple phases as illustrated by Figure 38.

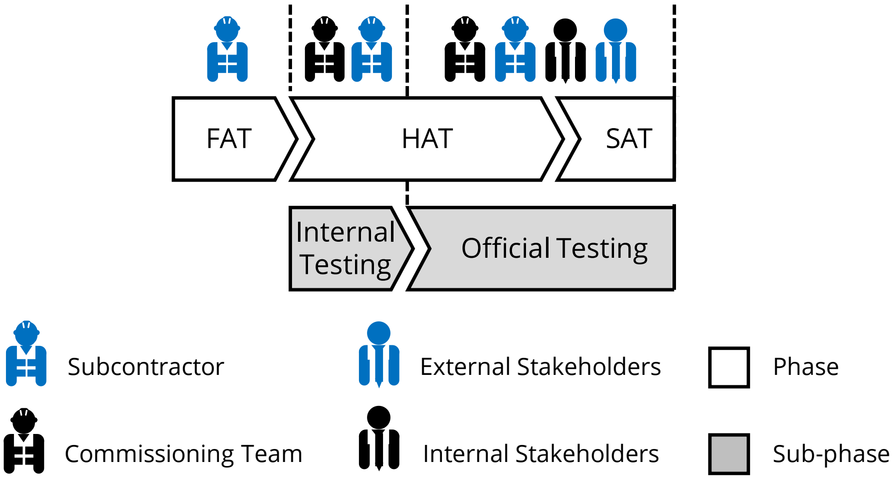


Figure 38: The sequence of executing a commissioning test in multiple phases

First, the subcontractor tests the equipment at the factory (FAT) before installing it on the ship. Second, without the presence of any external stakeholders, the equipment is tested on board (internal HAT), followed by the official testing sub-phase where all stakeholders, including the client and classification society members, are present. The official testing continues until the sea trials (SAT) are complete.

Each phase concludes with the generation of a signed protocol that documents the results of testing. Regardless of the phase, the technical procedures and steps involved with the commissioning test remain the same. As a result, by modifying only the protocols and resources required for each phase, the commissioning template can be used to automatically generate alternative versions of the commissioning test across all relevant phases.

To generate these test variations, the authoring assistant user must predefine all phases of testing after the commissioning project is initially configured. From the data modeling point of view, a phase can be represented as an additional property in the commissioning template data structure. The phase property contains information about the resources and protocols required for conducting the commissioning test. Consequently, the user can create a commissioning template and attach it to multiple phases, allowing the authoring assistant to generate a test for every phase taking into account the different protocols and the resources required for initiating the testing.

Types of Commissioning Tests

The commissioning team conducts tests to ensure the proper installation and operation of the ship's systems. Installation tests, as explained in Section 2.2.3, are basic checks to ensure that a system is properly installed. Operational tests, on the other hand, are conducted to ensure that the installed system is performing as expected in accordance with the client's requirements and classification society norms. Operational tests include functional and signal tests. Figure 39 depicts the distinctions between functional and signal tests.

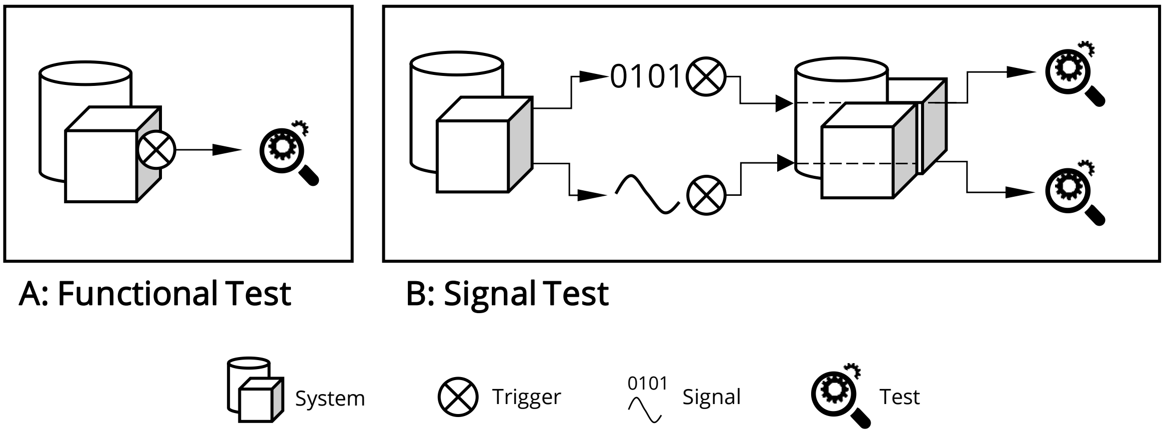


Figure 39: Functional and signal tests

According to Figure 39, to conduct a test on a system, the system must be first triggered to perform a specific functionality, and then the outcome is observed and compared against the functional requirements. What differentiates functional testing from signal testing is the source of the trigger.

In functional testing, the trigger comes from the system being tested when the tester conducts an action on the system. To illustrate, the process of testing the functionality of a door in a ship requires the tester to perform a series of actions on the door itself, such as opening and closing it, and observe whether the door opens and closes without producing noise or friction.

In signal testing, the trigger comes from an external signal and not from the system being tested. For example, an actuator responsible for the shutdown of a machine due to overheating requires a signal from a temperature sensor that is linked to the actuator. In this case, the tester replicates a situation that triggers the sensor to produce a signal, for instance, by subjecting the sensor's proximity to heat. When the actuator gets a signal from a sensor indicating a reading that is beyond a pre-established threshold, the actuator responds by performing a mechanical operation that leads to the stopping of the machine controlled by the actuator. It is worth noting that the actuator may be programmed to exhibit different behaviors based on the signal it receives from the sensor. For example, modifying the speed of a motor in response to the temperature signal received from the sensor. Therefore, it is common practice to carry out several signal tests per system.

The differences between functional and signal tests can be summarized using the previous example of the *temperature sensor* and the *actuator* as follows:

- **Functional test:** verifying that the sensor is correctly measuring temperature.
- **Signal test:** verifying that the actuator is correctly controlling a machine’s operation according to the signal received from the temperature sensor.

Expansion of the Commissioning Template Concept

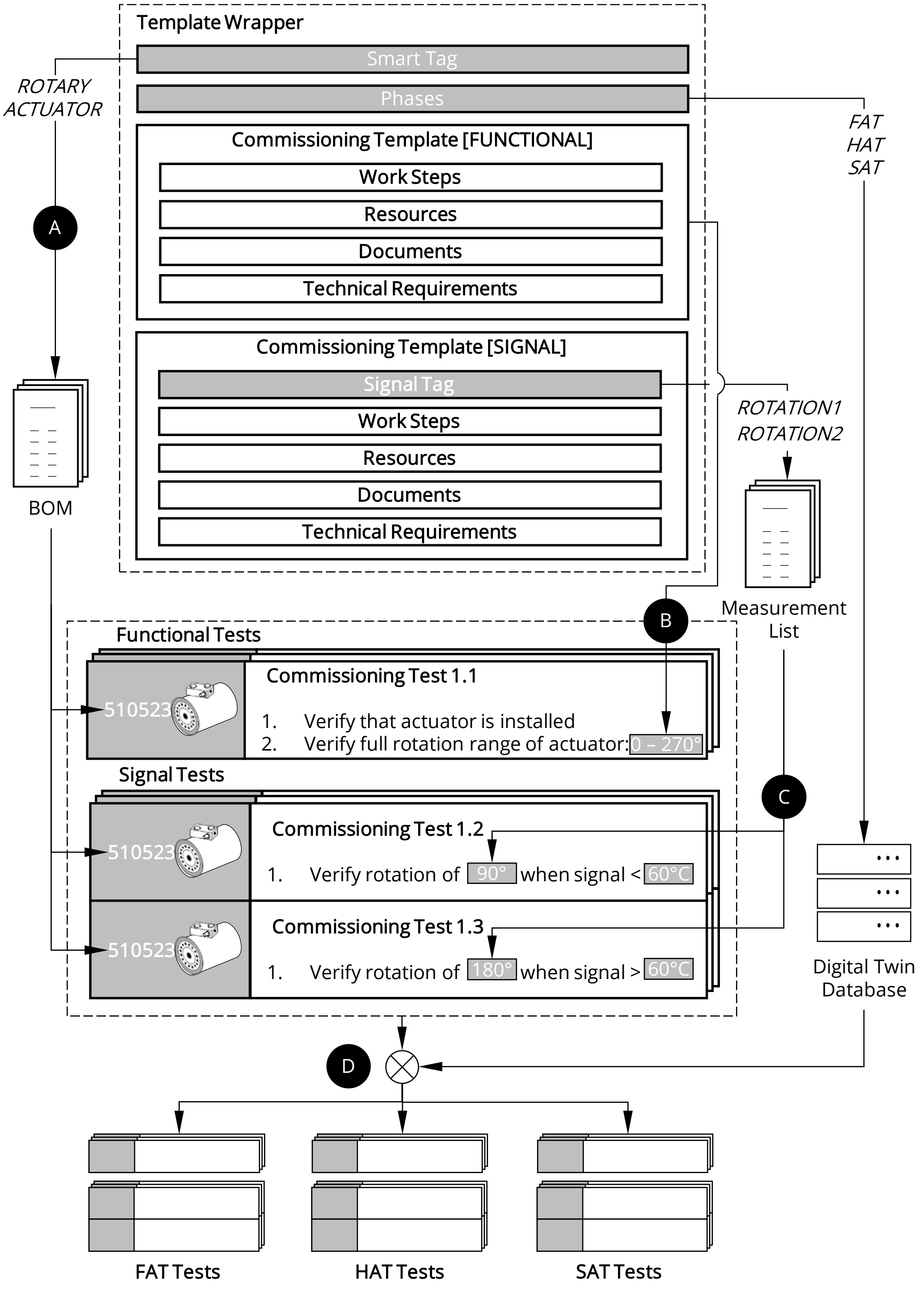
The concept of the commissioning template has been introduced to automatically generate a functional test for each individual system that belongs to a specified class. As mentioned in the prior subsections, it is necessary to generate several instances of the functional test in order to accommodate the different phases of testing. Additionally, it may be required to author more than one test for an individual system (signal testing). These requirements imply that the commissioning template has to be *expanded* to encompass the generation of several commissioning tests for the same system.

The commissioning template data structure is expanded by implementing the concept of *inheritance* in the OOP paradigm. Inheritance involves the creation of hierarchical structures of classes, where child classes *inherit* the properties of parent classes. This approach is beneficial for constructing complex data structures while also preserving the modularity of data [Stef85, P. 46f.]. Accordingly, a data structure called the *template wrapper* is developed to serve as a parent or container for multiple commissioning templates that vary in characteristics, e.g., *test type*, but possess identical properties, e.g., *Smart Tag*.

Figure 40 shows the workflow of the expanded commissioning template concept to support the different phases and types of commissioning tests. The figure shows that the template data structure includes additional variable attributes as follows:

- **Phases:** this attribute is used to determine the phases in which the commissioning tests have to be generated.
- **Signal Tag:** similar to the technical attribute shown in Figure 37. The *Signal Tag* is used to mark relevant technical values from a *measurement list* provided by system manufacturers and subcontractors. This list contains pertinent signal test values. Conventionally, the commissioning authority of the shipyard uses the measurement lists to define multiple signal tests per system. Consequently, the DAS authoring assistant can use the same list for the automatic generation of signal tests.

Figure 40 demonstrates that the *template wrapper* data structure contains two commissioning templates (functional and signal templates). The template wrapper data structure is utilized to store all the commissioning templates and attributes relevant to components of the same class. In other words, the template wrapper data structure can be regarded as a reusable commissioning plan for each class of components in the ship. The template wrapper can be reused across different commissioning projects as it incorporates only the rules of generating commissioning tests and not the actual technical values included in the tests.



A Search BOM for parts of class *ROTARY ACTUATOR* and generate functional tests for all parts of the class.

B Assign range of rotation values to functional tests using technical attributes in BOM.

C Generate signal tests and assign expected rotation values obtained from measurement list to signal tests.

D Generate instances of tests for FAT, HAT, and SAT phases including resources required for each phase.

Figure 40: Workflow of the extended commissioning template

6.2.6 Discussion

The authoring assistant, presented in Section 6.2, is a software artifact developed to fulfill the specifications of requirements *P1* and *P3* (see Section 4.2.2). The objective of this artifact is to enhance the process of authoring the commissioning plan and facilitate its use across multiple commissioning projects. This section provides a discussion of the authoring assistant, focusing on its qualitative benefits and limitations.

Benefits

The authoring assistant utilizes a workflow based on *commissioning templates*, allowing the commissioning authority to create templates that can automatically generate commissioning tests for every class of components in the ship. The template workflow can enhance the process of commissioning preparation by eliminating the need to manually define the specifications of each individual commissioning test in the ship. Moreover, utilizing a system comprising of the authoring assistant and a Digital Twin is advantageous for creating a database of organized information that constitutes a digital commissioning plan. The commissioning authority can utilize this data as a foundation for creating the commissioning plans for upcoming projects.

Limitations

To create a commissioning template for each class of component in the ship, it is necessary that the BOM obtained from the PLM system contains information that facilitates the clustering of components into groups or classes. If the ship's components are not naturally organized into groups, the DAS for commissioning offers a machine learning based algorithm to cluster the ship components according to their 3D models. However, the clustering algorithm requires further optimization to achieve more reliable clustering (see Section 6.2.2). Furthermore, the algorithm has not undergone testing for clustering a substantial quantity of components within the ship. This is mostly due to the challenge of obtaining complete BOM data from ships that have been previously commissioned.

6.3 Authoring Assistant for Technical Dependencies

As per requirement P2, it is necessary for the authoring assistant to provide its users with capabilities to define the technical dependencies between the generated commissioning tests. Additionally, the authoring assistant should be able to automatically generate a viable execution sequence for these tests according to the technical dependencies. Section 6.3 begins with modeling the technical dependencies between the commissioning tests and then discusses the developed functionalities for creating and visualizing the dependencies. In addition, the section demonstrates how the authoring assistant can automatically organize commissioning tests into viable execution sequences.

6.3.1 Modeling of Technical Dependencies

Within the context of marine commissioning, technical dependencies are essential prerequisites that must be satisfied in order to initiate a commissioning test. In detail, a commissioning test awaits the completion of an event until it can be initiated. The event could be one of the following two cases:

1. **Fulfilment of a technical requirement**: certain tests require specific technical resources to be available in order for the test to be executed. For instance, testing motion sensors requires light in the sensor's proximity. In the absence of light at the sensor installation location, the commissioning test cannot start.
2. **Completion of a commissioning test**: the testing of physically connected systems follows a logical sequence. For example, to test an electrical device connected to a power supply, the commissioning team must first ensure that the power supply is correctly installed, completely functional, and rated for the loads it supplies. Afterwards, the electrical device can then be put to the test. Reversing the sequence of testing places the devices connected to the power supply at risk.

Notably, the previously discussed two events must be treated differently using the authoring assistant. This is because the first event (fulfilment of a technical requirement) may result from the completion of a production activity or a commissioning test, while the second event (completion of a commissioning test) is the more general case when handling technical dependencies that result from commissioning work. In conclusion, a technical dependency is an essential property for determining whether a commissioning test can begin, thereby establishing the criteria for determining the execution sequence of the commissioning tests. Therefore, the technical dependency property should be included in the data model of the commissioning test as shown in Figure 41.

After modeling the technical dependencies in terms of data, it is crucial to select an appropriate visualization model for the dependencies. Shneiderman argues that hierarchical data structures, e.g., trees, are not always sufficient to describe complicated relationships among data items. Instead, it is more advantageous to employ a *network* structure to visualize these relationships [Shne96, P. 341]. Pearl and Verma state that a *directed graph* is the most suitable *network topology* for visualizing dependencies. In a directed graph, the nodes correspond to propositional variables, whereas the edges of the graph indicate the interdependencies between these variables. The *directed* edges in the graph are illustrated as *arrows* to indicate causality [Pear, P. 375]. Accordingly, the directed graph topology was selected for representing technical dependencies between commissioning tests in the DAS as shown in Figure 42.

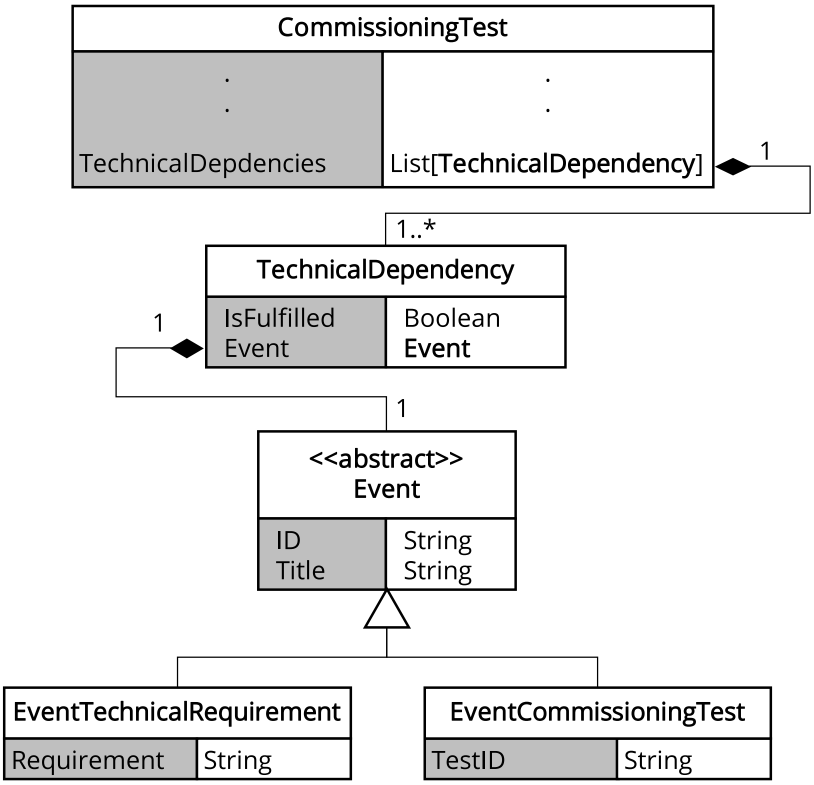


Figure 41: Simplified UML class diagram of technical dependencies

Figure 42 depicts a directed graph including three *nodes*, each representing a distinct commissioning test. The nodes are linked by two *edges* or arrows that symbolize the dependencies between the commissioning tests. Since the edges have a specific direction, it can be deduced that tests 2.1 and 2.3 depend on the outcome of test 1.1. Consequently, these two tests cannot commence until test 1.1 has been successfully concluded.

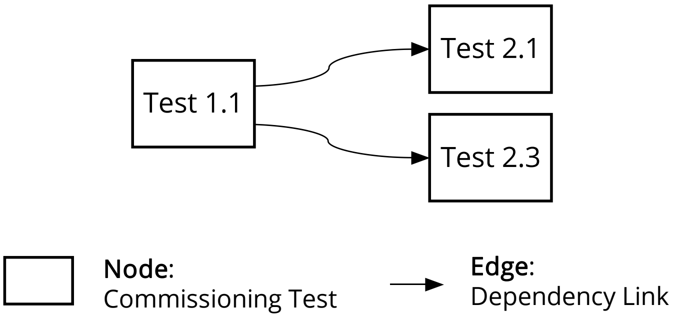


Figure 42: Visualization of technical dependencies using the directed graph topology

6.3.2 Overview of the Solution for Management of Technical Dependencies

The subsequent sections discuss the features for generating and visualizing technical dependencies. However, before discussing each feature in detail, it is helpful to first provide a concise overview of the solution. Figure 43 illustrates the features of the authoring assistant for dependency management and references the corresponding sections in this chapter that provide detailed explanations of each feature.

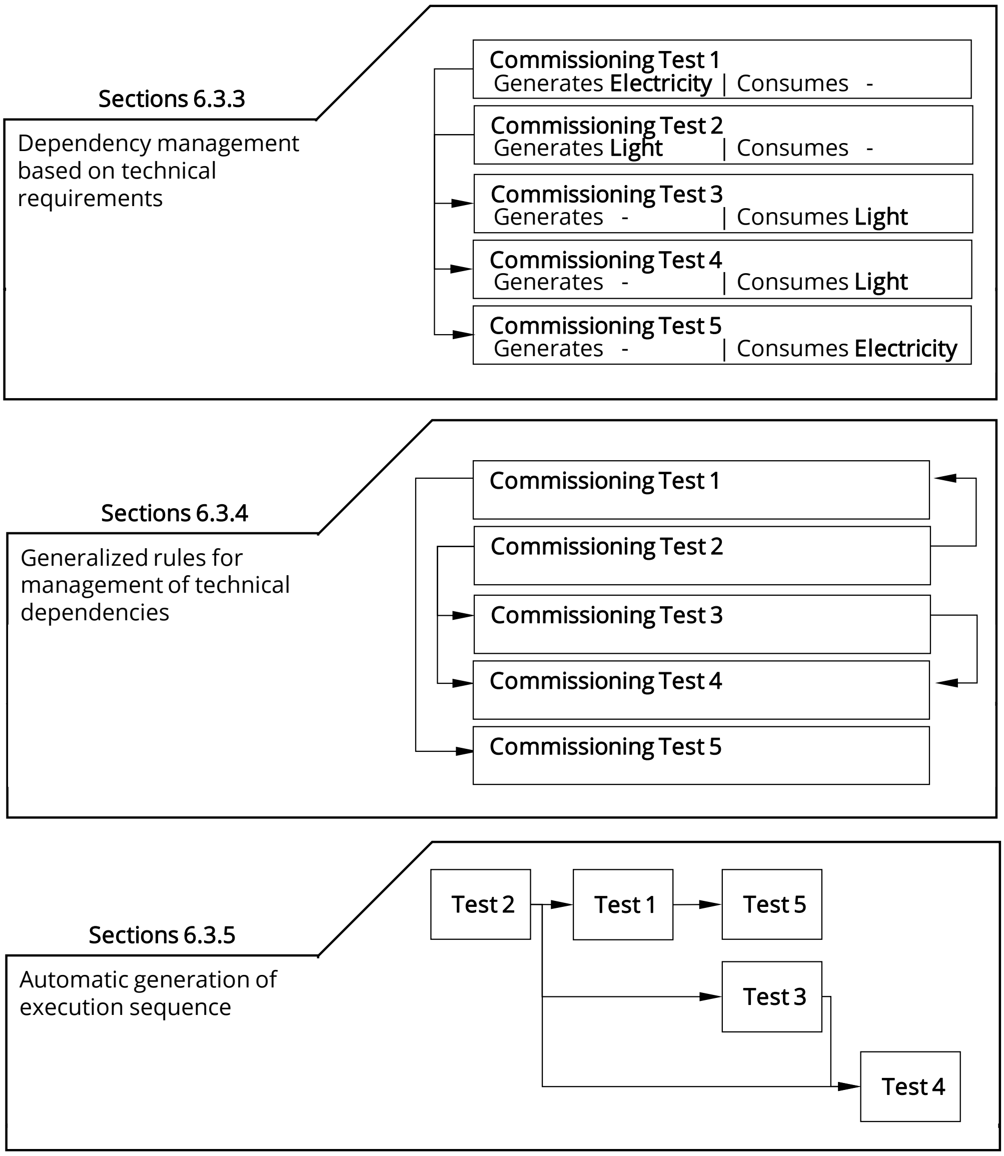


Figure 43: Features of the authoring assistant for managing technical dependencies

The figure depicts three key aspects of managing technical dependencies. Section 6.3.3 discusses the feature of generating dependency links based on the technical requirements of commissioning tests. The concept is to automatically pair commissioning tests that require specific technical resources with tests that generate the resources, i.e., consumer and generator, and create dependency links accordingly.

Section 6.3.4 explains how the authoring assistant enables the user to create generalized dependency rules with minimal effort. This functionality is beneficial when the user must define dependencies between commissioning tests that lack technical requirements attributes. For instance, managing dependencies caused by physical part connections.

Section 6.3.5 concludes with presenting an algorithm developed for the generation and visualization of execution sequences. The concept is to aggregate all generated commissioning tests as input, analyze their technical dependency properties, and then run an algorithm that automatically organizes the commissioning tests in a directed graph topology depicting a viable execution sequence of the commissioning tests.

6.3.3 Dependencies Based on Technical Requirements

A commissioning test can serve as either a *generator* or a *consumer* of a technical resource. The test designated as a technical resource generator is the predecessor to the commissioning test designated as a consumer of the same technical resource. This section outlines a method for defining technical requirements and assigning them to the commissioning tests.

Using Commissioning Templates for Defining Technical Requirements

Manually assigning technical requirements to each commissioning test is impractical due to the large number of tests typically included in the commissioning plan, which can exceed ten thousand according to the analysis of previous shipbuilding projects. To save time and effort, the concept of templates is utilized to develop a solution for automatic assignment of technical requirements, eliminating the need for manual iteration through each test to create dependency links. Figure 44 explains the solution schematically.

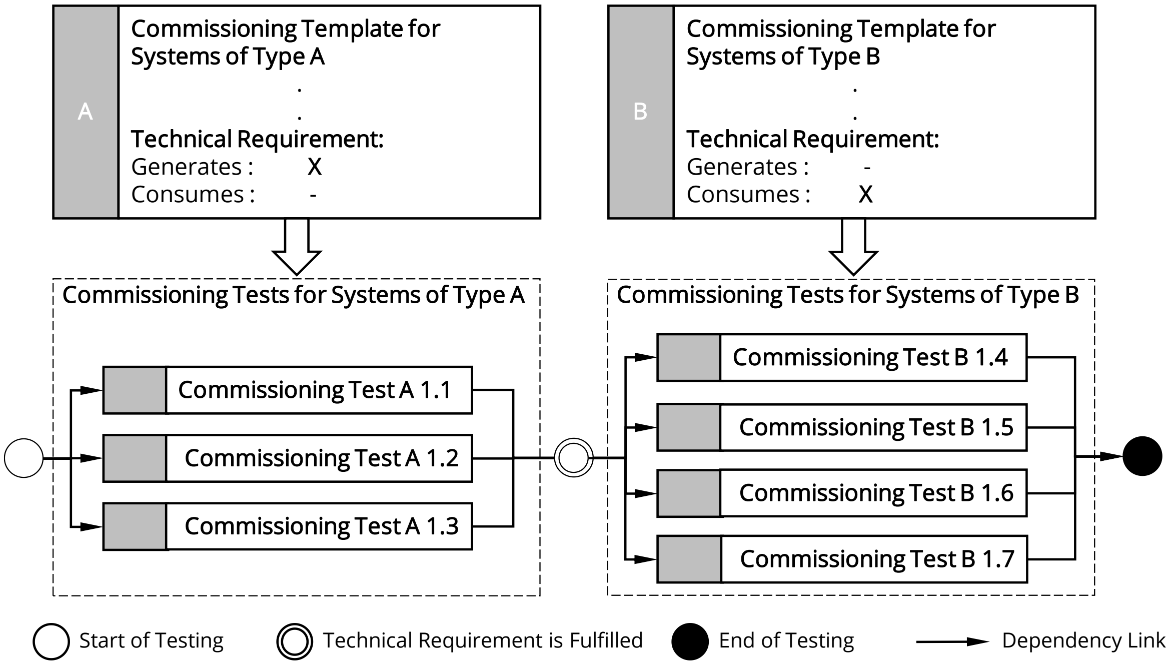


Figure 44: Using commissioning templates for technical requirement dependencies

Figure 44 shows two commissioning templates used to generate commissioning tests for two systems (A and B) aboard the ship. The template for system A includes a *technical requirement property* indicating that all tests generated from this template will inherit the property and be designated as resource X generators. In contrast, the system B template generates tests that utilize resource X. Using this approach, it is no longer necessary to iterate through all tests of systems A and B and assign them the technical requirement property. Figure 44 demonstrates that system A's commissioning tests must be completed before the tests of system B can begin.

However, this approach is not entirely effective since that the tests generated from the templates are for all systems of type A and B on the ship, and in reality, not all commissioning tests of system B depend on tests of system A. For instance, if system A is a power supply and system B is a pressure sensor, it is reasonable to expect that sensors on the ship are not all connected to the same power supply. Therefore, the approach of defining technical requirements using templates must be modified to account for the physical connections between the ship's systems.

Physical System Connections for Generating Realistic Dependency Links

Dependency links are visualized as edges in the directed graph topology, which determines the implementation sequence of commissioning tests. Figure 44's dependency graph, which is generated solely from the technical requirements, is unrealistic and must therefore be modified by removing irrelevant edges in the graph. A common technique for removing edges from a directed graph is referred to as *graph pruning*. To prune a graph, additional information is required to determine which edges are irrelevant. In the case of technical dependencies, this information can be obtained from documents that describe physical connections between systems in the ship, such as *cable lists*.

The shipyards use cable lists to identify all of the ship's cables, including their length, insulation type, cross-sectional area, and connected systems and components. Using the information regarding the systems connected by the cables, the algorithm for graph generation retains only the edges representing the physical connections between the systems; consequently, the commissioning tests can be organized in a more realistic sequence, as illustrated in Figure 45.

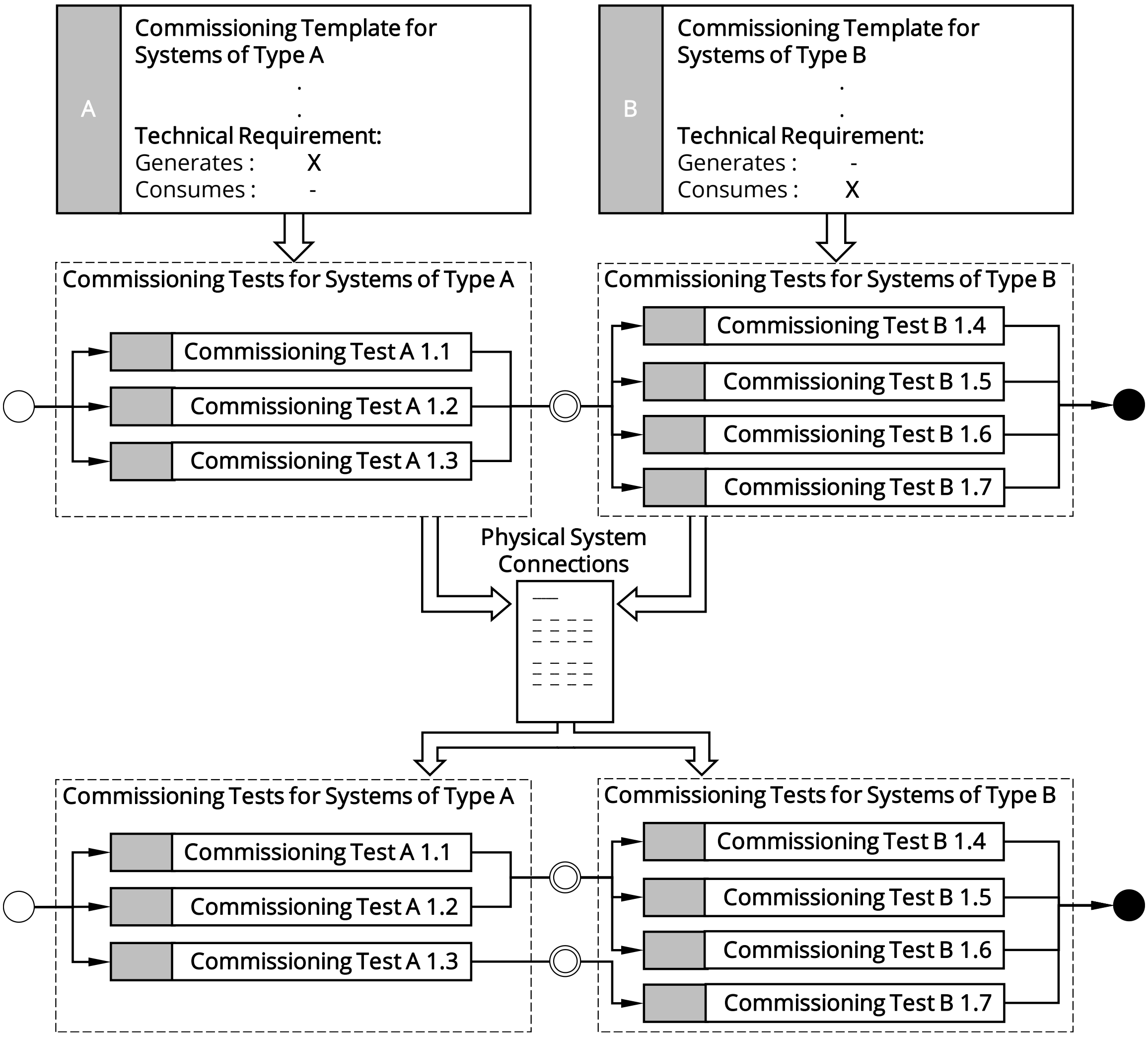


Figure 45: Considering physical system connections for generating realistic dependency links

Figure 45 illustrates a revised procedure for creating accurate dependency links by utilizing commissioning templates and taking into account the physical connections between the systems. Initially, the dependency links are created as previously demonstrated by Figure 44. Subsequently, the links are inspected in relation to a cable list to determine the edges that do not correspond to tangible physical connections between the systems. Finally, the edges are removed and the final dependency graph is produced, as depicted in Figure 45.

6.3.4 Generalization of Dependency Rules

The approach described in Section 6.3.3 is useful for constructing dependency graphs in situations where the implementation sequence of commissioning tests relies on the availability of specific technical resources. Nevertheless, the availability of technical resources is not the only event that creates a technical dependency. Therefore, a more global concept to address technical dependencies that arise not solely from technical resources is required.

This section provides a detailed explanation of a comprehensive concept referred to as the *dependency stack*. The objective of this concept is to facilitate the creation of dependency graphs in a time and resource-efficient manner, irrespective of the specific rules governing the interdependencies of commissioning tests.

Overview of the Dependency Stack Concept

As previously mentioned, the process of iterating through all commissioning tests and manually constructing the dependency graph is not feasible. Alternatively, it is more practical to provide the user with the ability to create a set of rules that an algorithm can employ for automatic generation of the dependency graph. One such approach could involve a programmatic framework that enables users to manually write queries for the purpose of establishing dependency rules. Nevertheless, this approach is not user-friendly and necessitates a significant investment of time and effort for adoption. Therefore, it is required to provide users with the ability to establish dependency rules through a user-friendly interface.

Allowing users to create dependency rules through a graphical user interface is similar to *visual programming*, a commonly employed method to simplify programming tasks for users who may lack programming expertise. Visual programming enables users to generate visual scripts that define operations and sequences by utilizing geometric shapes and objects [Davi11, P. 361].

Based on the principles of visual programming, the concept of the *dependency stack* has been developed. The dependency stack allows users to add and rearrange different elements inside a container or a *stack*. Each element in the stack represents a set of commissioning tests. The arrangement and the sequence of these elements in the stack determines the dependency rules between the commissioning tests represented by the elements. Figure 46 illustrates the types of elements included in the dependency stack and their respective contents.

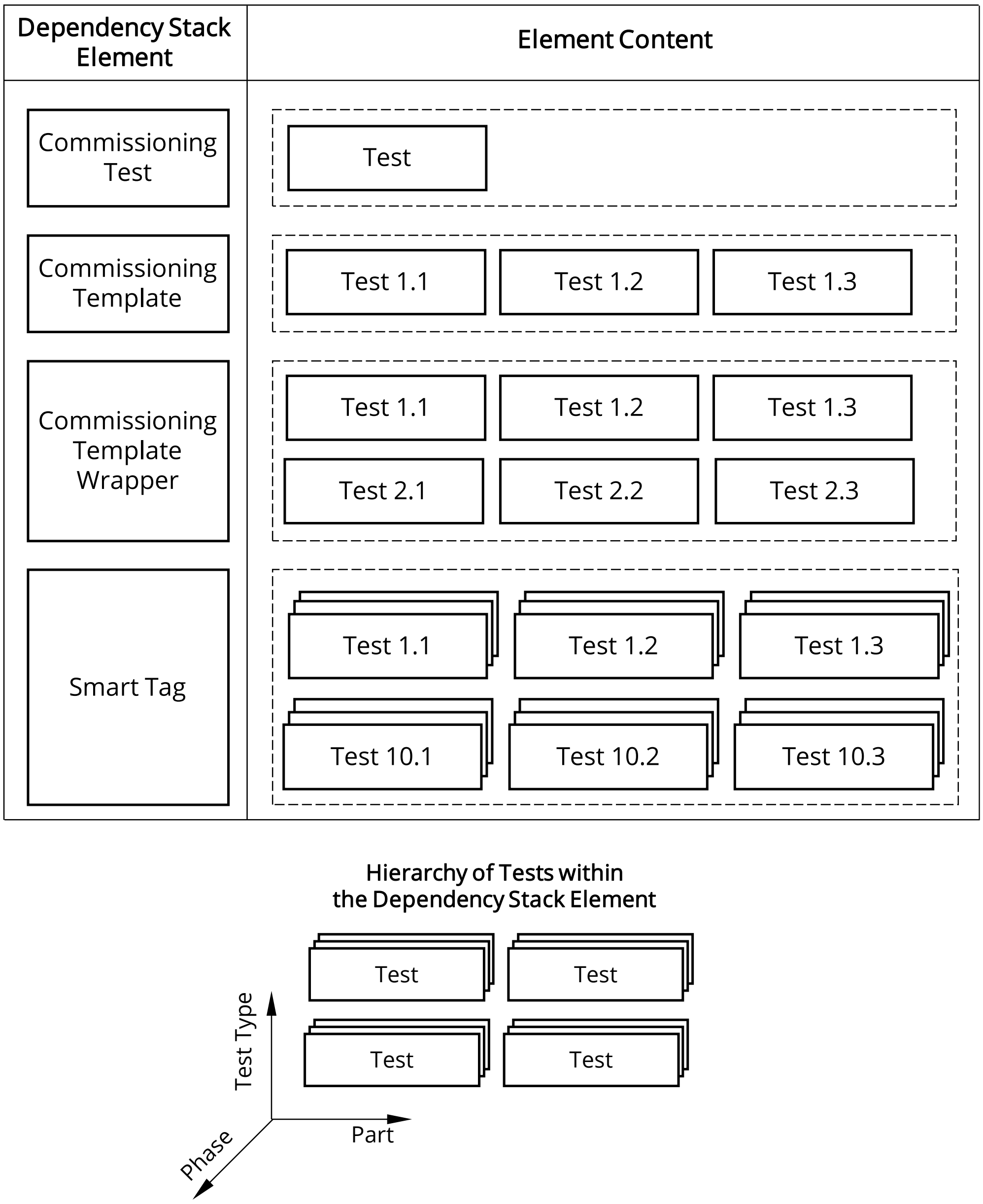


Figure 46: Elements of the dependency stack

The dependency stack consists of the four elements depicted in Figure 46 arranged sequentially. The user can combine various types of elements in the stack to define dependency rules. A stack element could be any of the following:

- **Commissioning Test:** this is the simplest type of elements that consists solely of an individual commissioning test. The user can drag and drop a specific commissioning test into the dependency stack to signify that it is a component of a dependency graph.
- **Commissioning Template:** this element contains all tests generated for all components and systems using a particular commissioning template. This element is required, for instance, when it is necessary to indicate that functional tests of a

particular class of components must be performed prior to signal tests of the same class of components.

- **Commissioning Template Wrapper:** a template wrapper element is used to position the commissioning tests generated for a class of components in a particular order without regard to the testing phases' defined sequence.
- **Smart Tag:** this is the most inclusive element in the dependency stack, used to include all commissioning tests generated for a class of components, including testing phases.

To demonstrate how the dependency stack is used, Figure 47 shows the resulting dependency graph from a dependency stack which contains four elements arranged in series.

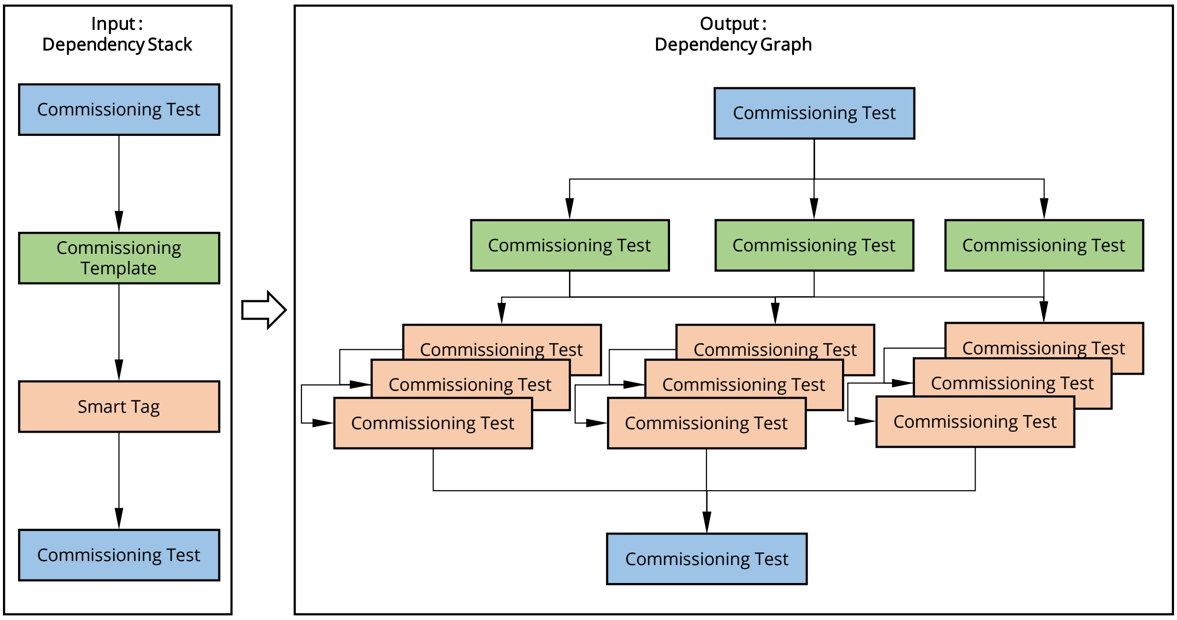


Figure 47: Dependency graph output

In Figure 47, it is shown that the user constructs a dependency stack on the left by stacking elements beginning with a specific commissioning test (blue), then a template (green), then a Smart Tag element (orange), and concluding with another specific commissioning test (blue). The dependency graph depicted on the right-hand side of Figure 47 illustrates the outcome of applying the rule established by the dependency stack to the commissioning tests associated with the elements within the dependency stack.

It is obvious that the effort invested by the user to create the dependency stack on the left-hand side of Figure 47 is much less than the effort required to create all the dependency links for every individual commissioning test. This effort reduction is possible due to the utilization of the *commissioning template* concept introduced in Section 6.2.4.

6.3.5 Process of Automatically Generating and Visualizing Testing Sequences

This section demonstrates the process of automatic generation of testing sequences and discusses the information visualization capabilities of the authoring assistant. Automatically generating testing sequences requires the following three steps:

1. Importing documents pertaining to physical part dependencies.
2. Creation of dependency rules based on technical requirements.
3. Creation of generalized dependency rules using the dependency stacks.

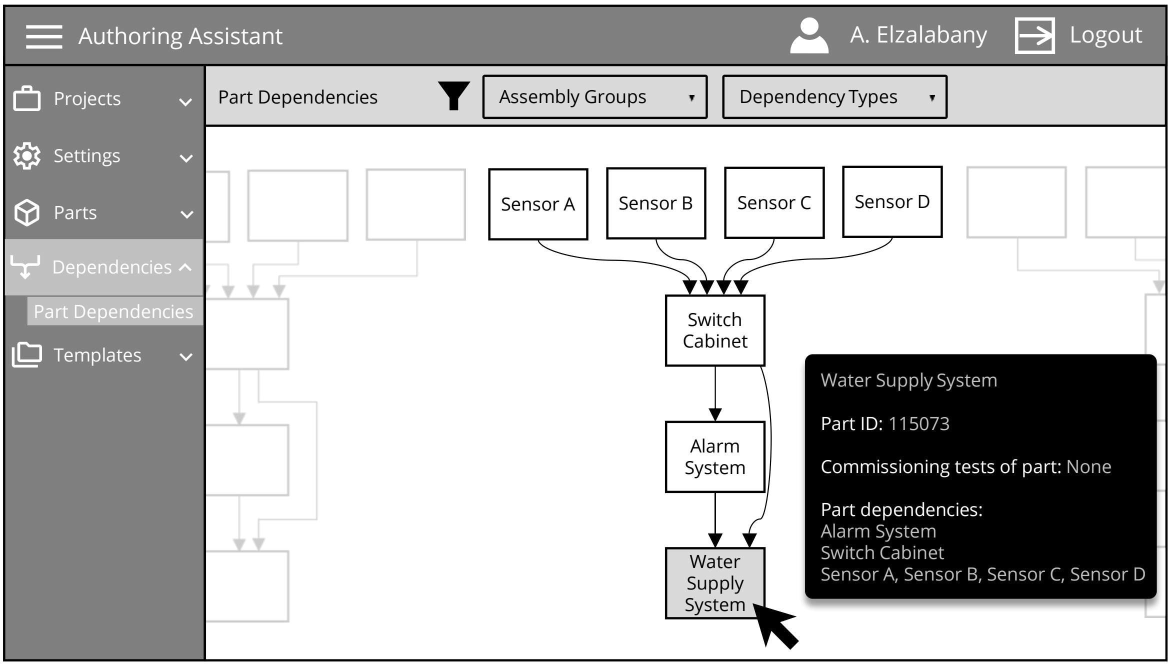
Importing Physical Part Dependency Documents

For the authoring assistant to be able to generate testing sequences based on physical part dependencies, the user must upload documents, e.g., cable lists, that pertain to the dependencies of the physical parts and systems on the ship (refer to Section 6.2.3). The authoring assistant uses this data to automatically construct links between the ship's systems and parts that are physically connected.

Figure 48 shows a schematic design of the authoring assistant user interface for physical part dependencies. The user interface of the authoring assistant is designed according to the principles of Shneiderman (see Section 6.1.1) as follows:

- **Overview**: offering the user a concise zoomed-out overview of all parts and systems in the ship, along with their physical connections. The parts and systems are represented as *nodes* in a directed graph topology, and the physical connections between the parts are represented as *arrows*.
- **Zoom and filter**: enabling the user to zoom-in and out on specific parts and systems and filter them based on criteria such as *assembly groups* and *dependency types*.
- **Details-on-demand**: offering comprehensive details on each part and system upon user request through mouse clicks.

Figure 48 illustrates the user's action of clicking a node that represents a system named *Water Supply System*. Upon clicking the system’s node, all non-relevant parts and systems are hidden from the overview. Moreover, by clicking the node, the user is provided with comprehensive information regarding the *Water Supply System*. This information is valuable for examining the commissioning tests linked with the system, as well as understanding its dependencies. Such functionalities are necessary for reviewing and editing the information imported from the PLM and ERP systems of the shipyard.



Water Supply System

Part ID: 115073

Commissioning tests of part: None

Part dependencies:
Alarm System
Switch Cabinet
Sensor A, Sensor B, Sensor C, Sensor D

Figure 48: Physical part dependencies

Creation of Technical Requirement Dependencies

In order for the user to create commissioning test dependencies according to technical requirements, the user must define global entities in the commissioning project managed by the authoring assistant. These entities correspond to the technical requirements or resources to be generated or consumed by commissioning tests. To demonstrate, the user may need, for example, two technical resources in the project, namely *light* and *power*. The user must designate commissioning templates in the project as generators or consumers of these resources.

Once the commissioning templates have been created and the commissioning tests have been generated, the user may arrange all the resulting commissioning tests in a dependency graph based on the technical dependencies and part connections. Figure 49 illustrates a schematic representation of the authoring assistant's UI, demonstrating the arrangement of commissioning tests in a dependency graph based on the pre-established technical requirements for *light* and *power*. The user interface adheres to the design principles that were mentioned in the preceding subsection.

Figure 49 illustrates two technical resources, specifically light and power, represented as oval nodes. The *power* resource is generated after the successful completion of test 1.1, while the *light* resource is generated after the successful completion of test 1.2. Conversely, tests 3.1, 3.2, and 3.3 require the availability of *power*, while tests 3.4 and 3.5 require *light* to start. An algorithm utilizes this data to establish the connections between the nodes, resulting in the development of a directed graph that represents the dependencies shown in Figure 49.

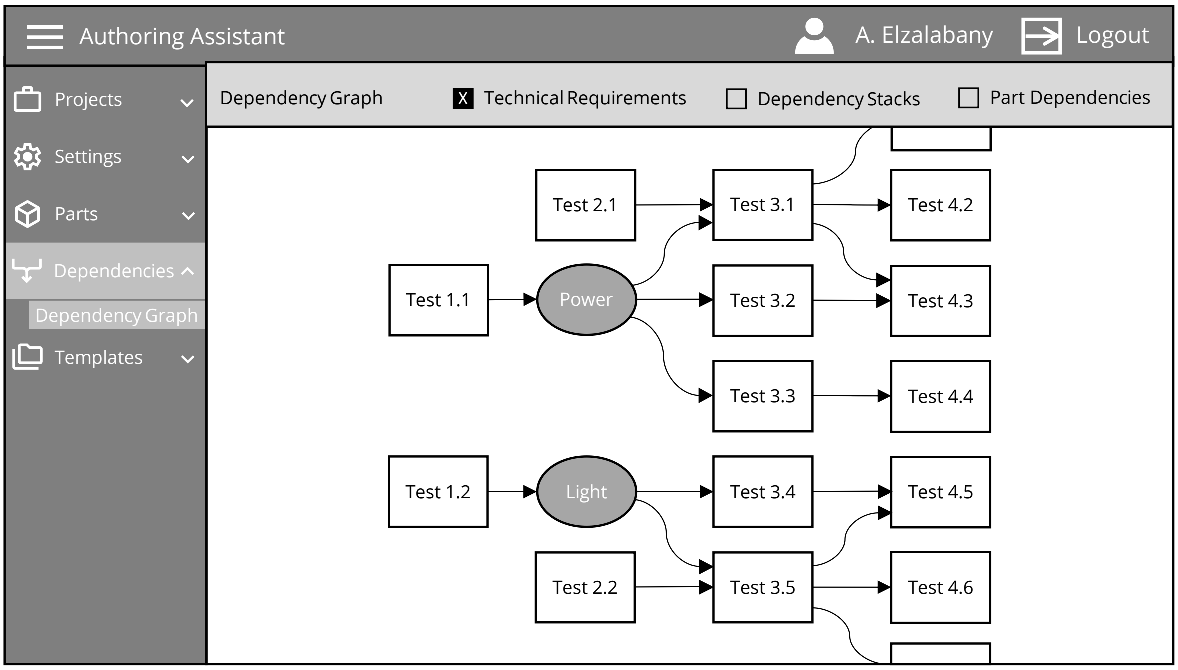


Figure 49: Commissioning tests arranged in a dependency graph

Creation and Merging of Dependency Stacks

The *dependency stacks* approach aims to provide the user with a programmatic user-friendly workflow for creating generalized dependency rules (Section 6.3.4 explains the technical details). This approach is necessary when dealing with complex dependency links between a large number of commissioning tests. As a result, the workflow and the user interface of the dependency stacks must be intuitive.

In order to create a user interface and workflow that is easy to understand and learn, the user interface was designed based on the principles of Shneiderman (see Section 6.1.1). Accordingly, the user is provided with lists that can be *filtered* to facilitate retrieving all the items necessary for creating the dependency rules. The contents of the items in the lists remain hidden until they are added to the dependency stack (*details on demand*). After the user places the item in the dependency stack, via drag and drop, a result representing a dependency rule is immediately shown.

For better demonstration, Figure 50 depicts a schematic representation of the interface of the authoring assistant that is utilized for the creation of dependency stacks. The figure shows that the user initiates the dependency stack creation by adding a *commissioning template* item (Generator FUNCTIONAL) that encompasses four tests for the ship's *generator* systems. The subsequent item in the dependency stack is a *Smart Tag* labeled as *Temp Sensor*. This Smart Tag encompasses all the tests that have been generated for the temperature sensors present on the ship, including the test variants previously generated for the different phases of commissioning, e.g., FAT, HAT, and SAT.

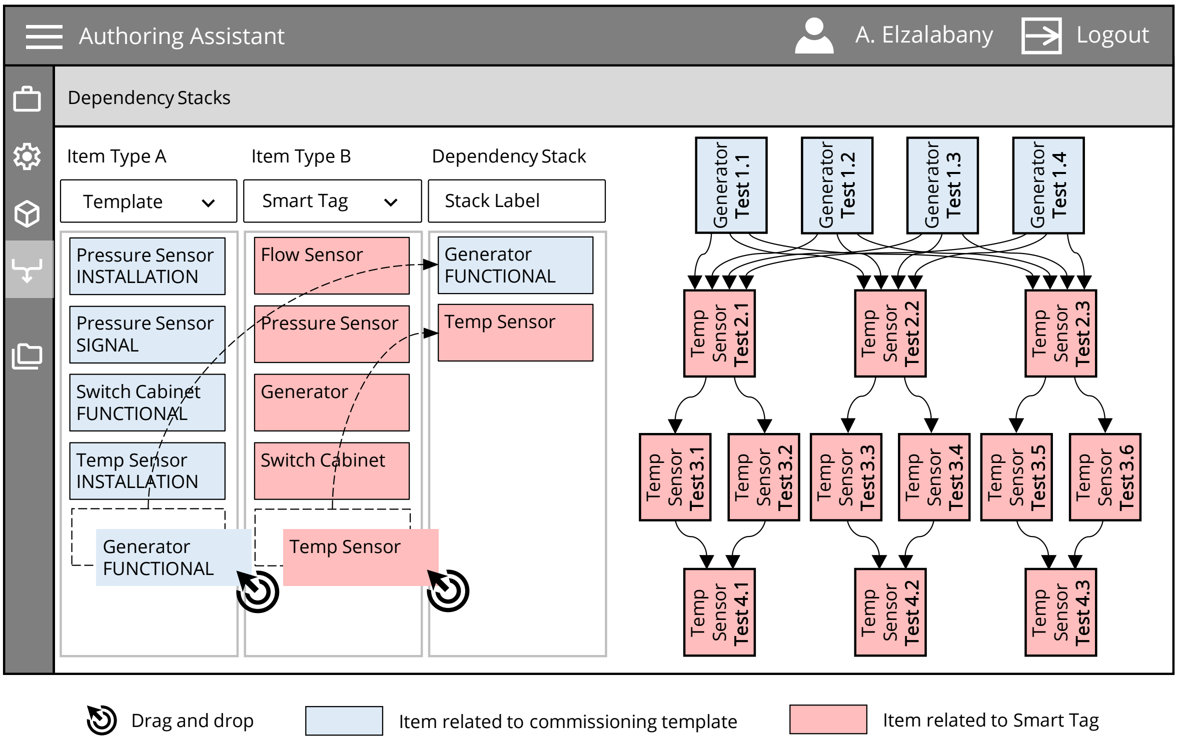


Figure 50: Dependency stack creation using the authoring assistant

The outcome is promptly shown to the user on the right side, where the user may observe all commissioning tests associated with the stack items. The dependency links and the execution sequence of the commissioning tests are automatically generated based on how the items are arranged in the stack (see Section 6.3.4).

Once the user has completed the building of a dependency stack, they can designate the stack with a label and store it in the commissioning project. According to the information provided in Section 6.3.4, a dependency stack can be understood as a *visual programming* method for creating dependency rules. The user must have the ability to create multiple stacks to accommodate different rules. Consequently, a functionality was developed to enable the authoring assistant to combine all the stacks and produce a comprehensive dependency graph that encompasses all the rules set by the user, as depicted in Appendix A.

The figure shown in Appendix A is an actual screenshot from the authoring assistant which depicts the result of generating a dependency graph based on the rules established by the user through the creation of dependency stacks and technical requirements. It is worth noting that the screenshot comprises 96 commissioning tests generated from only 9 templates. Also, the dependency links required the creation of only 9 simple dependency stacks. Consequently, it is evident that the authoring assistant offers the user a more effective method for autonomously generating dependency graphs that can be used to determine a viable testing sequence.

6.3.6 Discussion

The solution for dependency management, presented in Section 6.3, is developed to fulfill the specifications of requirement *P2* for *considering technical dependencies in the commissioning plan* (see Section 4.2.2). The primary objective of this solution is to enable the commissioning authority to create viable execution sequences for executing the commissioning tests, taking into account technical dependency constraints. This section provides a discussion of the solution for dependency management, focusing on its qualitative benefits and limitations.

Benefits

The use of standardized data models allows the Digital Twin to perform complex calculations and execute algorithms to generate and visualize sequences for conducting commissioning tests. It is not possible to define such sequences in the conventional workflow due to the usage of generic software applications like Microsoft Word and Excel to create the commissioning plan. The DAS-based dependency management solution provides a user-friendly interface for the commissioning authority to monitor the complex connections between ship components. Additionally, it grants the commissioning authority the capability to automatically create dependency links between commissioning tests based on different criteria, such as the availability of technical resources. By implementing this solution, it is anticipated that the time and effort dedicated to planning and searching for suitable and viable commissioning tasks will be reduced. Additionally, this approach can be beneficial for monitoring the advancement of commissioning work and identifying errors that arise from incorrect testing sequences.

Limitations

To generate testing sequences that align with technical requirements and relationships among ship components, it is necessary to have well-organized data derived from the shipyard's PLM system. If such data is not available, the DAS is unable to automatically generate dependency links according to the technical requirements. However, to address this limitation, the authoring assistant for dependency management provides a functionality for programmatically generating general dependency rules (see Section 6.3.4).

6.4 Commissioning Assistant for Implementation and Documentation

Based on *Requirements I1, I2, D1 - D3*, the DAS must enhance both implementation and documentation processes. The objectives can be achieved by reducing the effort and time required for information acquisition and submission of testing data. Furthermore, the utilization of a *context-aware* assistance system can effectively decrease the occurrence of conflicts, disruptions, and mistakes that arise from the dependence on traditional approaches for commissioning implementation and communication of issues. Moreover, the use of a Digital Twin can improve the documentation process through automated capturing of testing data.

This section begins with an overview of the mobile assistance system for commissioning implementation and documentation and subsequently examines the primary features and tools developed within the system to meet the requirements previously discussed in Sections 4.2.3 and 4.2.4.

6.4.1 Technology and Features of the Commissioning Assistant

The DAS incorporates a software solution that facilitates the process of commissioning implementation and documentation. The solution, designated as the *commissioning assistant,* runs on a hand-held device to be usable within the mobile work environment of the commissioning team, which requires the team to be able to move freely within the shipbuilding site. The primary features of the commissioning assistant involve the retrieval of tasks outlined in the commissioning plan and the documentation of the outcomes resulting from the execution of these tasks.

Choice of Technology for Developing the Commissioning Assistant

Given that the commissioning assistant is an integral component of the DAS for commissioning, it should be connected to the same network infrastructure that the DAS operates on. To facilitate the data exchange between the commissioning assistant and the authoring assistant, it would be advantageous to use the same data structures that were developed for the authoring assistant. Furthermore, it is important that the commissioning assistant functions on a hand-held device that facilitates the user's mobility.

On the basis of the aforementioned requirements, it is clear that the commissioning assistant should be developed using the same technology as the authoring assistant. Therefore, a multiple-criteria decision analysis is unnecessary for deciding on the technology for developing the commissioning assistant. As a result, it was determined that the commissioning assistant would be a web application that runs on a hand-held device such as a smartphone or a tablet. However, tablets are more advantageous than smartphones when it comes to data visualization and complex interactions, such as the presentation of 3D CAD models and 2D illustrations.

General Features of the Commissioning Assistant

The *commissioning team* is the primary user group of the commissioning assistant. The user begins the workflow by retrieving the most suitable tasks created by the authoring assistant based on different criteria such as user qualification, resource availability, schedule, and feasibility of testing. After task retrieval, the user can begin implementing the commissioning tests and finally document the outcome of testing. Figure 51 provides a concise overview of the general features of the commissioning assistant and references the corresponding sections in this chapter that provide detailed explanations of each feature.

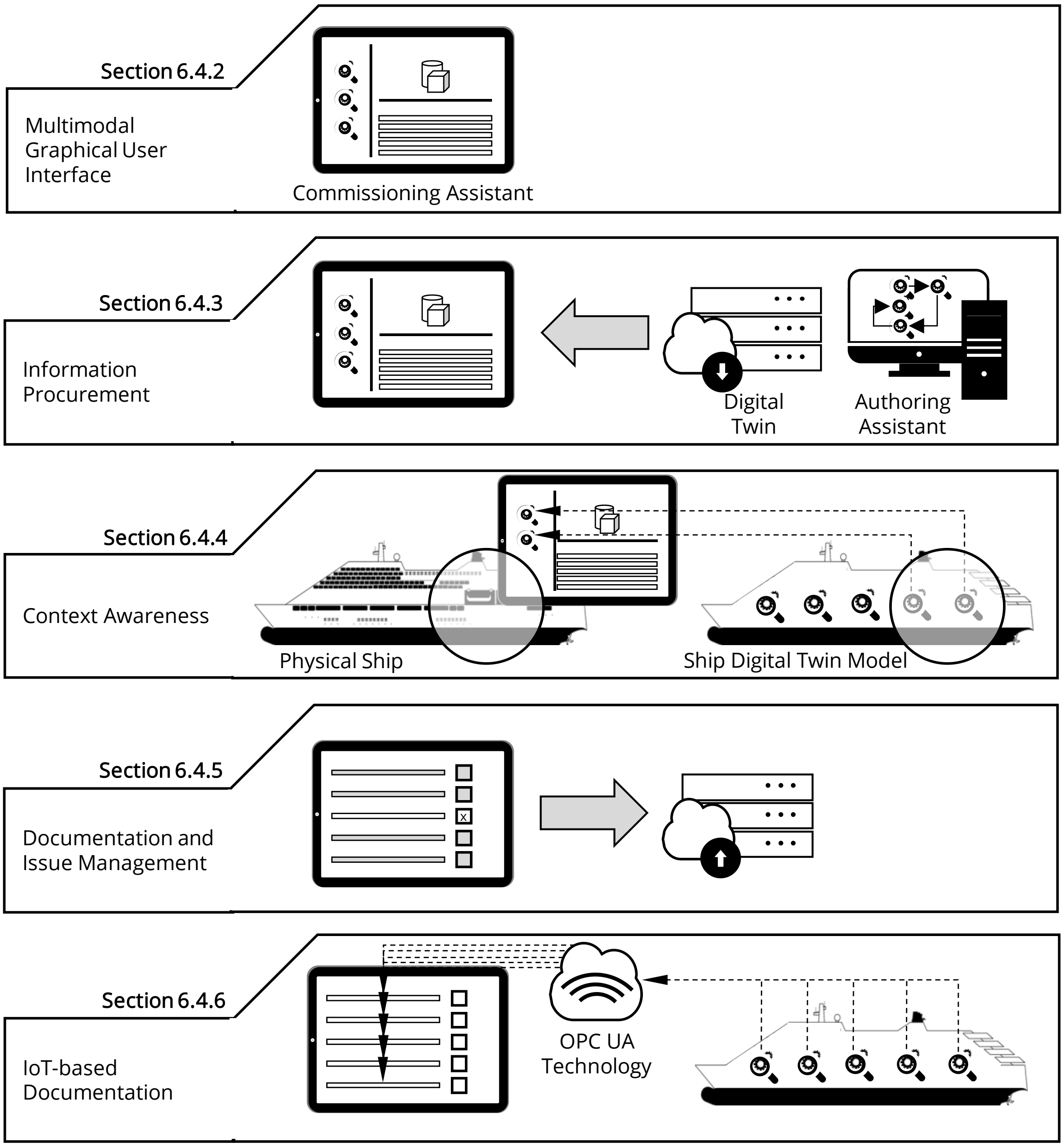


Figure 51: General features of the commissioning assistant

6.4.2 Multimodal Graphical User Interface

To achieve high usability and user-friendliness, the commissioning assistant presents its content via a graphical user interface (GUI), offering users access to textual information, 2D graphics, and 3D models. Hence, the graphical user interface (GUI) of the commissioning assistant exhibits multimodal characteristics. A multimodal GUI should be properly designed in order to mitigate the potential occurrence of attention-related problems that may arise as a result of frequent transitions between different media and sources of information. This criterion holds particular relevance as the user of the commissioning assistant operates in a dynamic environment with several sources of stimuli. Consequently, it is imperative that the interface of the commissioning assistant be carefully designed to enhance the user's productivity.

In his dissertation, Halata divides the user interface of his DAS into two primary sections for *visualization* and *process* [Hala18, P. 63]. The visualization section contains all spatial and geometrical information relevant for the work such as 3D models. While the process section contains all the work steps arranged in a sequential order which allows the user to transition through the work steps seamlessly without additional effort of manual search.

The Halata model can be utilized in the design of a commissioning assistant. This is because the user of the commissioning assistant is required to engage with 2D and 3D media in order to accurately identify and locate the systems aboard the ship that need to be tested. In addition, using the commissioning assistant involves the execution of testing procedures by carrying out a sequence of tasks, i.e., the commissioning tests. In other words, the user interactions with the commissioning assistant are similar to those of the Halata’s DAS. Figure 52 shows a preliminary design concept of the commissioning assistant based on the model of Halata.

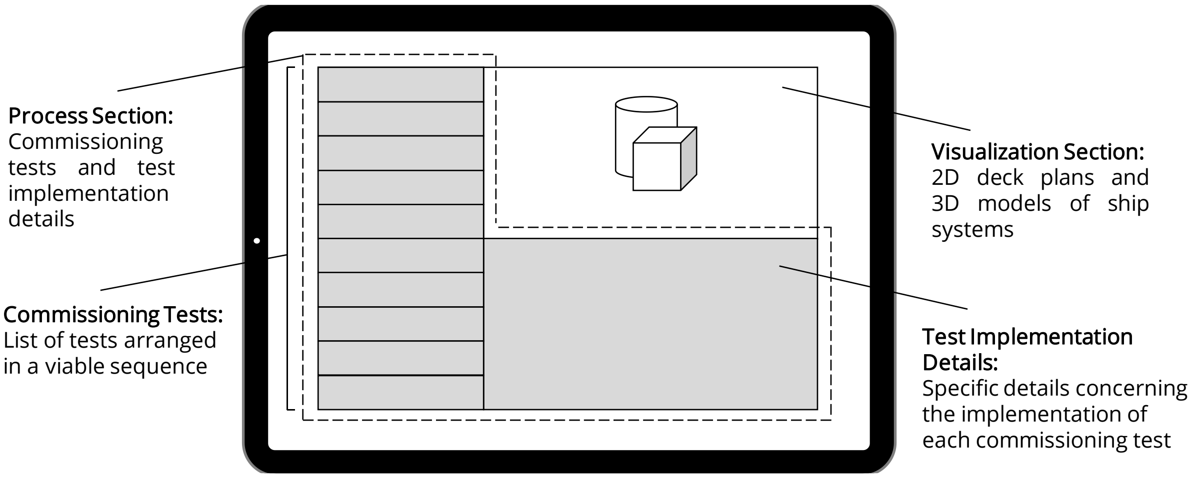


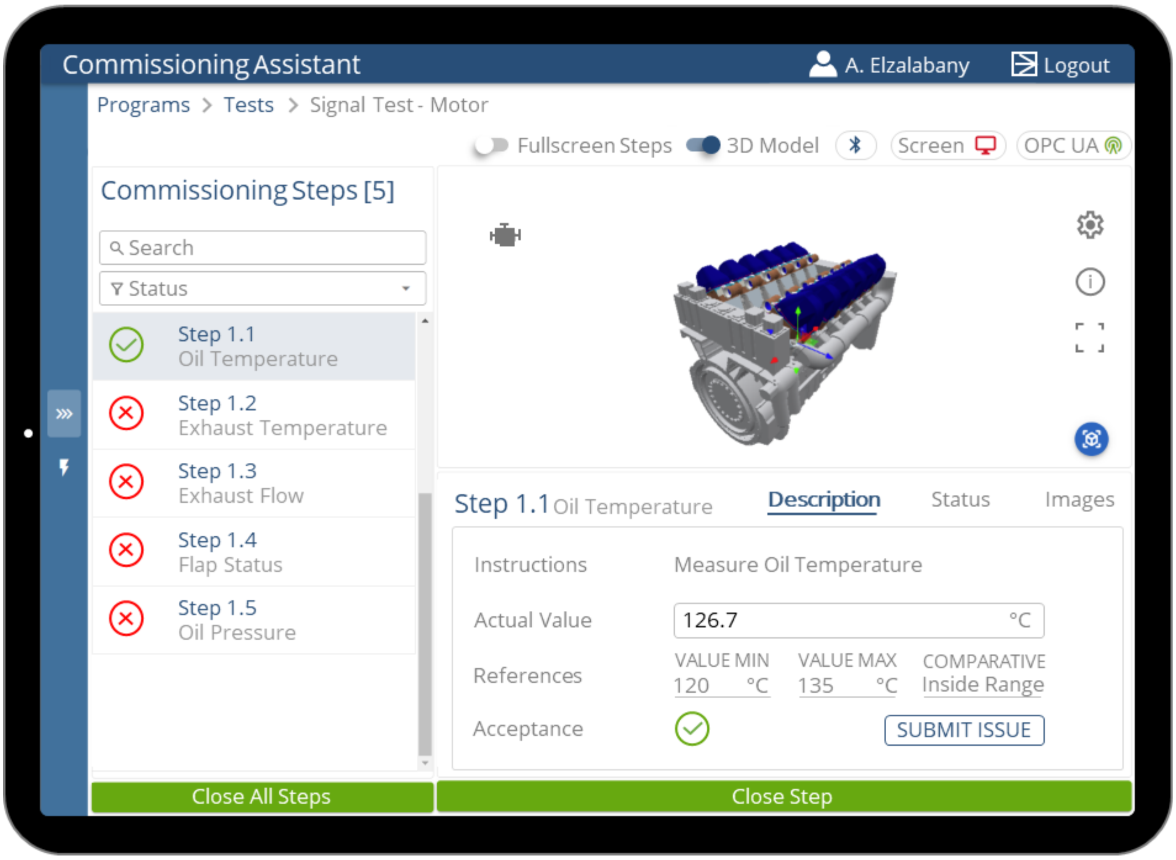
Figure 52: Graphical user interface design of the commissioning assistant

Figure 52 shows that the commissioning assistant interface consists of two primary sections:

- **Process Section:** this section contains a list of the commissioning tests transferred from the Digital Twin database to the commissioning assistant. The tests are arranged in the list in accordance with the sequence previously specified using the authoring assistant. In addition, each commissioning test in the list can be expanded to reveal specific details for carrying out the selected commissioning test.

- **Visualization Section:** this section can be toggled to display either a 2D deck plan corresponding to the location on the ship where the selected commissioning test should be executed, or a 3D model of the system to be tested.

The actual user interface of the commissioning assistant is shown in Figure 53.



Instructions: Measure Oil Temperature

Actual Value: 126.7 °C

References: VALUE MIN 120 °C, VALUE MAX 135 °C, COMPARATIVE Inside Range

Acceptance: ✓

Figure 53: Screenshot of the primary page of the commissioning assistant [3]

Figure 53 illustrates the main page, which serves as the primary area of activity for the commissioning team throughout the processes of implementation and documentation. The screenshot displays five *commissioning steps* that are presented on the left-hand side of the screen. These steps are part of a commissioning test for the motor, which is visually represented by a 3D model located on the right-hand side of the screen. The 3D model is required to facilitate the localization of specific parts in the system being tested.

According to the guidelines of Shneiderman for *information seeking* (see Section 6.1.1), it is more productive to present details to the user upon request. This notion is applied in the design of the commissioning assistant GUI by enabling user to select a step and view its

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[3] The 3D model used in the screenshot of the commissioning assistant (Figure 53) is designed by MAN Energy Solutions [MAN 23].

details in the bottom right corner section. The details section provides the user with a textual description and other fields to input values corresponding to the readings acquired during testing.

In the case of issues or deviations detected during the testing process, the user can report such issues by clicking the button labeled as *submit issue*. To generate digital documentation, the user can designate a step as *closed* by pressing the green button located at the bottom of the screen, which signifies that the step is complete without any issues. The user is also able to close all steps simultaneously, if needed. These functionalities are discussed in detail in the following sections. Additionally, the commissioning assistant GUI encompasses other pages that are required for functionalities such as user authentication, document visualization, and image capturing.

6.4.3 Information Procurement and Visualization

This section discusses the functionalities developed for the mobile assistance system to satisfy requirement I2 for efficient information procurement and visualization.

Information Procurement

Using the commissioning assistant, the commissioning team should not need to spend time manually gathering information and documents relevant for commissioning implementation. For this reason, the commissioning assistant uses a *filtering* mechanism to recommend work packages for the user based on different factors. Figure 54 shows a simplified BPMN diagram for the process of information procurement using the commissioning assistant.

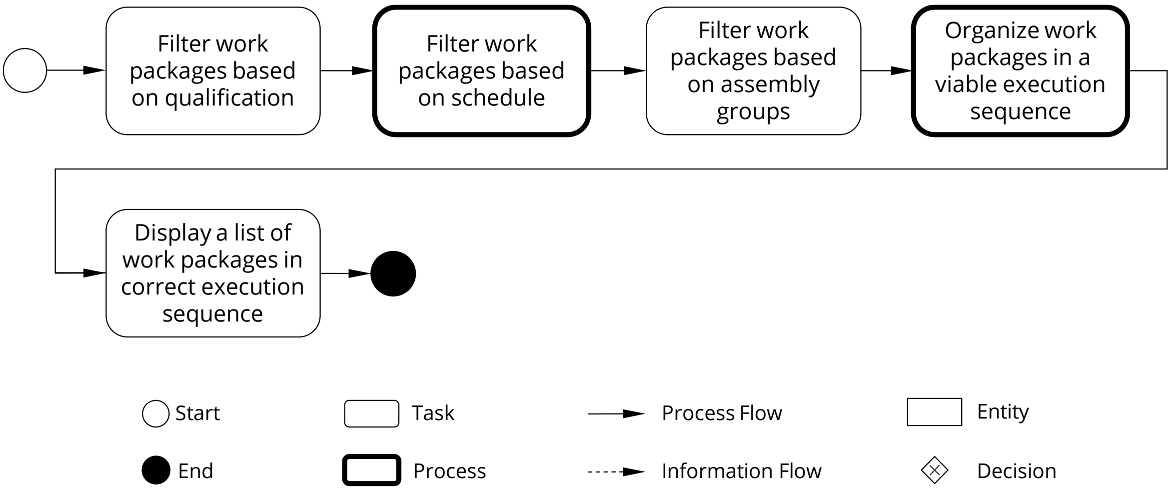


Figure 54: Information procurement process using the commissioning assistant

According to Figure 54, the commissioning assistant begins the information procurement process by filtering the available work packages according to the qualification required for test implementation. Beginning with this criterion for filtering speeds up the search process. The user is given the option to select and acquire work packages specifically tailored for their specialization, e.g., *electrical* or *mechanical* engineering. It is also worth mentioning that the commissioning assistant can automate this step by directly filtering the work packages based on the information stored in the commissioning assistant user profile.

The second step in the process of information procurement involves the application of a filtering mechanism to the work packages, with the purpose of determining their suitability based on timetable considerations, such as milestones and deadlines. As stated before, the topic of scheduling falls outside the scope of this dissertation. For more elaboration, the reader can consult the publication of Köster [Köst23].

The third step in the information procurement process is filtering the work packages based on the assembly groups. The user can choose to manually search for a specific work package linked to one or multiple assembly groups. This step can be automated by the commissioning assistant using *context-awareness* as discussed in Section 6.4.4.

After having filtered the work packages in accordance with the assembly groups, the commissioning assistant then communicates with the Digital Twin by placing a request to arrange the filtered work packages and their content in a sequence based on the technical dependencies that were defined using the authoring assistant. Finally, the user can start carrying out the activities outlined in the work packages.

Information Visualization

The work activities of the commissioning assistant adhere to a hierarchical structure that closely resembles that of the conventional commissioning plan. This structure is adopted for several reasons, such as facilitating the transition from the conventional approach to the DAS and reducing the time required to acquire proficiency in the new system. In the context of the commissioning assistant, a work package is the highest level in the hierarchy and consists of a set of commissioning tests that are applicable to a particular assembly group or system. The second level of the hierarchy is the commissioning test, which has multiple steps. This is especially true when the test requires the completion of a complex activity that can be broken down into separate steps.

Figure 55 displays the hierarchical structure of the information within a work package and the user interface within the commissioning assistant. The user interface is designed based on Shneiderman's principles (see Section 6.1.1), utilizing a list format to provide users with an *overview* of their work activities, including *work packages*, *commissioning tests*, and *steps*. Users can *filter* the work activities and engage with them by clicking on the item representing a work activity to display extra information (*details-on-demand*).

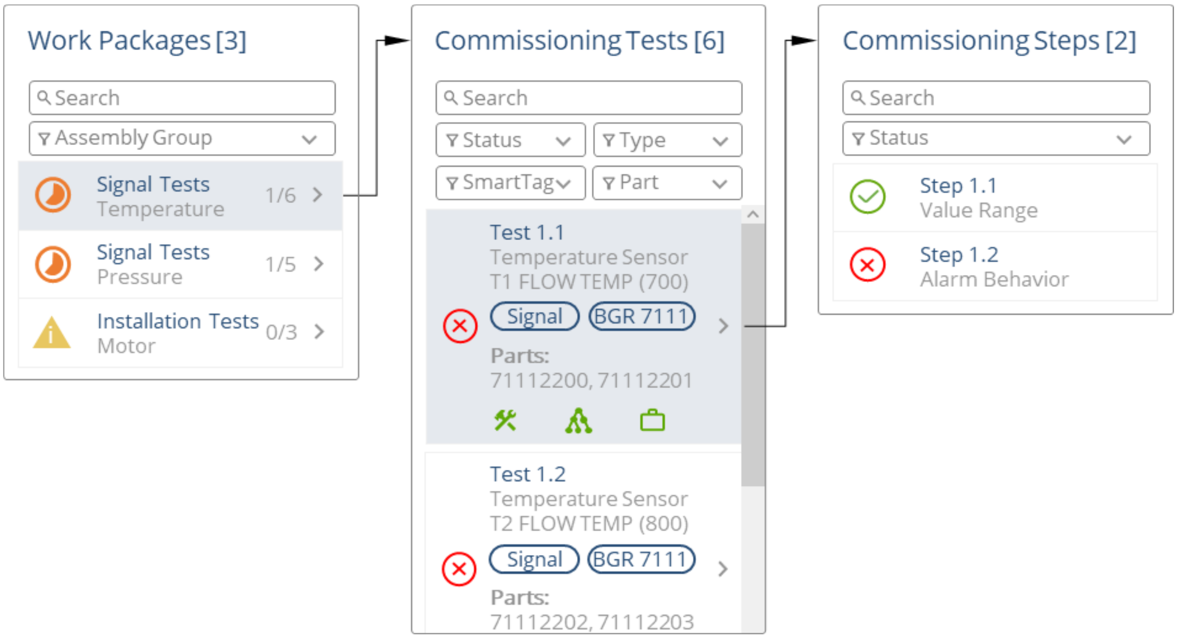


Figure 55: Hierarchy of work package content in the commissioning assistant

Throughout the commissioning implementation and documentation, the commissioning assistant user mostly engages with the lists of commissioning tests and steps, as these lists hold significant relevance for their technical tasks. Hence, it is crucial to carefully design the items in these lists in a manner that enhances the productivity of the user. The idea is to utilize the principle of *Spatial Contiguity* to design a graphical representation which minimizes the *split-attention effect* by placing graphical icons and text close to each other. Figure 56 displays a list of commissioning tests that are presented to the user of the commissioning assistant. To retrieve suitable work activities, users have the option to search the list for a specific test or apply a filter to view a subset of tests that align with specific parameters. The following are the filtering parameters:

- **Status:** this parameter provides users with the ability to choose whether they want to view tests that are now open, tests that are in progress, or tests that have already been closed.
- **Type:** this parameter is employed to filter the tests based on their respective types. For instance, a test may be categorized as an installation test, a function test, or a signal test.
- **Smart Tag:** enables users to apply filters to commissioning tests based on the classification of parts, defined using the Smart Tag property. As an illustration, the user may opt to display the tests exclusively relevant to temperature sensors in the currently selected assembly group.
- **Part:** the user can filter the tests according to the part ID. This can be useful, for example, if the user intends to review the results obtained after performing all the tests of a specific part.

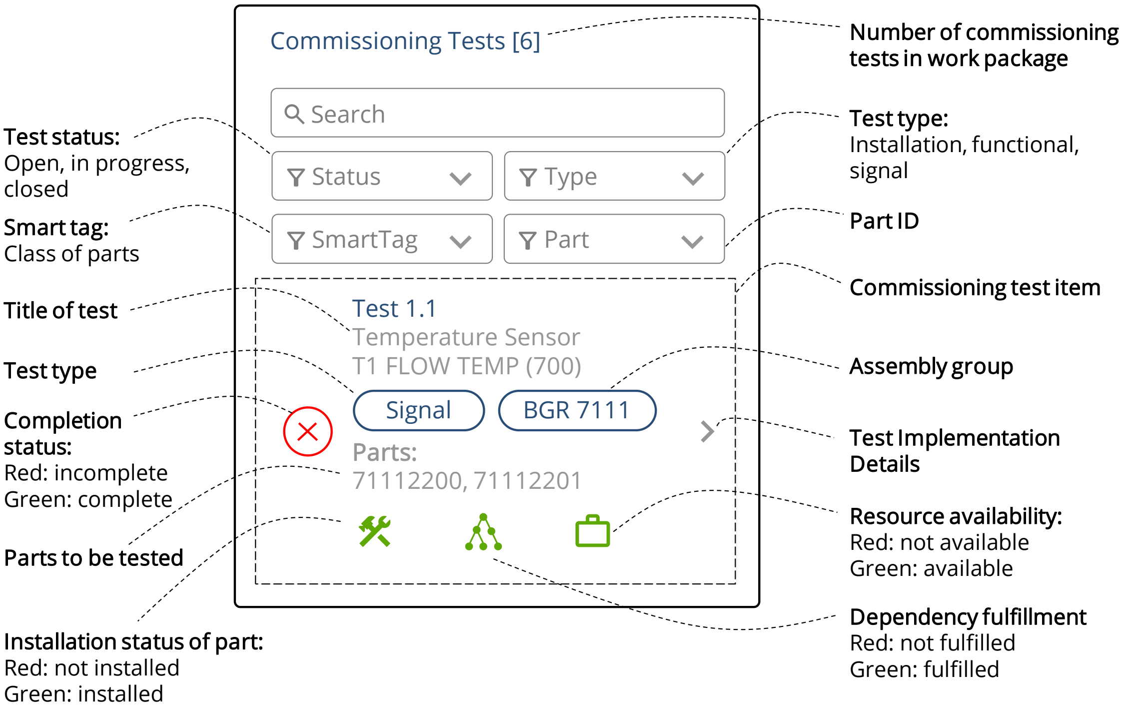
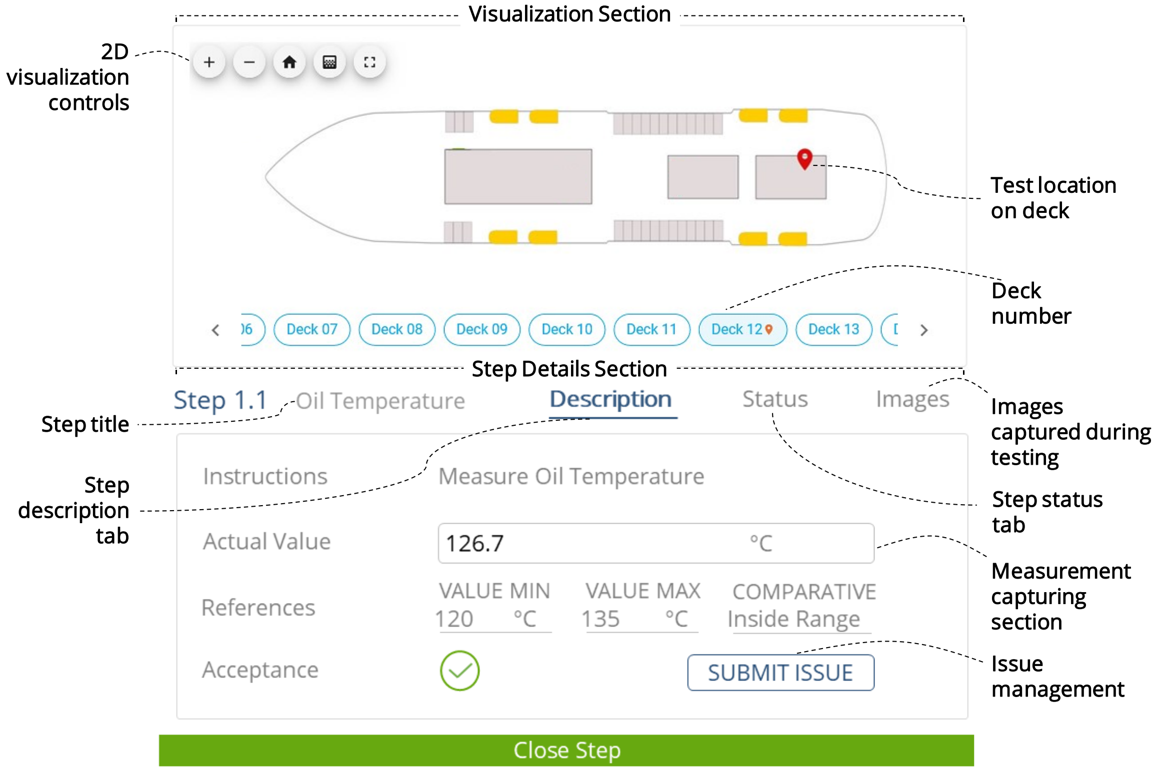


Figure 56: List of commissioning tests in the commissioning assistant

In the list, the commissioning test is represented as an element that contains consolidated information through short text or interactive icons. This representation allows users to quickly grasp an overview of the test element without having to click on it and go into the details. The provision of consolidated information in this manner has the potential to optimize user efficiency by minimizing time spent on information retrieval and mitigating attention-related issues associated with frequent navigation in the software (see the principles of Shneiderman in Section 6.1.1). The commissioning test element has a title text box that provides the user with information regarding the specific test type, the name of the part to be tested, and the signal or functionality that will be assessed. Additionally, the test element includes a symbol that signifies whether the test is open or closed, hence streamlining the user's workflow by eliminating the need to individually click on each test. Additionally, the test element comprises three icons that could take the colors green or red. The functionality of each icon is described as follows:

- **Installation status:** a green icon indicates that the part to be tested has been successfully installed. Which saves the commissioning team the time and effort to visit the site test to verify whether the part has been installed.
- **Dependency fulfillment:** a green icon indicates that all the dependencies associated with this test are fulfilled. Alternatively, if the icon is red, the user can highlight the icon to access information about the tests that must be executed prior to the selected test.
- **Tools and resources:** a green icon signifies that all required tools and resources for executing the test are currently accessible.

In contrast to the conventional method of using paper documents for commissioning, the utilization of a commissioning assistant should provide the commissioning team with structured information that facilitates the execution and documentation of testing procedures. Using the commissioning assistant, users are relieved from the task of manually searching through physical documents to obtain information pertaining to the testing location and expected outcomes. Therefore, it is necessary to provide localization and documentation functionalities in a user-friendly manner (see Figure 57).


Step 1.1 Oil Temperature

Instructions: Measure Oil Temperature

Actual Value: 126.7 °C

References: VALUE MIN 120 °C; VALUE MAX 135 °C; COMPARATIVE Inside Range

Acceptance: ✓

Figure 57: Step details user interface

The screenshot depicted in Figure 57 displays a cropped view of the commissioning assistant, wherein the user has chosen a step identified as *Step 1.1 Oil Temperature*.

An interface for 2D visualization is created to alleviate the user from the task of manually searching through the deck plans to locate the testing area. The upper section of the screenshot displays the 2D deck plan where the testing is planned to take place. The commissioning assistant automatically determines the exact location of the testing and presents it to the user on the deck plan using a *red pin* icon. To obtain detailed information, the user can modify the two-dimensional plan view using a range of controls that enable zooming in and out, displaying a default view, activating a heatmap view, and providing a full-screen representation of the deck plan.

The lower section of Figure 57 shows the interface for technical information related to the user-selected step. This interface enables users to easily access information regarding the assigned tasks and record the outcome of testing. By utilizing this interface, the process of decision making is made simpler as the user can input the measurement value obtained during testing, and the system automatically determines whether the measurement value meets the criteria of acceptability, which are also presented to the user. If the measurement value is deemed unacceptable, it is necessary to raise an issue. Section 6.4.6 provides a detailed explanation of the method of problem capturing.

6.4.4 Context Awareness for Installation Status and Conflict Detection

Due to the overlap between production and commissioning activities, the commissioning team spends significant time and effort searching for suitable work packages by first scouting the testing site of the potential work package (see Section 3.2.2). This is done to ensure that the systems to be tested are installed and that the site is free from disturbances, in order to avoid conflicts with production activities. As a result, *requirement I1* mandates that the DAS should employ *context-awareness* strategies to reduce time and effort by automatically determining the most suitable work packages. In other words, avoiding work packages that include systems and components that have not yet been installed or sites that are currently blocked due to production activities.

Installation Status Detection

The most fundamental prerequisite that must be met before a commissioning test for a system can be implemented is that the system must have already been installed aboard the ship. Consequently, the DAS must be able to filter work packages according to the installation status of systems and components, and intelligently display context-related work packages to the user via the commissioning assistant. Obviously, this case does not apply for FAT procedures where the systems are testing by subcontractors before being delivered to the shipyard. The process for filtering work packages based on installation status of systems is demonstrated in Figure 58 as a BPMN model.

As shown in Figure 58, the process of installation status detection encompasses three systems: the *commissioning assistant*, the *Digital Twin*, and a *DAS for production*. The commissioning team uses the commissioning assistant to initiate the information retrieving procedure. The commissioning team selects prospective work packages, and thereafter, the commissioning assistant interacts with the Digital Twin to inquire about the installation status of the parts and systems associated with the chosen work packages.

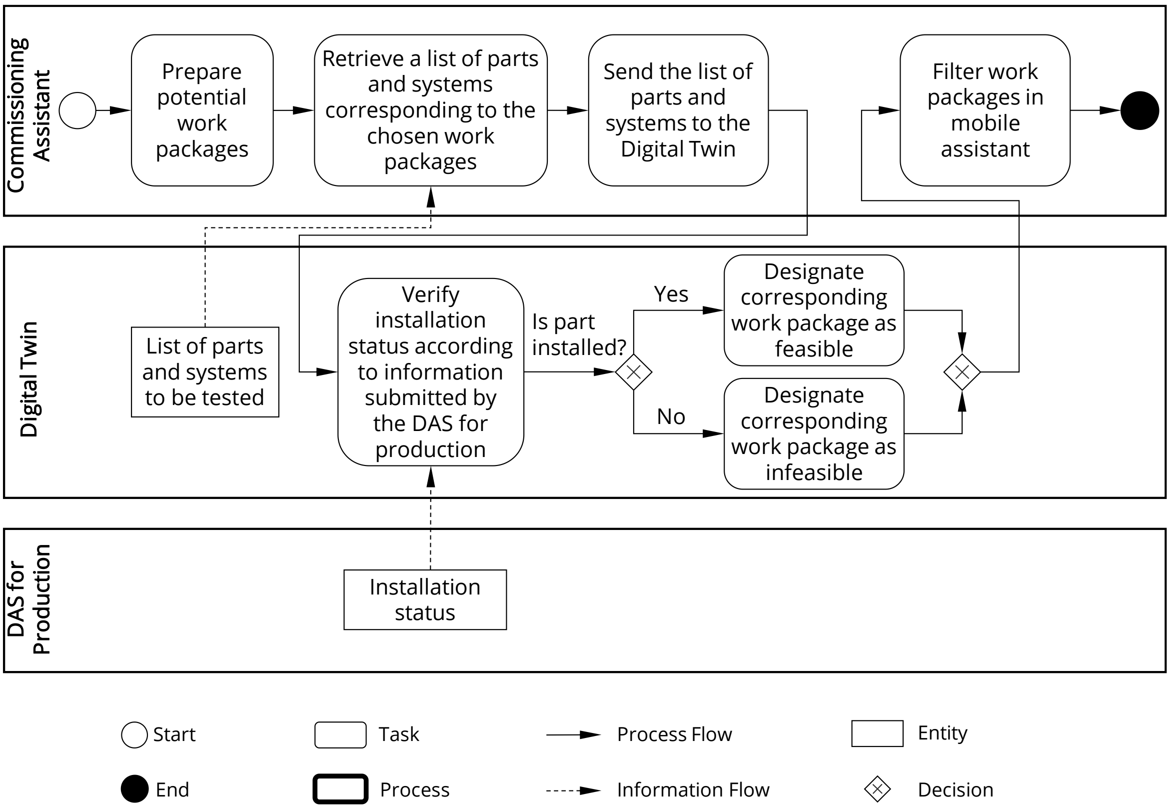


Figure 58: Process of work package filtering according to installation status

The procedure of inquiring about the installation status necessitates the integration of a DAS for production with the shipyard's infrastructure, as outlined by *requirement O2* in Section 4.2.1. Once the assembly of the parts and systems has been finalized, the production field worker proceeds to report this information using the DAS for production, thereby updating the Digital Twin with the installation progress. The Digital Twin, as demonstrated in Figure 58, classifies the chosen work packages as either *feasible* or *infeasible* based on the data obtained from the DAS. Finally, the Digital Twin presents the work packages that are determined to be feasible to the commissioning assistant, enabling the commissioning team to proceed with their tasks while guaranteeing that their work packages are achievable.

In order to implement the process illustrated in Figure 58, a simulation was constructed for a DAS used in the context of production. The simulation incorporates a feature that allows for the designation of parts in the part tree as either installed or not installed. The commissioning assistant responds to this designation by marking feasible and infeasible commissioning tests and providing recommendations for work packages accordingly.

Conflict Detection

To mitigate conflicts that may develop from production activities, such as the temporary unavailability of a room on a ship due to critical production tasks like welding, the Digital

Twin system monitors the production status as reported by the DAS for production. The Digital Twin has the capability to detect the specific area where the production activity is being carried out. It can afterwards search its database for commissioning tests scheduled to be conducted in that particular area. The data can afterwards be utilized by the commissioning assistant to identify commissioning tests as infeasible if they have to be conducted in the same area.

At the shipbuilding site, the manual submission of information to the Digital Twin for assessing potential conflicts between production and commissioning operations is not deemed feasible. Consequently, automation is necessary. Automation can be accomplished by employing the DAS for production to enable the automated transfer of spatial data (acquired from the product structure and the 3D model) to the Digital Twin and the status of production. This information is then utilized for conflict detection between production and commissioning. To clarify, the production field worker begins their tasks by visiting the production site while being equipped with a DAS for production. The DAS autonomously transmits data to the Digital Twin in regards to the parts being assembled by the worker, the worker's location (according to the product structure and the 3D model), and the production status. The aforementioned data is then employed for the purpose of identifying conflicts that may arise between the production and commissioning phases.

To assess the feasibility of the conflict detection approach within the framework of this dissertation, a DAS for production and a local positioning system were required. however, to save resources, a software program for *conflict simulation* was built. By utilizing the conflict simulation software, users can create rectangular shapes that represent defined regions for production activities. The boundaries of the rectangles on the two-dimensional plane are determined by the Digital Twin. Subsequently, the Digital Twin identifies the commissioning tests that lie within these bounds and designates the corresponding commissioning tests as unachievable.

Figure 59 shows a 2D plan of a room floor which contains two disturbance rectangles. The screenshot depicted in Figure 59 illustrates that the initial commissioning test listed is deemed infeasible, as indicated by the presence of a red dashed rectangle encompassing the commissioning test item within the list. The same conclusion can also be made by examining the 2D plan which shows that the commissioning test falls inside the top right disturbance rectangle. On the other hand, the second test in the list is considered to be feasible due to its positioning outside the disturbance bounds, as visually depicted on the two-dimensional plan by using a green pin.

Test 1.1
Temperature Sensor T1
Parts:
71112200

Test 1.2
Pressure Sensor P1
Parts:
71112201

Figure 59: Conflict detection via the commissioning assistant

6.4.5 Documentation and Issue Management

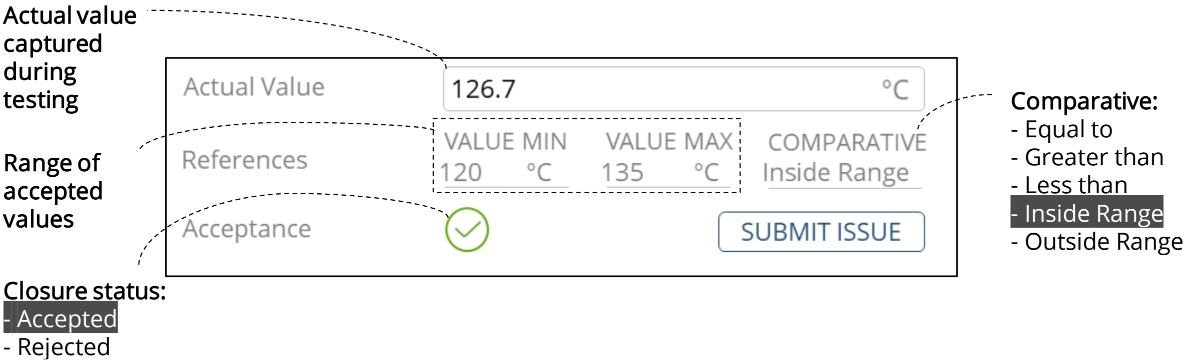
After the implementation of the commissioning tests, it is necessary to systematically document and archive the outcome of testing. Therefore, this section concentrates on the *documentation* process using the commissioning assistant by outlining the functionalities for capturing commissioning test results and documenting issues and deviations identified during testing.

Documentation of Commissioning Test Results

The type of results acquired from conducting a commissioning test depends on the type of commissioning test. For instance, the result of an installation test is a binary value that indicates whether a component or a part was successfully installed or not. Functional and signal testing can yield either a binary value indicating that a system is operational or a numeric value representing a technical measurement.

For documentation of installation test results, the user of the commissioning assistant can simply designate a test as *done* to indicate that the corresponding system is installed. In addition, the commissioning assistant includes a functionality for closing all commissioning tests belonging to the same assembly group if needed. This saves the time and effort of running through each test individually and marking each as done.

For documentation of functional and signal test results using the commissioning assistant, the user is presented with the dialog shown in Figure 60.



Actual Value: 126.7 °C

References: VALUE MIN 120 °C, VALUE MAX 135 °C, COMPARATIVE Inside Range

Acceptance: ✓

Figure 60: Commissioning test documentation dialog

Figure 60 shows a screenshot of a dialog shown to the user to document the result of measuring a temperature value. The dialog contains the following components:

- **Actual value captured during testing:** the user can input the actual value captured during testing in this text field. In the example shown in Figure 60, the user inputs the value of 126.7 °C, which is considered accepted since that it falls within a predefined range of acceptance.
- **Range of accepted values:** this is a read-only component containing one or two fields that indicate the expected value from the test. In the example displayed in Figure 60, a temperature value between 120 and 135 °C is considered acceptable.
- **Comparative:** this read-only text field indicates the comparative used to determine the acceptance of the reading. This property can take one of the following values:
    - **Equal to:** indicating that the actual value that the user inputs must be equal to a predefined value to be considered accepted.
    - **Greater than:** indicating that the actual value is only accepted when it's greater than a predefined value.
    - **Less than:** indicating that the actual value is only accepted when it's lower than a predefined value.
    - **Inside range:** indicating that the actual value is only accepted when it falls *inside* a predefined range.
    - **Outside range:** indicating that the actual value is only accepted when it falls *outside* a predefined range.
- **Closure status:** this icon signifies whether or not the captured value has been accepted or rejected. A red cross indicates that the value is outside of the acceptable range, while a green check mark indicates that the value is acceptable.

After inputting the actual test value, the user can archive the result by clicking a button. The result, whether accepted or rejected, is then transferred to the Digital Twin and saved immediately on the central database. In case where the outcome is not acceptable, an *issue* can be raised as discussed in the following sub-section of issue management.

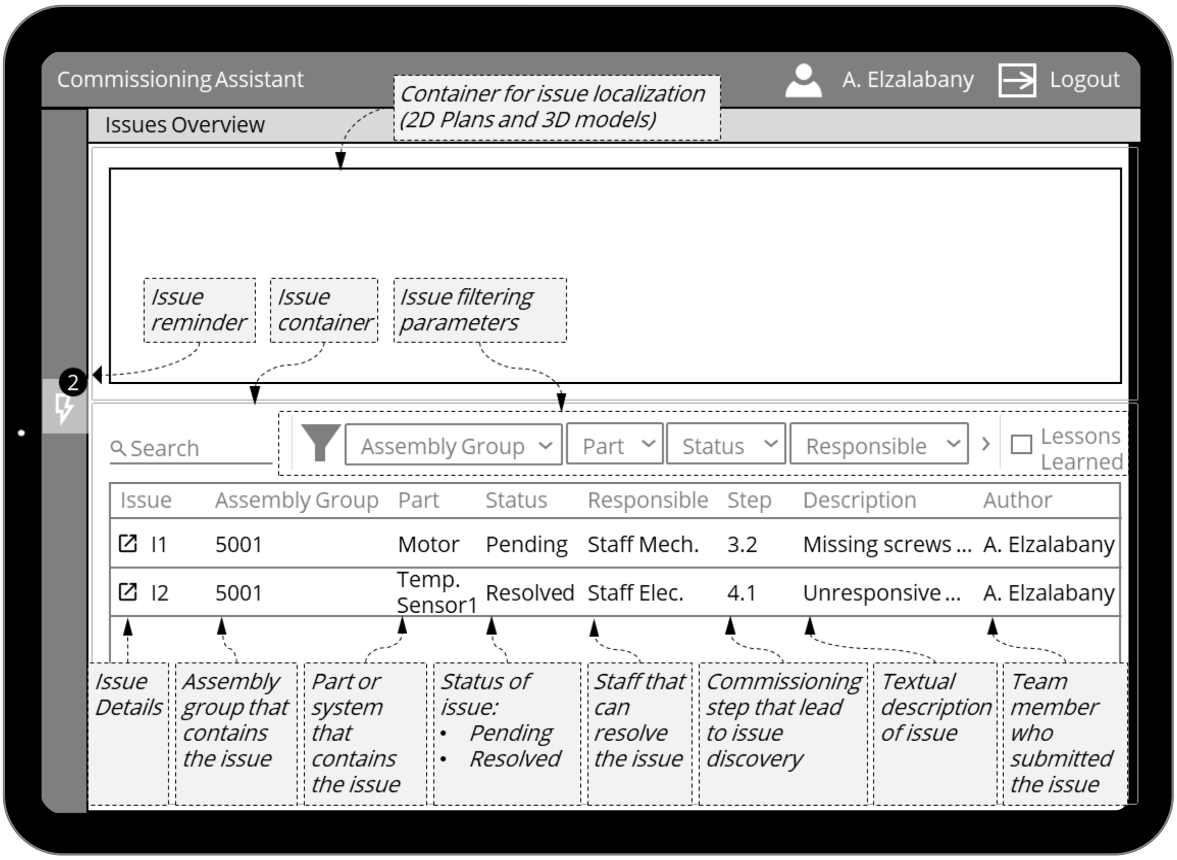
Issue Management

Issue management is a functionality developed to fulfil *requirements D2* and *D3* for systematic documentation of issues and maintaining real-time overview of commissioning progress. While conducting commissioning tests, the commissioning team needs a means to record any identified problems or issues. Hence, the commissioning assistant provides its users with a functionality to generate an entry that explains the identified issue and the steps taken to address it. Jahn et al. present a comprehensive framework for addressing disruptions or issues in One-of-a-Kind Productions (OKP) and suggest a user interface layout for capturing and reviewing such issues [Jahn22]. The concept proposed in this dissertation utilizes the findings of Jahn et al. as a foundation for the development of issue management through the usage of the DAS for commissioning.

According to Jahn et al., creating a new issue requires details including creation date, due date, category, description, and associated part [Jahn22, P. 181]. Therefore, to initiate the process of submitting an issue in the commissioning assistant, the user must follow these steps: identify the step and the part for which the issue is discovered, open an issue dialog, specify a due date for resolving the issue, assign a category to the issue, and indicate if it is a reoccurring issue. This will help create a repository of lessons learned. Additionally, the user must describe the issue either using a set of predefined keywords, textual description, or photographs. If the issue cannot be rectified immediately upon detection, the user has the option to create a new commissioning step that corresponds to the discovered issue and designate appropriate persons to address and resolve the issue. The newly generated step is then automatically integrated into the database of the Digital Twin. Put simply, the newly generated step serves as an update to the digital commissioning plan.

Figure 61 shows a schematic design of the user interface of the commissioning assistant for issue management and reviewing. The design is based on the work of Jahn et al. [Jahn22, P. 185]. As shown in Figure 61, the user interface consists of two sections. The upper section is a container which is used for issue localization via 2D plans or 3D models. This functionality is useful for quickly finding the location of detected issues and for tracking the progress of commissioning visually.

The commissioning team requires the ability to search and sort issues based on their qualifications. To facilitate this, the lower section of the issue overview interface in Figure 61 includes a tabular view that displays all issues. These issues can be filtered and grouped using various parameters such as assembly group, part, status, and responsibility. Clicking on an issue item provides the user with more details.



Issue	Assembly Group	Part	Status	Responsible	Step	Description	Author
I1	5001	Motor	Pending	Staff Mech.	3.2	Missing screws ...	A. Elzalabany
I2	5001	Temp. Sensor1	Resolved	Staff Elec.	4.1	Unresponsive ...	A. Elzalabany

Figure 61: Overview of created issues

6.4.6 IOT-Based Documentation

According to *requirement D1*, the commissioning assistant should incorporate automation technologies for facilitating the documentation of complex test results. This section explains how the commissioning assistant together with the Digital Twin implement automated documentation using the technology of Internet-of-Things (IOT). The section first discusses the utilized technology and the data flow for IOT-based documentation then presents the workflow of automated capturing of technical measurements using the commissioning assistant.

Technology and Data Flow

A structured data flow must be designed to facilitate the capturing of complex measurements during testing. The idea is to utilize IOT-based documentation for capturing measurements resulting specifically from signal tests, as signal tests require the most comprehensive workflow when it comes to capturing and documenting technical measurements. Moreover, it is known that a ship nowadays generates around 120,000 signals due to the rise of automation technology [WAGO23b]. For data transfer and communication, the OPC UA communication protocol is used. The decision to use this particular communication protocol is due to its spread in ship's automation systems.

In order to establish an organized flow of information, the signals generated during the testing process necessitate distinct *identifiers*. According to Section 6.2.5, each signal on the DAS is identified by a data attribute called the *Signal Tag*. The documentation infrastructure based on IoT employs the Signal Tag attribute as a distinct identifier for the exchange and flow of data between the physical equipment being tested and the DAS. To manage the exchange of thousands of messages originating from signals, it is necessary to create a data flow model (see Figure 62).

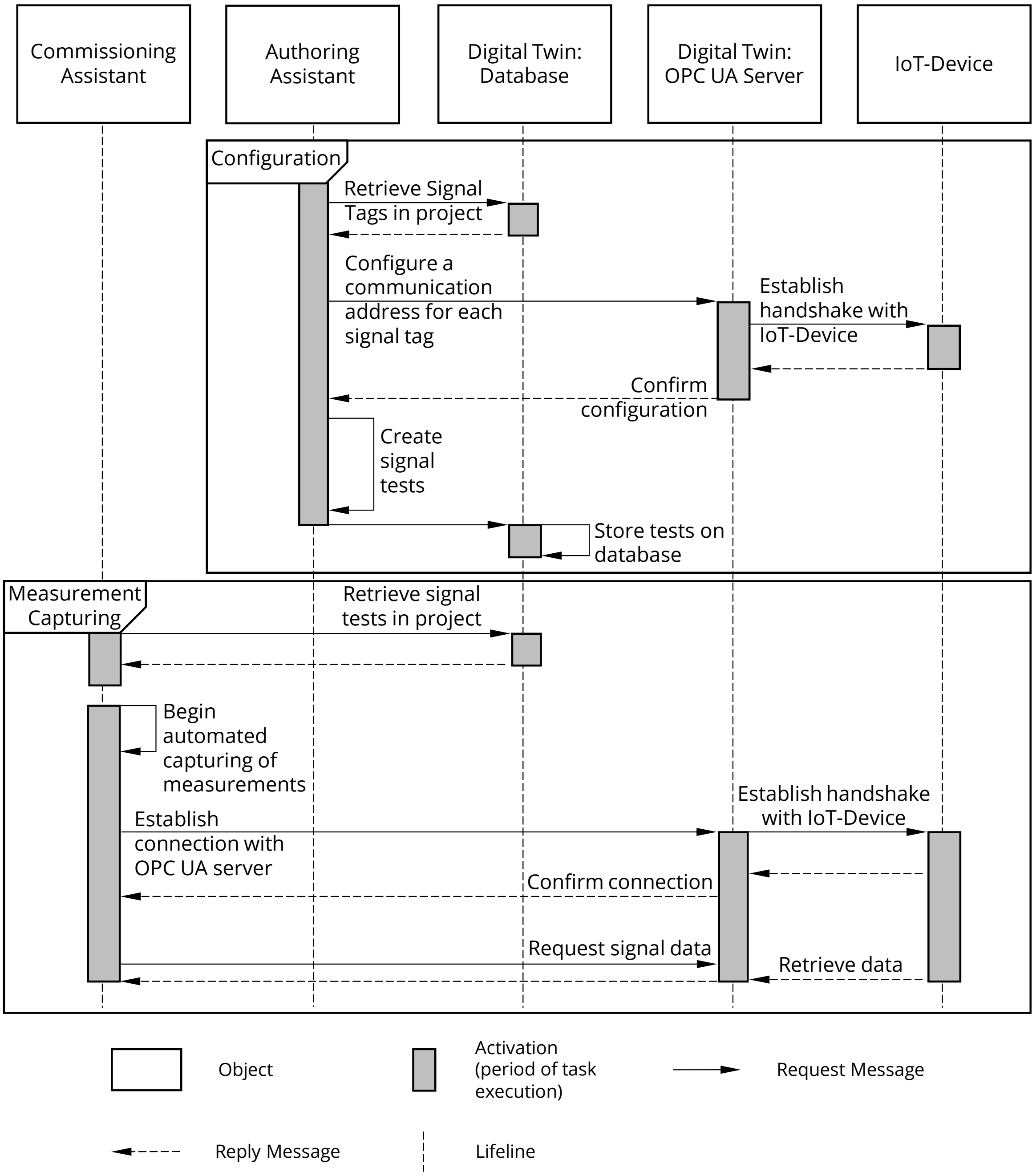


Figure 62: UML sequence diagram for IoT-based documentation

The UML sequence diagram depicted in Figure 62 illustrates that the users must first initiate a configuration process of the signals in the commissioning project, wherein every signal is assigned a unique communication address. In the context of the OPC UA server, a signal is denoted as a *node*. The label assigned to a node is the same as the Signal Tag, and the address of the node is managed using the OPC UA server. The configuration process is carried out through the authoring assistant. Following the configuration process, users can proceed with creating signal tests, as outlined in Section 6.2.5.

Once the signal tests are generated and each signal is allocated a specific node on the OPC UA server, the user of the commissioning assistant can initiate the process of importing the signal tests from the Digital Twin database. To establish a connection between the OPC UA server and the commissioning assistant, the user is required to commence the process by selecting the signal test for which the measurements are intended to be automatically captured. The commissioning assistant subsequently establishes a reliable connection to the OPC UA server, which remains in place until the completion of the commissioning test implementation. Once the user navigates away from the signal test, the connection is then terminated automatically.

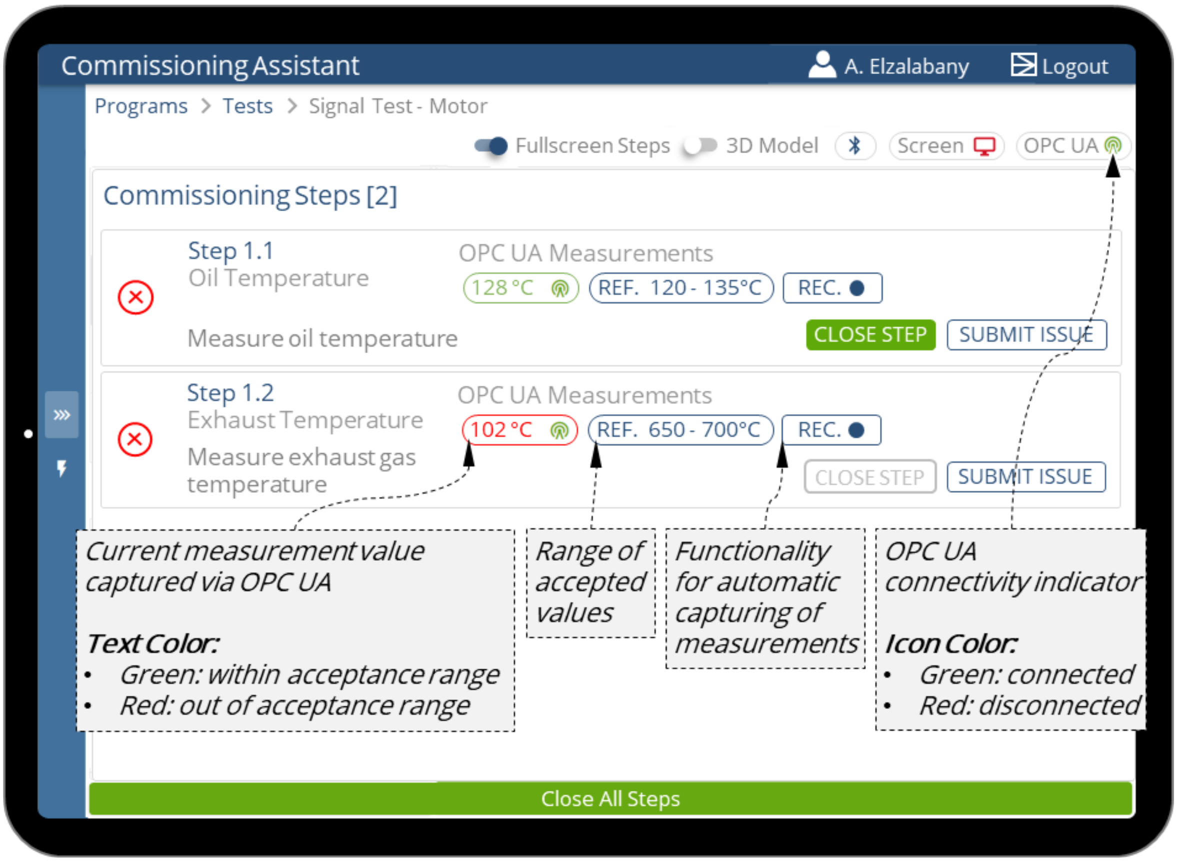
Workflow for Automated Capturing of Technical Measurements

The IoT-based documentation approach is designed to address the limitations of manual documentation, such as the significant time and effort required for documenting continuous data, as well as the inaccuracies and errors that might occur when measurement values and readings are overlooked. Consequently, the process of capturing technical measurements must be fully automated.

To reduce the effort for data capturing, the paradigm of *time-driven* communication is utilized. This paradigm indicates that a time-driven system consistently updates its state with each *clock tick* [Cass14, P. 3]. When employing this paradigm for IoT-based documentation, the user does not need to manually ask for measurement values from the OPC UA server. Instead, the commissioning assistant carries out these requests automatically at regular intervals and updates the measurement values in its user interface. This allows the user to have a real-time overview of all signals being transmitted during a single commissioning test. The user interface for IoT-based documentation was designed to achieve such an overview (see Figure 63).

Figure 63 displays a screenshot of the commissioning assistant, presenting the user with a comprehensive overview of the commissioning steps associated with a signal test. Within this perspective, the user is able to observe the precise technical measurements of each step, which are regularly updated at fixed intervals. Based on these measurement values, the user can make a decision to either close the step or report an issue. This perspective is valuable for addressing the challenge of simultaneously recording multiple measurements.

Conventionally, this task necessitates the involvement of multiple individuals working at the same time to capture measurement values at the same time. Using the commissioning assistant, this is no longer necessary which saves resources.



Current measurement value captured via OPC UA

Text Color:

- *Green: within acceptance range*
- *Red: out of acceptance range*

Range of accepted values

Functionality for automatic capturing of measurements

OPC UA connectivity indicator

Icon Color:

- *Green: connected*
- *Red: disconnected*

Figure 63: Monitoring measurements captured via the OPC UA server

In order to minimize the chances of incorrect interpretation of data, the commissioning assistant interface employs a color scheme to signify whether the technical measurement is deemed acceptable or not. For instance, in the event that a value deviates from a predetermined acceptance range, it will be visually emphasized by being written in the color red, otherwise, it will be written in green as shown in Figure 63. Moreover, the assistant system will not permit closing the step if the measurement is deemed unacceptable.

Moreover, to reduce the effort where there is a need to capture and track measurements over an extended duration, a functionality for *automatic continuous capturing* is required. The implementation of this functionality aims to address the deficit labeled as *D1: inefficient documentation of commissioning test results* (see Section 3.2.3). Accordingly, the capture button, depicted in Figure 63, allows the user to record measurement values and store the corresponding measurement values with a time-stamp. When the user clicks this button, a dialog is shown which displays the measurement values over time. To demonstrate, Figure 64 depicts a scenario in which the user is engaged in the monitoring of readings acquired from a temperature sensor over the duration of one minute.

Figure 64: Monitoring the history of a measurement value

6.4.7 Discussion

The commissioning assistant, presented in Section 6.4, is a software artifact designed for handheld devices such as tablets. The software is created to meet the specifications of requirements *I1*, *I2*, *D1*, *D2*, and *D3* (see Sections 4.2.4 and 4.2.5). The primary objective of this artifact is to improve the commissioning team's workflow through more efficient information procurement and storage. This section provides a discussion of the commissioning assistant, focusing on its qualitative benefits and limitations.

Benefits

The commissioning assistant is developed to replace the conventional approach of *paper-based* information procurement, visualization, and documentation. To achieve an efficient workflow, the software includes the following functionalities:

- **Context-awareness:** automatically providing the commissioning team with the most suitable work packages. This is done by considering factors such as the installation status of systems, conflicts with production, and technical dependencies. Consequently, context-awareness is expected to reduce the time and effort needed to search for suitable commissioning tasks.
- **Localization:** providing coarse and fine localization of components and systems

on the ship through the use of 2D plans and 3D models. Therefore, increasing the productivity of the commissioning team by reducing the time required for locating the components and systems.

- **Digital documentation:** offering the commissioning team a digital platform to record testing outcomes and document issues and faults, so enhancing information management and facilitating more effective communication. In addition, utilizing IoT technologies for automated measurement capture, which can minimize the likelihood of inaccurate documentation and decrease the time and resources needed for capturing complex measurements. It is also worth mentioning that achieving a digital repository of documentation is useful for creating maintenance plans after the commissioning process is concluded. These digital maintenance plans can be generated to conform to the data models supported by assistance systems for maintenance such as the system developed by Meluzov [Melu22, P. 50].

Limitations

The commissioning assistant requires structured data obtained from different systems in the shipyard so that it can be used to its fullest extent. The lack of such data negatively affects the performance of the commissioning assistant as follows:

- **Context-awareness:** in order to achieve context awareness, the commissioning assistant necessitates the implementation of a DAS for production within the shipyard's infrastructure. The DAS for production facilitates the submission of information pertaining to the installation status of the systems and the ongoing production activities. In the absence of such information, the commissioning process incorporates context-awareness solely by considering factors such as technical dependencies and detected issues during commissioning.
- **Localization:** the commissioning assistant utilizes 2D plans to determine and visualize the testing location. That being said, the commissioning assistant only provides the user with the testing location, without offering the most efficient route for reaching the location. The reason for not implementing such functionality is because the 2D plans used by the shipyards are simple image files that are not *intelligent* enough to offer *navigational* capabilities.
- **Digital documentation:** the implementation of IoT-based documentation is contingent upon the ship's components being equipped with IoT interfaces. Fortunately, as the ship automation system becomes increasingly complex, there is a progressive adoption of components that comply with IoT standards. Nevertheless, if IoT-compliant equipment are unavailable, the commissioning assistant can still provide the ability of manual digital documentation.

7 Evaluation

The primary objective of the evaluation outlined in this chapter is to determine if the developed *Digital Assistance System* (DAS) can resolve the shortcomings of the conventional commissioning process. In other words, the evaluation systematically examines the qualitative and quantitative effects of incorporating the DAS into the maritime commissioning process. Before conducting the evaluation, it was necessary to design experiments that adhere to the solution requirements previously defined in Section 4.2. Figure 65 displays a concise overview of the requirements, together with their corresponding evaluation metrics, experiment domains, and methods used to assess the fulfillment of each requirement.

Requirement	Metric	Experiment Domain	Method
Organization of information			
O1: Centralized system	Usability	Industry	Survey
O2: Integration with production	Functionality Relevance	Industry	Survey
Preparation of commissioning plan			
P1: Efficient authoring of commissioning plan	Time	Industry, Laboratory	Measurement
P2: Technical dependency authoring	Functionality Relevance	Industry, Laboratory	Survey, Measurement
Implementation of commissioning tests			
I1: Low-effort for initial preparation	Time	Industry	Survey, Measurement
I2: Efficient information procurement	Time	Industry, Laboratory	Survey, Measurement
Documentation of commissioning results			
D1: Productive documentation of results	Time	Industry, Laboratory	Survey, Measurement
D2: Systematic documentation of issues	Functionality Relevance	Industry	Survey
Acceptance			
A1: Easy integration with shipyard infrastructure	Integration Capability	Industry	Survey
A2: User satisfaction	Usability	Laboratory	Survey

Figure 65: Overview of the requirements and their allocation to evaluation metrics, experiment domains, and methods

This chapter focuses on the evaluation of the DAS through three main sections: Section 7.1 explores the qualitative assessment of the DAS. Section 7.2 covers the quantitative assessment of the *authoring assistant* developed for commissioning preparation, while Section 7.3 addresses the quantitative assessment of the *commissioning assistant* developed for commissioning implementation and documentation.

7.1 Qualitative Assessment: System Integration and Functionality Relevance

To validate the compatibility of the newly developed DAS with the shipyard's infrastructure and its usability in the commissioning workflow, it is crucial to initially grant the shipyard access to the DAS. This was done by deploying the DAS over the internet and providing the shipyard users with secure access. This section provides details on how the integration capability of the DAS into the infrastructure of the shipyard was evaluated (Section 7.1.1). Moreover, it offers the results of validating the relevance of the DAS functionalities with respect to enhancing the overall process of commissioning (Section 7.1.2). Finally, Section 7.1.3 provides a discussion.

7.1.1 System Integration

If the shipyard can utilize the DAS to import actual data from past and ongoing commissioning projects, then it can be inferred that the DAS can be integrated into the shipyard infrastructure.

To enable the shipyards to transfer data from previous commissioning projects to the DAS, interfaces were developed that mimic the connection between the DAS and the shipyard's PLM and ERP systems (see Sections 6.2.2 and 6.2.3). These interfaces allow the shipyards to import data including 3D models, 2D deck plans, and technical documents such as cable lists and signal lists. After these interfaces were implemented, the shipyards were able to test the DAS functionalities for viewing and using the data obtained from the PLM and ERP systems to author and implement commissioning plans.

As previously stated, validating the DAS integration capability is contingent upon demonstrating that the system can effectively import and utilize real data from the shipyard's systems to create and implement commissioning plans. To verify this, the DAS was provided for testing to professionals who held roles as members of commissioning authorities at three prominent shipyards in Germany. Subsequently, a survey was conducted among a group of eight shipyard professionals who tested the system. The survey participants were instructed to rate the functionalities of the DAS based on their perceived relevance for improving the workflow of maritime commissioning. The survey comprises a total of 16 statements related to the functionalities created for commissioning preparation and information organization (see Appendix B). Figure 66 displays the rating scale used in the survey to assess the functionalities, together with the average results of four specific functionalities related to importing and editing data from the shipyard systems.

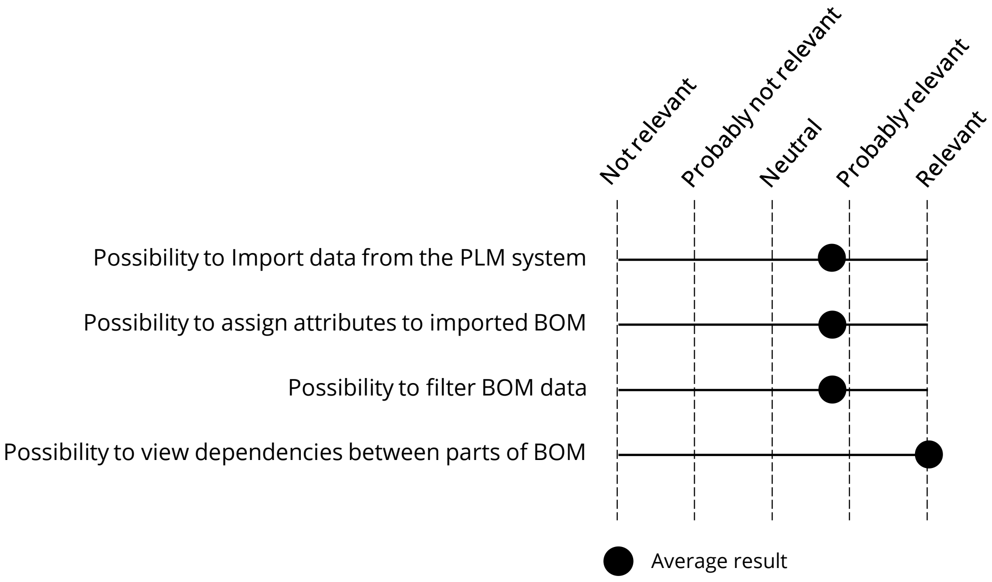


Figure 66: Average results of perceived relevance of the DAS functionalities for importing the shipyard data (n=8)

Figure 66 implies that shipyard professionals, via the DAS, had the capability to transfer data, such as the BOM, from their PLM systems. They were able to assign attributes to the imported BOM, filter the BOM data, and examine dependency information. The shipyard professionals rated the functionalities positively for their relevance in enhancing the process of commissioning preparation and information organization. This is an indication that the shipyard professionals see that the DAS can be integrated into the shipyard's existing infrastructure.

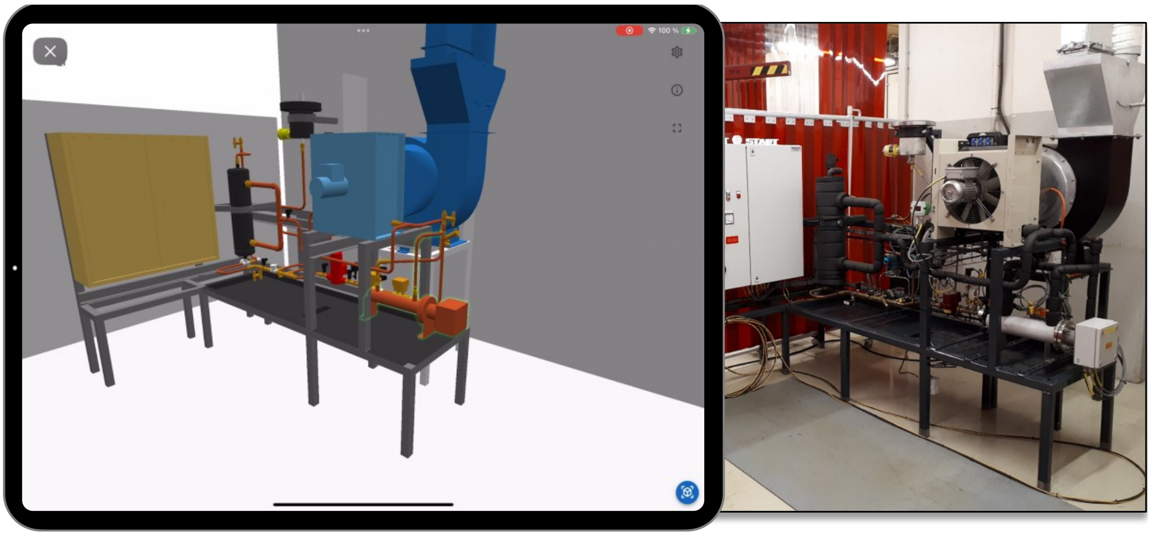
7.1.2 Functionality Relevance

To test the applicability of the DAS for different systems on the ship, and to validate the relevance of functionalities of the DAS, the system was locally installed at three shipyards, and each shipyard selected a specific independent use case scenario for testing the DAS. The use case scenarios are described as follows:

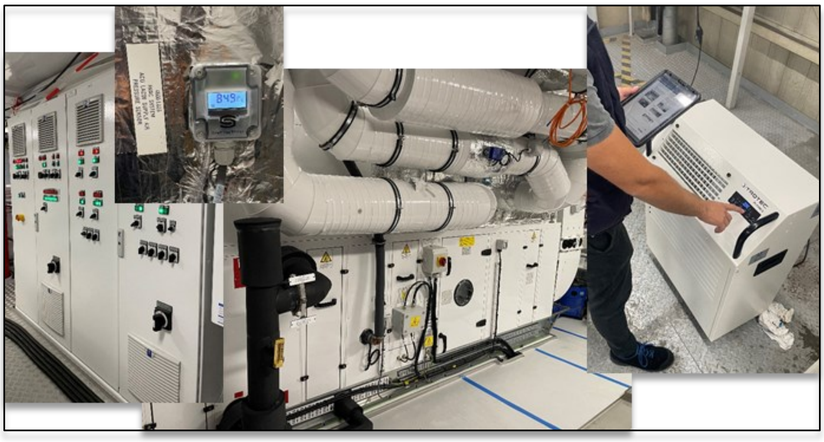
- **Electronic systems:** *shipyard 1* applied this scenario to evaluate the DAS for commissioning electronic systems on the ship. To clarify, shipyard 1 primarily aimed to evaluate the functionalities for conducting *IoT-based signal tests* using the DAS.
- **HVAC systems:** *shipyard 2* use this scenario to assess the DAS for commissioning heating, ventilation, and air-conditioning *systems*. The DAS was utilized to conduct *installation*, *functional*, and *signal tests* in this particular situation.
- **Mechanical systems:** *shipyard 3* utilizes this scenario to assess the DAS for commissioning mechanical systems such shell doors, platforms, and hatches. The DAS was utilized to conduct *installation* and *functional tests* in this particular situation.

Actual photographs captured for the testing scenarios at shipyards 1 and 2 are displayed in

Figure 67 [Jans23b, P. 146]. For the purpose of evaluating the DAS, shipyard 1 constructed a cooling water system, as illustrated in Figure 67(A). The cooling water system contained actuators and sensors that support the OPC UA technology, which is essential for testing the DAS's IoT-based documentation functionalities during signal testing. Moreover, Figure 67(B) shows stationary and mobile air-conditioning devices at shipyard 2 that are being tested using the DAS. The air-conditioning devices underwent testing through the execution of installation, functional, and signal tests. However, the signal testing for the systems of shipyard 2 was conducted without incorporating the OPC UA technology.



A - Shipyard 1 use case scenario: cooling water system



B - Shipyard 2 use case scenario: mobile and stationary air-conditioning systems

Figure 67: Use case scenarios at two shipyards for evaluating the DAS

The systems depicted in Figure 67 are complex and necessitate substantial effort for test authoring, implementation, and documentation. Intentionally selecting such scenarios served the purpose of validating the DAS's capacity to handle complex tasks. In order to assess the DAS-built functionalities for enhancing the overall workflow of maritime commissioning, it was necessary to use the DAS for commissioning these systems. As a result, professionals from the commissioning authorities and teams in shipyards 1 and 2 received training on how to use the DAS. Upon completion of the training, they were asked to develop commissioning plans, conduct the tests, and document the results of the tests using the DAS. The relevance of the implemented functionalities in enhancing the commissioning preparation, implementation, and documentation processes was assessed through two surveys. A total of 19 professionals from both shipyards participated in these surveys after completing the commissioning work using the DAS. Figure 68 displays the rating scale used in the survey to assess the functionalities, together with the average results of the functionalities for commissioning preparation, implementation, and documentation.

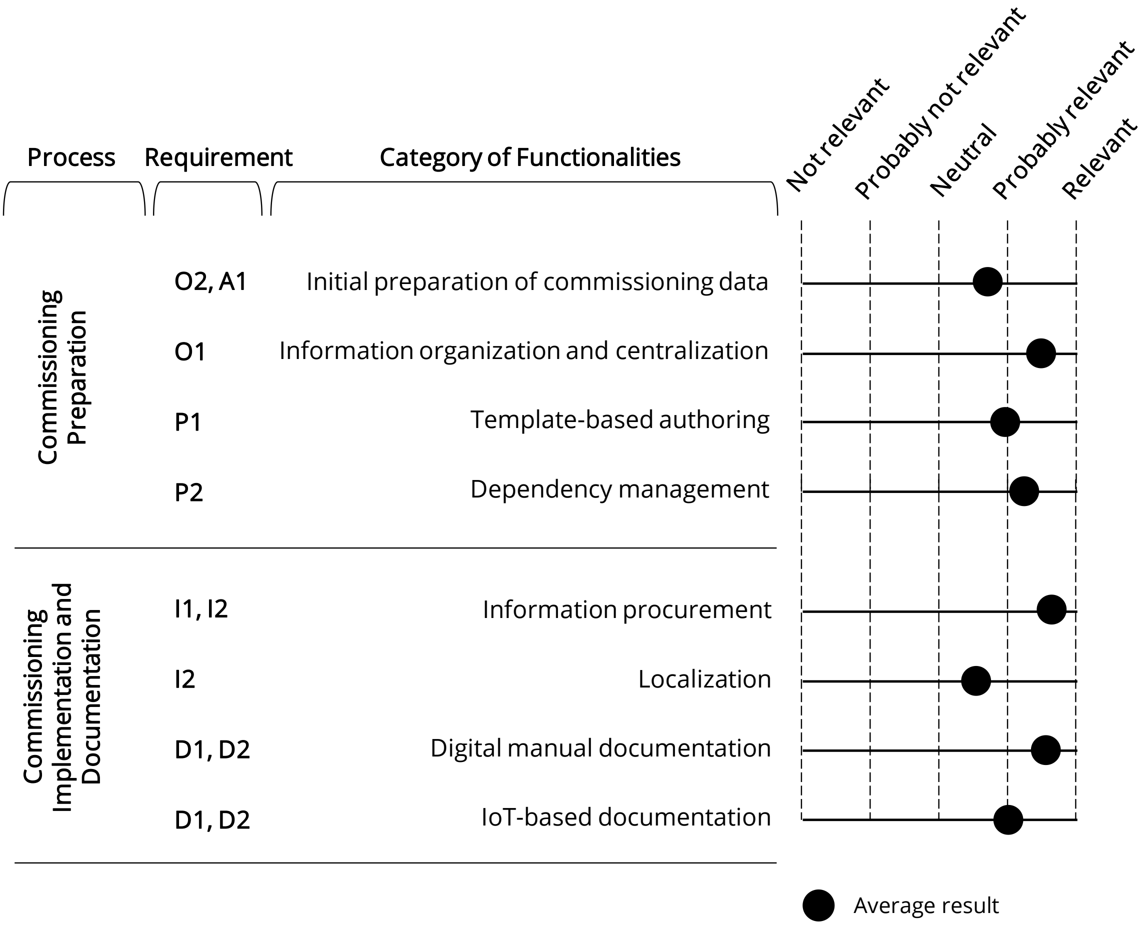


Figure 68: Average results of perceived relevance of the overall DAS functionalities (n=19)

It is worth mentioning that Figure 68 displays aggregated results. This means that the surveys included a collective of 31 statements that correspond to different functionalities of the DAS (see Appendix B). An average rating is initially computed for each statement in the survey. Later, the functionalities were classified into the eight categories as depicted in Figure 68, and an average rating is determined for each category.

Figure 68 illustrates the categorization of functionalities, aligning with the solution requirements previously defined in Section 4.2. The results demonstrate a positive outcome, indicating that the functionalities required for enhancing the commissioning process through the DAS have been implemented as planned. However, it is important to note that these results reflect a *qualitative assessment*, indicating that the surveys do not quantitatively measure the improvement to the process. Sections 7.2 and 7.3 focus on the *quantitative assessment* of the DAS.

7.1.3 Discussion

While the surveys mentioned in Sections 7.1.1 and 7.1.2 indicate positive results regarding the relevance of the developed DAS functionalities, it is crucial to examine these results with a critical perspective. This section provides an interpretation of the results for the processes of commissioning namely: *preparation*, *implementation*, and *documentation*. To interpret the results, the professionals who took part in the surveys were asked to provide written and verbal feedback.

Commissioning Preparation

According to Figure 68, the functionalities related to organizing and centralizing information in the system were considered the most relevant for improving the preparation process. This is a valid conclusion because these functionalities play a crucial role in transitioning from the conventional workflow to the DAS. Conversely, the shipyard professionals showed that functionalities such as the ability to import 2D plans and 3D models are not as essential. The rationale behind this is that the data is not consistently accessible in a format that optimizes navigation capabilities. As stated earlier in Section 6.4.7, the 2D plans used for the tests were basic picture files that were not suitable for generating routes to the commissioning tests aboard the ship.

Commissioning Implementation

Figure 68 illustrates that shipyards prioritize *context-awareness* for information procurement as a crucial functionality for improving the implementation process. This functionality is considered relevant because the commissioning team identifies the search for appropriate tasks and resources as one of the main factors contributing to a decrease in productivity. Conversely, *localization* received the lowest rating due to the aforementioned factors regarding its limited navigational capabilities. Furthermore, the highly experienced members of the commissioning team deemed it unnecessary to have assistance in identifying the ship's components using 3D models. However, this functionality may be particularly useful for persons with less experience.

Commissioning Documentation

Figure 68 demonstrates that shipyard professionals give higher importance to digital manual documentation through the DAS compared to IoT-based documentation. One possible explanation for this is that some of the professionals who tested the system were unable to evaluate IoT-based documentation because they did not have access to OPC UA compatible components in their test case scenarios. Instead, they were only presented with a technical demonstration of the functionality. Another justification for favoring manual digital documentation is the perception that IoT-based documentation could promote lack of confidence in the accuracy of measurement values automatically captured by the DAS. To overcome this concern, it was suggested that the DAS would incorporate a feedback workflow for reviewing the measurement values acquired using the OPC UA technology.

7.2 Quantitative Assessment of the Authoring Assistant

This section provides a *quantitative* assessment of the *authoring assistant* that was introduced in in Sections 6.2 and 6.3. The objective is to measure the impact of utilizing the authoring assistant on the productivity of the commissioning authority, as compared to the conventional process. Moreover, the evaluation also includes a systematic usability assessment, which is necessary for measuring user acceptance in accordance with requirement *A2*. In order to obtain reliable results, the system undergoes an initial assessment in an actual industrial setting (Section 7.2.1), followed by an assessment in a controlled laboratory setting (Section 7.2.2).

7.2.1 Industrial Setting

The most realistic testing environment for quantitatively assessing the authoring assistant's effects is the shipyard. Consequently, it is necessary to deploy the authoring assistant at the shipyard and subject it to testing throughout a commissioning project, comparing its performance to the conventional workflow. Collecting measurements throughout the lifecycle of an ongoing commissioning project would require a significant amount of time, which is not feasible given the time frame of this dissertation. To overcome this limitation, the method of *analytical estimating* is chosen for measurement collection as it is commonly used when the collection of measurements is not feasible due to time limitations [BMI18, P. 242]. Analytical estimating can be summarized as a method used where domain experts are asked to estimate the time required for executing a set of tasks within their domain of expertise. To explain the method of analytical estimating, Figure 69 shows a process model illustrating the steps of applying analytical estimating for measurement collection.

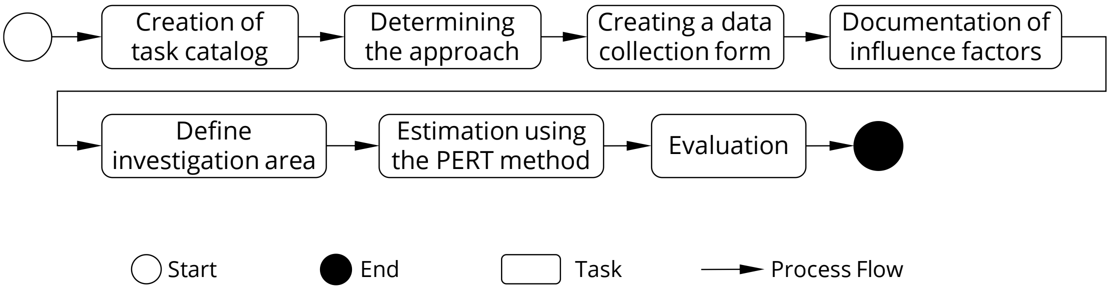


Figure 69: Process of applying the method of analytical estimating for measurement collection

Figure 69 illustrates that the initial step of implementing analytical estimating involves creating a *task catalog*. The task catalog should encompass all tasks that necessitate estimation by the participants. The second step involves categorizing the tasks in the catalog based on the expertise of the participants involved in the estimation. Subsequently, the task catalog is migrated to a *data collection form* that is organized to include specific instructions and meta-information for carrying out the estimation. The data collection form includes fields to document *influence factors*. For instance, the participants are asked to document any cases or constraints that may affect the task duration. Subsequently, the *investigation area* is defined, wherein specific participants are chosen for each set of tasks. Next, participants are requested to provide their estimation for each task by submitting three values that represent the duration required to complete the task under the most favorable conditions (t_{min}), typical conditions (t_{norm}), and the most unfavorable conditions (t_{max}). This procedure is referred to as the *Program Evaluation and Review Technique* or PERT-method [BMI18, P. 247]. The PERT method calculates the average duration using the following equation:

$$t_{avg} = \frac{t_{min} + 4t_{norm} + t_{max}}{6} \tag{1}$$

Once the estimation values are submitted, they are added up to determine the average duration needed to complete the process comprised by the predefined set of tasks.

To assess the authoring assistant, a task catalog was developed and distributed to seven experts in a shipyard as a survey. The experts were all members of the commissioning authority at the shipyard. The purpose was to estimate the time required to complete a set of tasks in the commissioning preparation process, using both the conventional workflow and the DAS-based workflow. The task catalog is displayed in Appendix C. It is important to note that the experts who took part in the survey received training for the authoring assistant and possessed sufficient knowledge regarding the details of the application.

Productivity Assessment Results

As a result of non-disclosure agreements (NDAs), it is not permissible to disclose or discuss the raw data that represent the estimated duration of tasks performed by the commissioning authority at the shipyard. Consequently, the results are expressed as percentage values that describe the estimated change in average duration for each task by using the authoring assistant for commissioning preparation (see Figure 70).

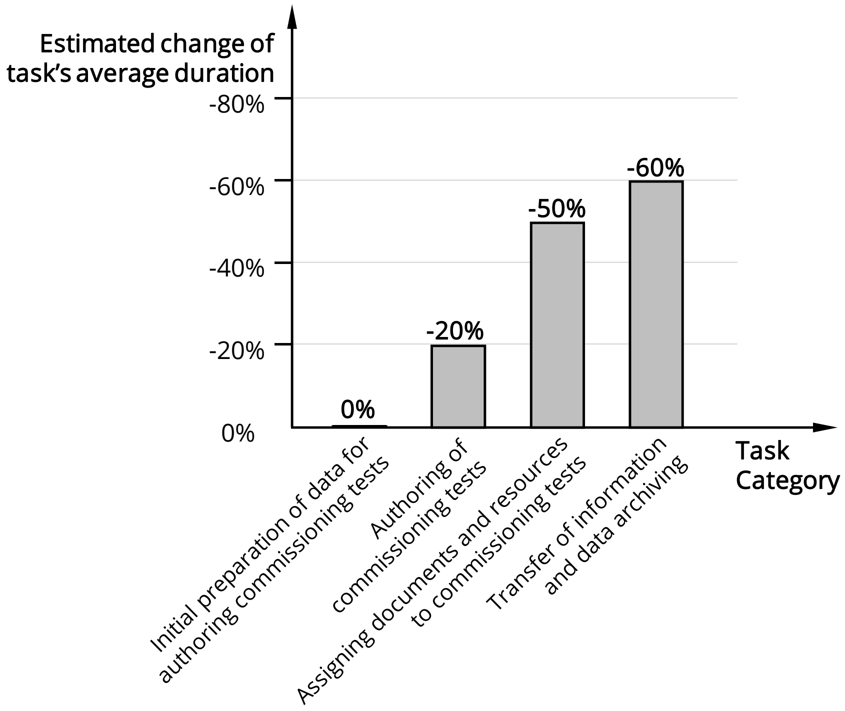


Figure 70: Estimated change of task's average duration through the use of the authoring assistant (n=7)

According to Figure 70, the experts expect that the authoring assistant will not decrease the time required to initially prepare commissioning data. To clarify, the initial preparation of commissioning data involves the creation and review of technical documents for ship components, the preparation of measurement lists, and the creation and review of technical illustrations and 3D models. This outcome is comprehensible as a majority of the data preparation tasks are carried out on the PLM and ERP systems of the shipyard, and not on the authoring assistant.

On the other hand, experts predict that the authoring assistant has the potential to reduce the time required for authoring commissioning tests by 20%. The reduction in time can be attributed to the implementation of template-based authoring, which enables the commissioning authority to automatically generate commissioning tests using predefined templates. Additionally, it is anticipated that the duration for allocating documents and resources to the commissioning tests using the authoring assistant can be decreased by 50%. Likewise, the task of transferring information from the authoring assistant for the purpose of commissioning implementation and documentation would be completed in 60% less time. Both results stem from the use of a digital centralized system for information management (Digital Twin) instead of a paper-based workflow.

7.2.2 Laboratory Setting

The industry assessment indicates a tendency towards enhanced productivity through the utilization of the authoring assistant. That said, the use of the *analytical estimating* method and the limited sample size are factors that lead to statistically insignificant findings. In order to achieve statistically significant results, it is important to conduct a practical evaluation that incorporates time measurement instead of estimating and comprises a larger sample size. Due to the inability of conducting an evaluation under the given conditions at the shipyards, laboratory experiments were carried out. Hence, a total of 20 experiment runs, involving 10 participants (students and research associates), were conducted. The experiments were systematically designed and executed within the framework of a student project [Schm23], which was supervised as a part of this doctoral research. Consequently, the results presented in this section are based on the data gathered by Schmiel [Schm23, P. 30–57]. This section provides a concise overview of the laboratory experiments' objectives, experimental design, and the resulting outcomes.

Hypothesis, Objectives, and Experimental Design

The experiment aims to test the hypothesis that the innovative workflow for authoring commissioning tests via the authoring assistant surpasses the conventional workflow in terms of productivity, reliability, and user-friendliness. Accordingly, a *null hypothesis* can be formulated as follows: "*There is no difference in terms of authoring time, error rate, or usability between the authoring assistant and the conventional tools*". Hence, the selected target variables for experimental design are authoring time, number of errors, and user acceptance level.

The first target of the laboratory experiments is to measure the time reduction achieved by utilizing the authoring assistant for the task of *authoring commissioning tests*. It was reasonable to conduct experiments primarily for the purpose of measuring the time taken to author commissioning tests, as this task has been identified as the most time-consuming. This means that unlike the industry assessment (Section 7.2.1), the laboratory experiments did not take into account other tasks such as *data preparation* and *resource allocation*. This is because the authoring assistant was tested in a simulated environment, i.e., without being integrated with the shipyard's PLM or ERP systems.

Moreover, to ensure reliability of the authoring assistant, the laboratory assessment measures the *number of errors or mistakes* made during the task of authoring commissioning tests. The errors examined in this experiment pertain to technical aspects, such as incorrect reference values for technical measurements and generating inaccurate testing sequences.

Furthermore, as per requirement *A2*, it is imperative to evaluate *user satisfaction*. As a result, the authoring assistant was subjected to usability assessment using surveys. For this, the *System Usability Scale* (SUS) and the *User Experience Questionnaire (*UEQ) are used. The SUS is a widely employed technique for quantifying the usability of a system. The technique was formulated by Brooke [Broo95, P. 189–194] and comprises a questionnaire with 10 items (see Appendix E). The UEQ is primarily used for usability assessment of *software products* [Laug08, P. 69] unlike the SUS which can be applied to any type of product (see Appendix F).

In order to accomplish the aforementioned targets, an experiment was designed in which each participant was directed to complete two tasks. The first task involved authoring commissioning tests for a specific ship system (a motor) using conventional tools (Word and Excel), while the second task involved authoring commissioning tests for a different system (steam turbine) using the authoring assistant application. After finishing the tasks, every participant was asked to take part in an SUS survey.

To attain statistical significance, the number of participants in the experiment had to be systematically calculated. Schmiel establishes the minimum number of participants to be 10. The calculation of the minimum number of participants is performed in relation to the estimated *effect size* for each target variable in the experiment, i.e., the *time needed to author commissioning tests,* the *number of errors* made during authoring commissioning tests, and the *user acceptance score* [Schm23, P. 42f.]. Figure 71 shows the minimum number of participants based on the effect size for each target variable.

	Authoring Time [minute]	Authoring Errors [number]	User Acceptance [SUS* Score]
Estimated Effect Size (δ)	1.25	1	1.25
Minimum Number of Participants (n)	4	6.25	4

*SUS: System Usability Scale

Figure 71: Minimum number of participants according to the estimated effect size [Schm23, P. 43]

Figure 71 shows that the estimated minimum number of participants is 6.25, however, since that usability is also to be evaluated, Hwang and Salvendy estimate that to identify 80% of usability problems in a software system, 10±2 participants are required [Hwan10, P. 133]. Accordingly, it was decided to have 10 participants in the evaluation.

The effect size (δ) is calculated based on Cohen's formula [Cohe88, P. 20]. See Equation (2).

$$\delta = \frac{\mu_A - \mu_B}{\sigma} \tag{2}$$

δ	Estimated effect Size
μ_A, μ_B	Population means
σ	Standard deviation of either population

In order to determine the effect size using Cohen’s formula, it is necessary that the population means and the standard deviation of either population are known. To accomplish this, Schmiel estimates the values of the means and standard deviations by conducted preliminary experiments [Schm23, P. 43].

To calculate the minimum number of participants (n), Equation (3) is used [Bort10, P. 106].

$$n = \left(\frac{z_\beta - z_{1-\alpha}}{\delta}\right)^2 \; ; \; z_\beta = -z_{1-\beta} \tag{3}$$

n	Sample size
z_β	Z-value of β error (mistaken failure to reject null hypothesis)
z_α	Z-value of α error (mistaken rejection of null hypothesis)
δ	Effect size

In this experiment, a confidence interval of 95% is chosen. Accordingly, Z-values are determined using the standard normal tables [Bort10, P. 587], and the minimum number of participants shown in Figure 71 is calculated.

Productivity Assessment Results

To prepare the participant for the productivity assessment experiment, the participant received an introductory explanation of the maritime commissioning process. They were also given documents that included examples of commissioning tests authored using conventional tools such as Word and Excel.

Subsequently, each participant was directed to author installation tests and signal tests for a selected system using the conventional tools. The necessary data for authoring the tests was provided in the form of Excel and Word files that mimic the format of the data retrieved from the shipyard’s PLM system. Once the participant has completed the process of authoring the tests, they were instructed to arrange the tests in a logical order of execution based on specific rules outlined in a document that illustrates the technical dependencies between the system's components.

Once the participant has completed creating the commissioning tests using the conventional tools, the second phase of the experiment commences. During this phase, the participant was required to author commissioning tests for another system using the authoring assistant. Therefore, prior to commencing this phase of the experiment, a brief training session was provided on how to use the authoring assistant. After the authoring process is concluded, the participant was instructed to use the dependency management functionality in the authoring assistant for generating a viable testing sequence.

Throughout both phases of the experiment, a stopwatch was used to record time to compare the duration of authoring commissioning tests using both the conventional system and the authoring assistant. Moreover, after the experiments were completed, the results of the commissioned tests were evaluated to determine the number of errors made by the participants during the authoring process.

Figure 72 displays the average duration of authoring installation and signal tests conducted with both the conventional system and the authoring assistant. The data illustrates that the authoring assistant achieves a reduction of 80% in the average duration of authoring signal tests, and a reduction of 88% in the average duration of authoring installation tests.

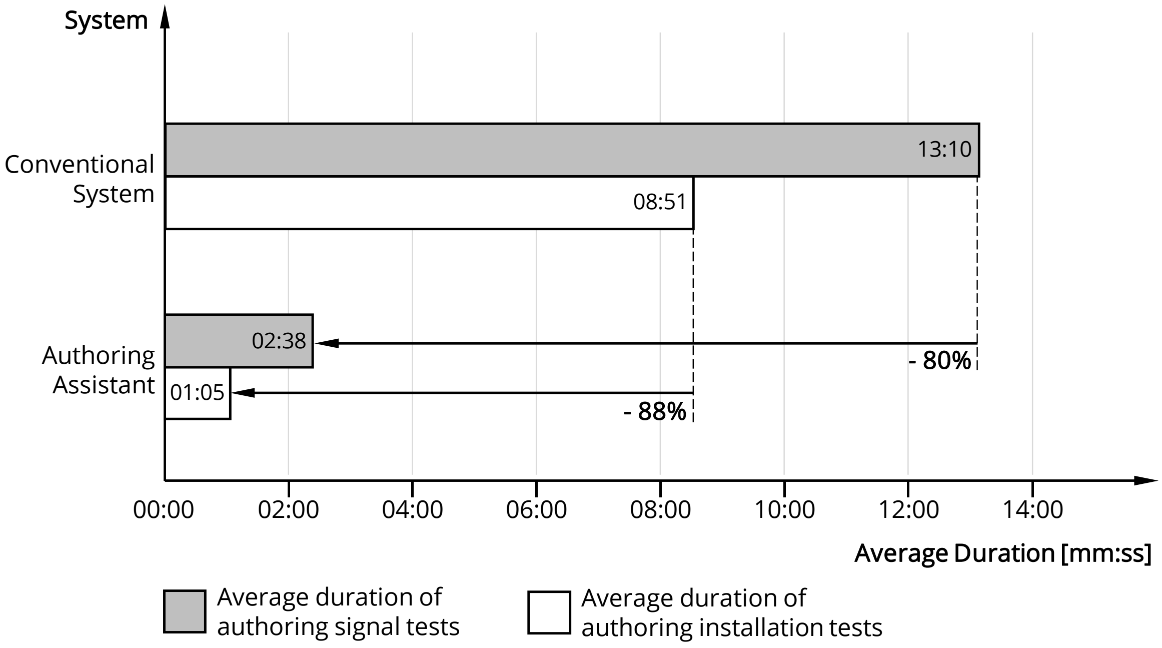


Figure 72: Average duration of authoring commissioning tests using the conventional system and the authoring assistant (n=10)

Since that the innovative process using the digital assistant includes arranging commissioning tests in a viable sequence according to technical dependencies, the duration for creating a testing sequence was also considered in the evaluation. Accordingly, the total average duration is presented in Figure 73.

Figure 73 demonstrates that the overall average duration of the authoring process was reduced by 78% when utilizing the authoring assistant. In order to assess the statistical significance of the findings, the *paired t-test* [Bort10, P. 120–122] was employed since it is usable when comparing the mean difference between two groups. The t-test demonstrated a significant difference between using the authoring assistant and the conventional system for authoring commissioning tests, thus rejecting the null hypothesis (see Appendix I for calculation details) [Schm23, P. 49]. This concludes the following:

> *"The use of the developed authoring assistant significantly decreases the time needed to author commissioning tests in comparison to conventional tools like Word and Excel."*

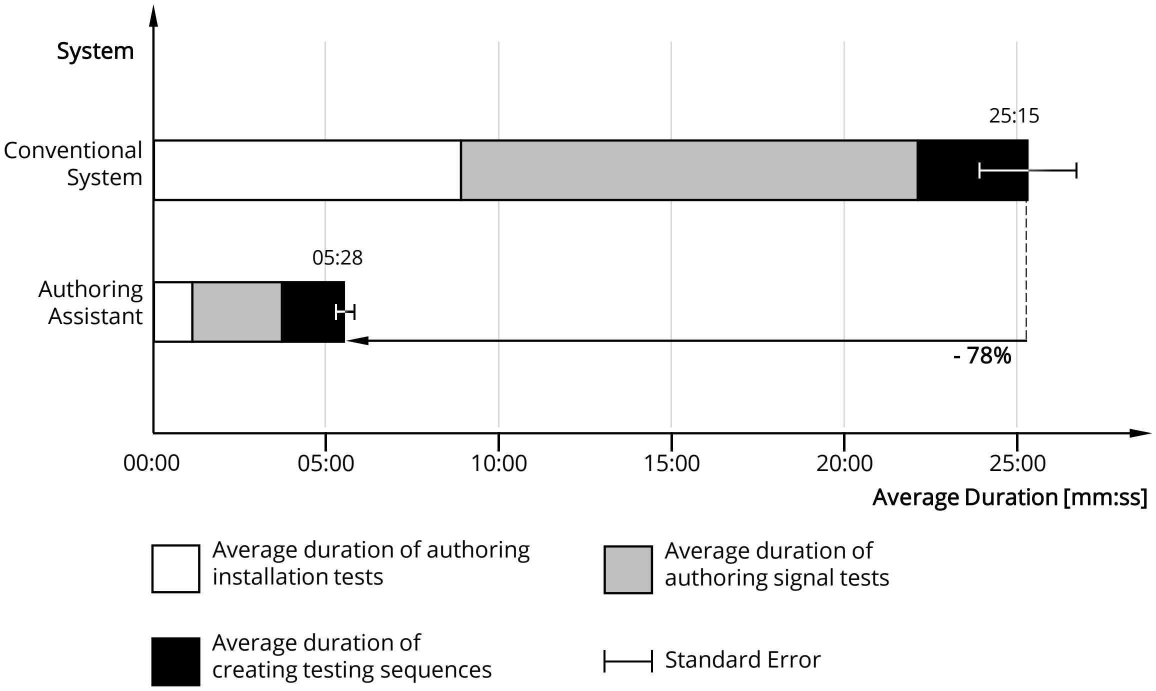


Figure 73: Total average duration including the time for creating testing sequences (n=10)

As previously mentioned, to evaluate the reliability of the authoring assistant, the number of errors made by participants were counted. Figure 74 shows the error rate per participant.

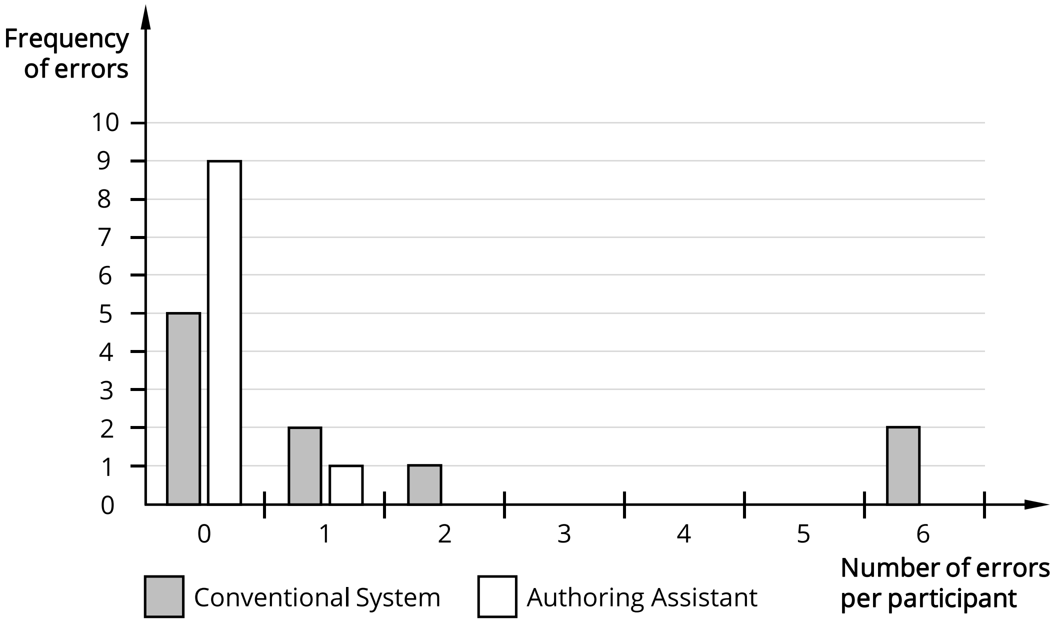


Figure 74: Error rate per participant (n=10)

When analyzing the data presented in Figure 74, it can be determined that with the conventional system, 5 out of 10 participants managed the authoring process without committing any errors. The average number of errors per participant using the conventional system was found to be 1.6. On the other hand, when utilizing the authoring assistant, 9 out of 10 participants managed the authoring process without committing any errors, and the average number of errors per participant using the authoring assistant was found to be 0.1. These results indicate a decrease of 94% in the error rate when due to the use of the authoring assistant. Additionally, the t-test was utilized and demonstrated a statistically significant difference, which rejects the null hypothesis and leads to the following conclusion:

"The use of the developed authoring assistant for authoring commissioning tests significantly reduces the error rate in comparison to conventional tools like Word and Excel."

Usability Assessment Results

A direct comparison between the conventional system and the authoring assistant in terms of user satisfaction is conducted using the System Usability Scale (SUS) and the User Experience Questionnaire (UEQ). Figure 75 depicts the frequency distribution of SUS ratings. The ratings for the digital assistant indicate a higher level of user satisfaction. The statistical analysis via the t-test reveals significant differences in the SUS scores. Therefore, the null hypothesis must be rejected. The mean score for the authoring assistant is approximately 83. This value is considered *good* and falls slightly below an *excellent* score. The mean score for authoring tests with Word/Excel is 46. This value is considered *poor*.

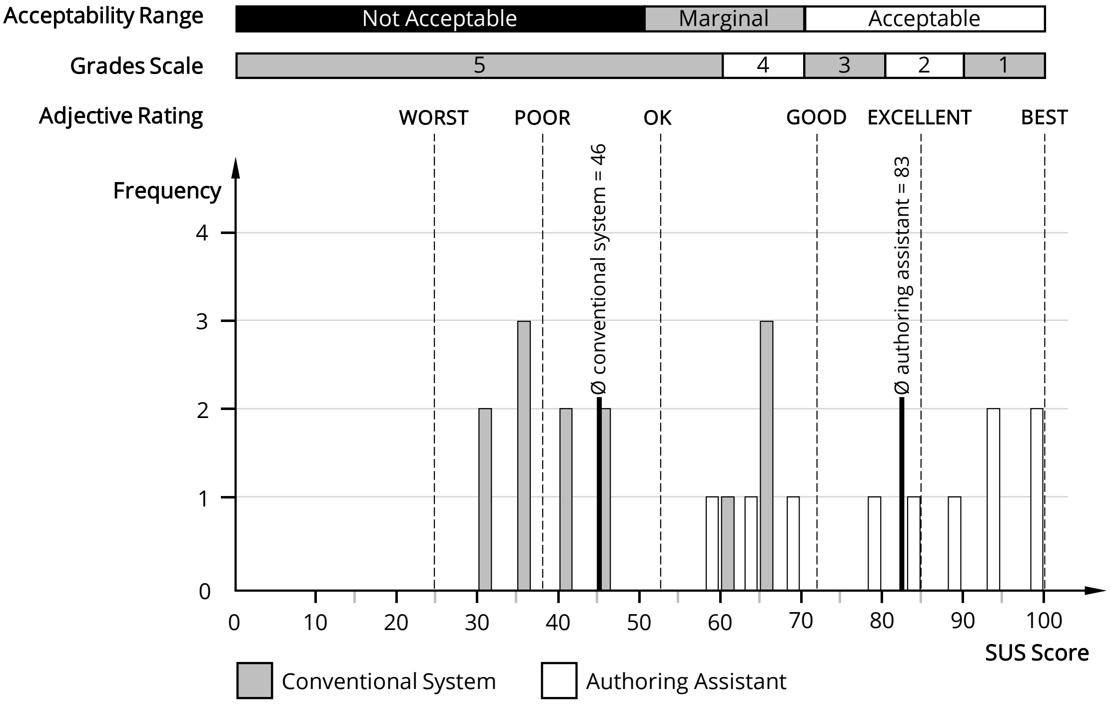


Figure 75: SUS evaluation result for commissioning preparation (n=10)

The second method used for usability assessment is the UEQ (see Appendix F). The UEQ covers the impression of the user in terms of factors such as *efficiency* (speed and organization of software), *perspicuity* (ability to quickly learn the software), *dependability* (predictability and controllability of software), *originality* (creativity and innovation), and *stimulation* (interest and excitement) [Laug08, P. 69]. shows the evaluation results of the UEQ.

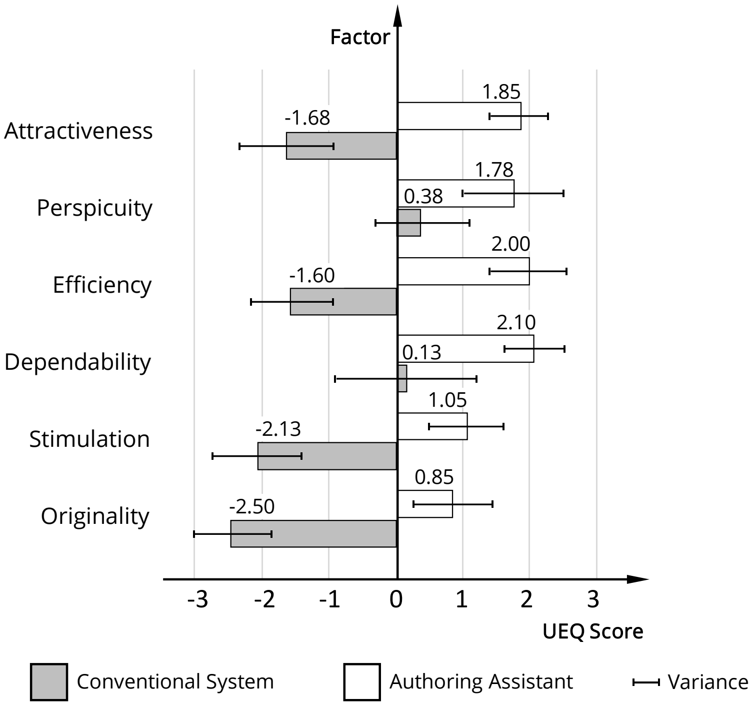


Figure 76: UEQ evaluation result – commissioning preparation (n=10)

The results presented in demonstrates that the authoring assistant received the highest ratings in terms of efficiency and dependability. This suggests that the user perceives the software as capable of quickly and reliably completing tasks in an organized manner. Conversely, the authoring assistant received relatively low ratings in terms of stimulation and originality. One possible explanation is that the user interface of the authoring assistant was specifically designed to handle practical technical tasks. Put simply, the solution does not prioritize the uniqueness of the interface over its functionality.

The conventional system received the highest ratings in terms of clarity and reliability. This is logical because the system incorporates generic tools like Word and Excel, which the participants are already familiar with. However, the scores of these factors are still lower than these of the authoring assistant. Moreover, the system received the lowest rating in terms of stimulation and originality, which is also comprehensible.

When analyzing the authoring assistant's UEQ results in comparison to existing software in the industry to determine benchmarking (see Appendix G), the authoring assistant demonstrates above average results. This outcome indicates that the software fulfills the requirements of user acceptance.

7.2.3 Discussion

The authoring assistant has been evaluated through industry and laboratory assessments, which have confirmed that the developed solution meets the requirements for improving the commissioning preparation process. Moreover, the evaluations have shown that the authoring assistant outperforms the conventional method in terms of productivity, reliability, and user acceptance.

That said, it is crucial to note that the results of the industry assessment vary from those of the laboratory assessment in regards to the enhancement of productivity. For example, the industry evaluation projected a 20% reduction in time by utilizing the authoring assistant, whereas laboratory experiments indicate a significantly higher decrease of nearly 80%. The absence of a systematic explanation for this difference within the scope of this evaluation is attributed to the inability to conduct large-scale practical experiments at the industry. However, interviews with industry experts revealed that their analytical estimating results were influenced by their experiences with other automation-based solutions in the field of shipbuilding.

Moreover, it is crucial to acknowledge that the laboratory tests were conducted independently without integrating an actual PLM system. Therefore, in the future, it is essential to employ a comparable experiment by incorporating real data from a PLM system to fully assess the system's capabilities.

Finally, when considering usability and user acceptance, it is crucial to critically examine the participants' statements regarding their evaluation of usability. Especially that the participants of the experiment lacked practical experience in the field of maritime commissioning. Moreover, since that most of the laboratory experiment participants were students, it can be inferred that the participants' age makes them more likely to be receptive to new technologies, as opposed to the personnel of the shipyard.

7.3 Quantitative Assessment of the Commissioning Assistant

This section provides a *quantitative* assessment of the *commissioning assistant* that was introduced in in Section 6.4. The objective is to measure the impact of utilizing the commissioning assistant on the productivity of the *commissioning team*, as compared to the conventional process. Moreover, the evaluation also includes a systematic usability assessment, which is necessary for measuring user acceptance in accordance with requirement *A2*. In order to obtain reliable results, the system undergoes an initial assessment in an actual industrial setting (Section 7.3.1), followed by an assessment in a controlled laboratory setting (Section 7.3.2).

7.3.1 Industrial Setting

For achieving quantitative assessment of the commissioning assistant at the shipyard, the method of *analytical estimating* is used. The decision to perform an estimation rather than an experiment is motivated by the difficulties associated with conducting extensive large-scale experiments at the shipyard (see Section 7.2.1). An overview of the evaluation method and design is presented in Section 7.2.1. Therefore, Section 7.3.1 will exclude specific details about the evaluation setting to avoid redundancy. Consequently, the results of the productivity evaluation for the commissioning assistant will be presented and discussed directly.

Productivity Assessment Results

As a result of non-disclosure agreements (NDAs), it is not permissible to disclose or discuss the raw data that represent the estimated duration of tasks performed by the commissioning team at the shipyard. Consequently, the results are expressed as percentage values that describe the estimated change in average duration for each task by using the commissioning assistant for commissioning implementation and documentation (see Figure 77).

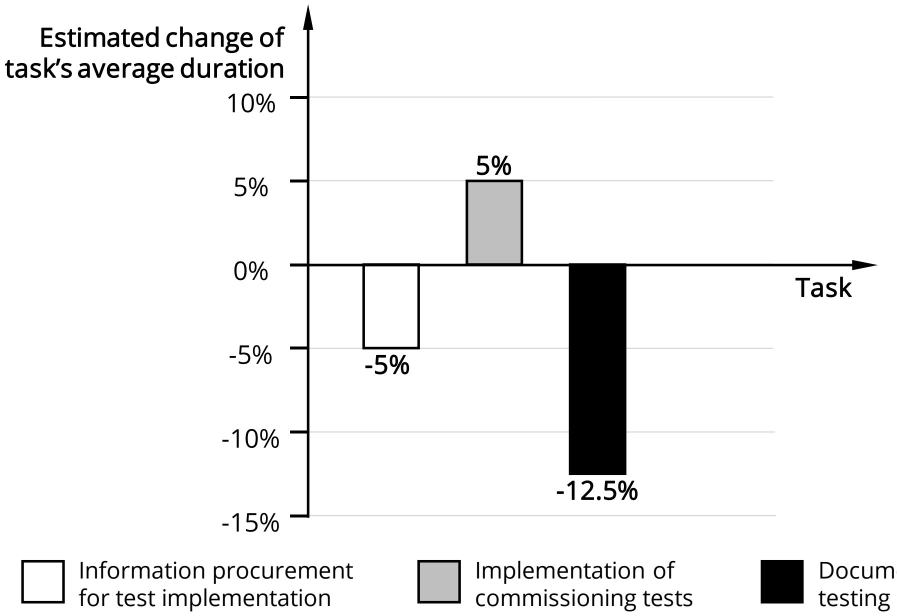


Figure 77: Estimated reduction of task's average duration through the use of the commissioning assistant (n=2)

As shown in Figure 77, the experts estimate that the commissioning assistant can *decrease* the time required for information procurement by 5%. Information procurement involves various tasks, including retrieving tasks specified in the commissioning plan, ensuring the fulfillment of test requirements, navigating to the testing location, and locating equipment and systems on board. Through one-to-one interviews, the experts emphasized that they consider navigation to the testing location to be a vital functionality that would further reduce the time of information procurement. However, as a result of the limitations outlined in Section 6.4.7, this functionality was not fully implemented. Hence, the projected decrease in the duration for information procurement through the commissioning assistant was only 5%.

Conversely, the experts estimate that the involvement of the commissioning assistant will *increase* the duration of commissioning tests by 5%. The experts attribute the increase in time to the introduction of a new device (hand-held tablet) on board, which could cause physical limitations to the commissioning team when conducting the commissioning tests. However, the experts assert that despite the initial time increase, the use of the commissioning assistant is expected to yield other benefits such as improved documentation efficiency and enhanced information archival capabilities. Consequently, the experts estimate a decrease of 12.5% in the time required for documentation of testing results.

7.3.2 Laboratory Setting

Despite the industry evaluation suggesting improved productivity with the use of the commissioning assistant, it is important to note that the sample size was too small (n=2) to draw any statistically significant conclusions. Moreover, the industry evaluation was based on estimation. Consequently, practical laboratory experiments with a higher sample size (n=10) were conducted. This section discusses the laboratory experiments that were carried out, focusing on their objectives, design, and the final results obtained regarding productivity and usability.

Hypothesis, Objectives, and Experimental Design

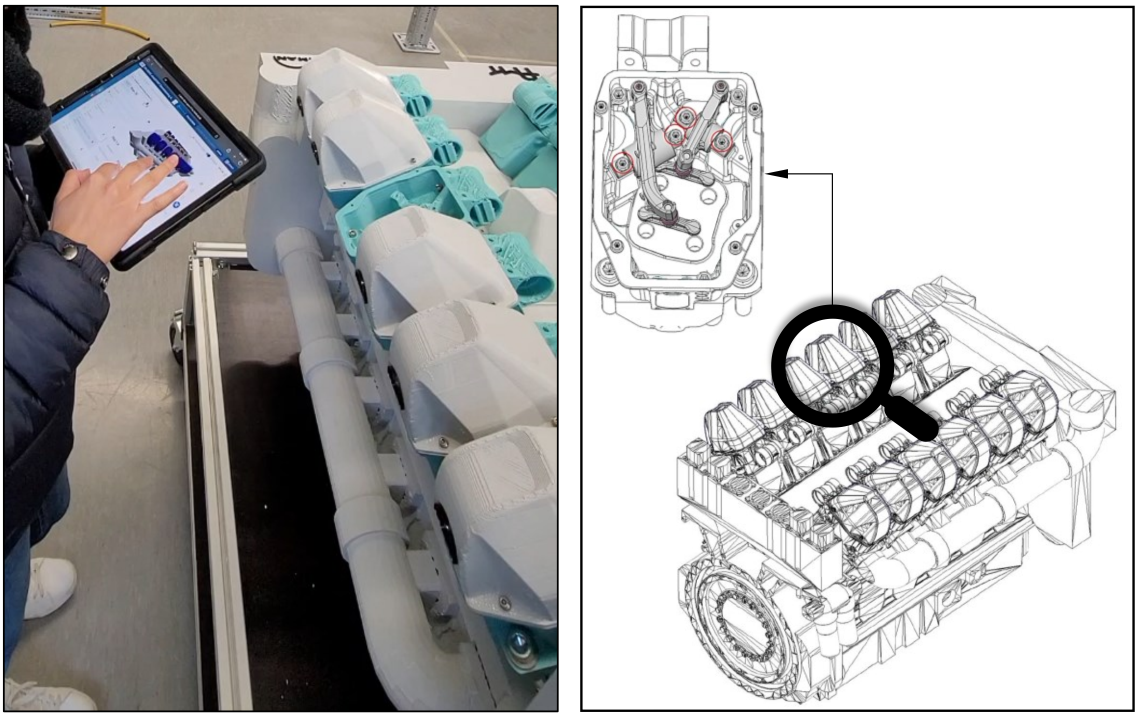
The experiment seeks to test the hypothesis that the innovative workflow using the commissioning assistant outperforms the paper-based workflow in terms of efficiency and ease of use for commissioning implementation and documentation. Hence, a null hypothesis can be stated as follows: "*There is no difference in the time needed for implementing and documenting commissioning tests or in the user acceptance levels between the commissioning assistant and the conventional workflow*". Therefore, the target variables selected for experimental design are time for information procurement, test implementation, and documentation, and the level of user acceptance. The selection of these target variables was based on the pre-established requirements outlined in Section 4.2. Furthermore, the utilization of these target variables simplifies the comparison to the analytical estimating outcomes obtained from the industry (refer to Section 7.3.1).

In order to assess the targets mentioned above, an experiment was set up in which each participant was instructed to complete two tasks. The first task entailed conducting an *installation test* for a particular ship system, namely a motor, utilizing either the conventional workflow involving paper or the innovative workflow involving the commissioning assistant. The second task entailed conducting a *signal test* for the same system, utilizing either the conventional workflow or the commissioning assistant. It is important to mention that the participant did not use the same workflow for both tasks in order to reduce the influence of the learning effect in the experiment. After finishing the tasks, every participant was asked to take part in usability surveys. Finally, the participants were interviewed to give their personal feedback in regards to both workflow variations.

Productivity Assessment

To prepare the participants for the experiment, each participant was provided with an introductory explanation of the maritime commissioning process. Afterwards, the participant was instructed to assume the role of a member of the commissioning team responsible for conducting an installation test on a ship motor. The objective was to disassemble a specific cylinder head of the motor and verify the proper installation of all internal components within the cylinder head. To conduct the installation test using the conventional workflow, the participant was provided with physical paper documents that included a description of the task, the protocols for documentation, and the technical drawings. On the other hand, when conducting the installation test using the innovative workflow, the participant was provided solely with the commissioning assistant. The participant received training on how to use the commissioning assistant before beginning the experiment.

Figure 78 displays the motor used in the experiment, which was 3D printed to avoid the size and logistic limitations of obtaining a real ship motor. The figure shows a participant utilizing the commissioning assistant to conduct the test (innovative workflow). For participants of the conventional workflow, the figure also illustrates an instance of the technical drawings that was provided in hard copy to the participant for the purpose of localization and identification of components within the motor.



Installation test using the commissioning assistant Installation test using the conventional workflow

Figure 78: Installation testing using the conventional and innovative workflow (n=10)

After the installation testing is concluded, the second phase of the experiment begins. During this phase, the participant was required to conduct a signal test by capturing simulated sensor readings from a screen. The screen mimics interfaces of analog and digital sensors. To conduct the signal testing using the conventional workflow, the participant was provided with physical paper documents that included a description of the task and the protocols for documentation. On the other hand, when conducting the signal test using the innovative workflow, the participant was provided solely with the commissioning assistant which was connected to the Digital Twin to capture the signal readings automatically from an OPC UA server.

It is worth mentioning that the entire experiment was filmed using a video camera for the purpose of accurate analysis. The videos facilitated the process of breaking down the tasks into categories and accurately recording the duration of each task. The tasks were classified into three categories according to the previously defined target variables as follows: *information procurement*, *test implementation*, and *documentation*. It's also worth noting that the experiment scenario is based on the work of a student project [Karl23] which was supervised as a part of this doctoral research.

Figure 79 shows the average duration for commissioning implementation and documentation of installation tests using both the conventional and innovative workflows.

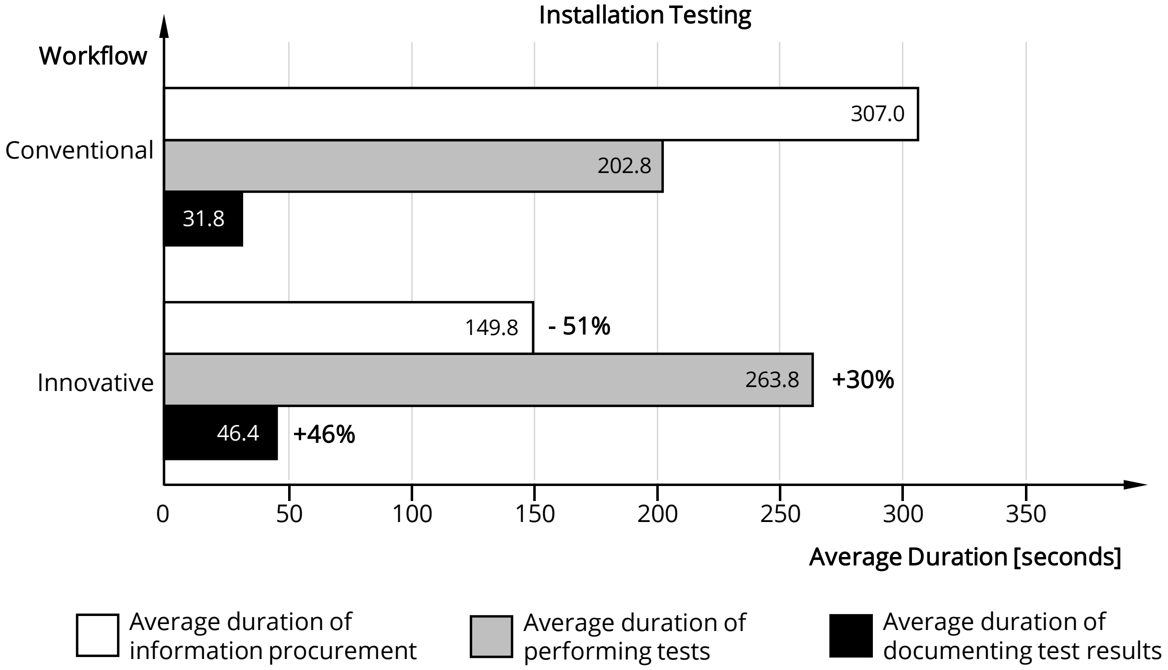


Figure 79: Average duration for commissioning implementation and documentation of installation tests using the conventional and the innovative workflow (n=10)

The data demonstrates that the commissioning assistant achieves a decrease of 51% in the time required for information procurement. The participants' statements suggest that the decrease in time can be attributed to the utilization of 3D localization features in the commissioning assistant. The majority of the participants acknowledged the usefulness of this functionality for identifying the motor’s cylinder head required for testing.

In contrast, the data suggests that the commissioning assistant *increases* the duration of conducting the installation tests by 30%. It also increases the time for documenting the testing results by 46%. This rise can be attributed to the fact that running the tests using a *valuable* physical device, such as a tablet, equipped with the commissioning assistant software, may impose physical constraints on performing the actual testing tasks. To clarify, it was observed that during the disassembly of the motor’s cylinder head in the laboratory experiment, the participants would walk away from the motor in order to place the tablet device in a secure location to avoid damage to the device. Each time the participants required to retrieve information from the tablet or document testing results, they had to walk to the location where the tablet was placed. These recurring movements caused an increase in the time needed to complete physical tasks, such as assembling or disassembling the cylinder’s head. Also, the documentation time increased accordingly. In the conventional workflow, the participants did not need to store the papers in a distant location. Instead, they simply placed the paper directly on the motor being tested which speeded up the process of testing and documentation.

Furthermore, even though the experiments indicate that the use of the commissioning assistant leads to slower testing and documentation, it is crucial to note that the documentation results submitted through the commissioning assistant are organized in a structured manner, in contrast to documenting the results on paper. In other words, the commissioning assistant leads to other benefits than time reduction when it comes to implementation and documentation of installation tests. To further investigate the change in average duration using the commissioning assistant, Figure 80 shows the results in the case of *signal testing*.

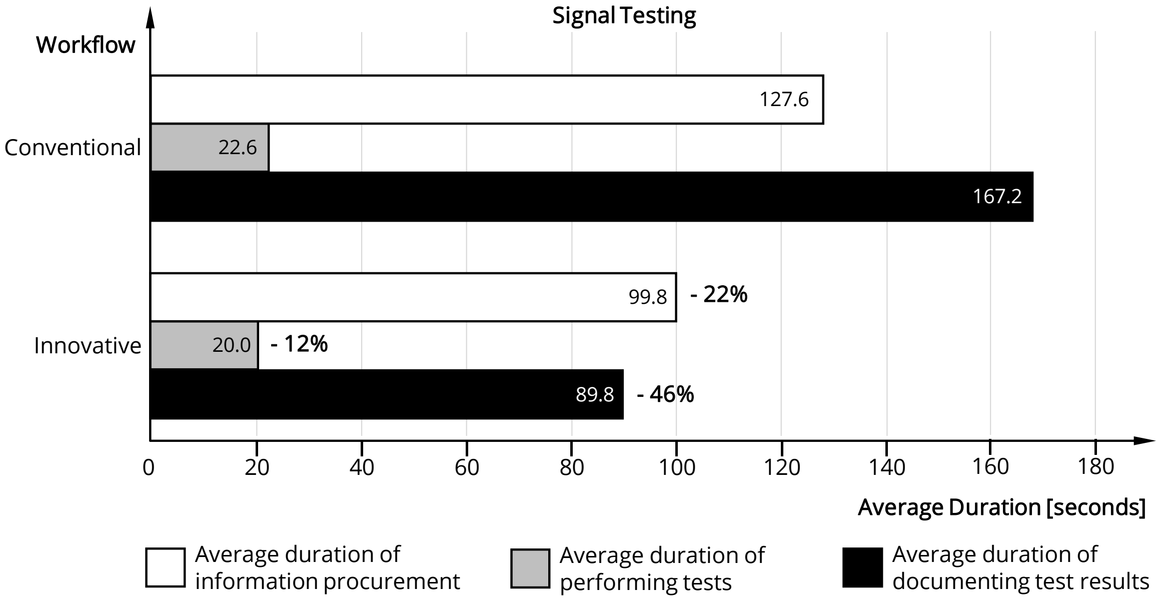


Figure 80: Average duration for commissioning implementation and documentation of signal tests using the conventional and the innovative workflow (n=5)

The results depicted in Figure 80 indicate that the commissioning assistant reduces the time needed for information procurement by 22%. The decrease can be attributed to the participants no longer needing to manually search for the sensors that produce the measurement values to be captured, as the values are now automatically captured through the OPC UA server. The same rationale applies when examining the results for the average duration of documentation where the commissioning assistant achieves the highest reduction in time, with a decrease of 46%.

Regarding the duration for the actual execution of tests. The time difference between the innovative workflow and the paper-based workflow was relatively low. The commissioning assistant achieved a reduction of 12% in this particular case. The slight difference is logical as the signal testing procedure does not involve intricate operations such as assembly or disassembly. Instead, it primarily entails extracting data from sensors and monitoring equipment response to specific signal.

In reality, ship systems necessitate installation testing, as well as signal and/or functional testing. Hence, Figure 81 shows the cumulated results for both installation and signal tests. Results were cumulated to make an overall conclusion about the productivity benefits of the commissioning assistant.

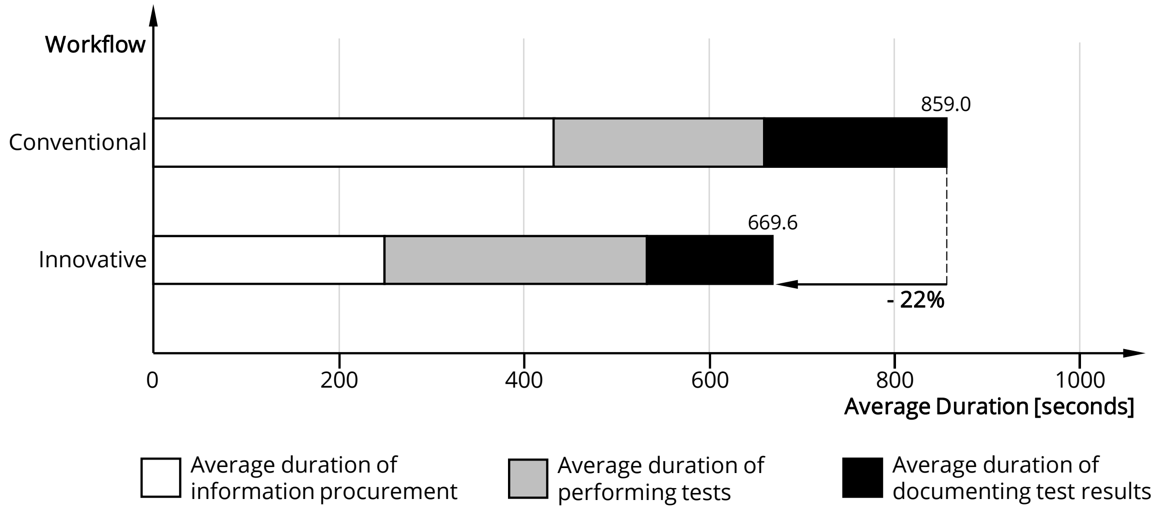


Figure 81: Cumulated average duration for commissioning implementation and documentation (n=10)

The data presented in Figure 81 demonstrates that the utilization of the commissioning assistant leads to an overall reduction of 22% in the time required for commissioning implementation and documentation. The most noticeable decrease is observed in the context of information procurement. In summary, the commissioning assistant decreases the duration of information procurement by 43%. Additionally, it decreases the duration for documentation by 32%. Conversely, the findings suggest that the commissioning assistant increases duration of testing by 26%.

It is important to mention that when performing the two-sample t-test for examining statistical significance, it was shown that the results are *not statistically significant* (see Appendix J for calculation details). Therefore, the following conclusion can be made:

> *"The use of the developed commissioning assistant shows potential for reducing the overall time needed for commissioning test implementation and documentation. However, due to the statistically insignificant results, the null hypothesis, which indicates that there is no difference between the innovative and the conventional workflow for productivity enhancement, cannot be rejected"*

Usability Assessment

A direct comparison between the conventional workflow and the innovative workflow in terms of user satisfaction is conducted using the System Usability Scale (SUS) and the User Experience Questionnaire (UEQ).

Figure 82 depicts the distribution of SUS ratings. The ratings for the commissioning assistant indicate a higher level of user satisfaction. The mean score for the commissioning assistant is approximately 77. This value is considered *good*. The mean score for conventional workflow is 53. This value is considered *OK*. The statistical analysis via the t-test reveals significant differences in the SUS scores. Therefore, the commissioning assistant is considered more satisfactory than the conventional workflow.

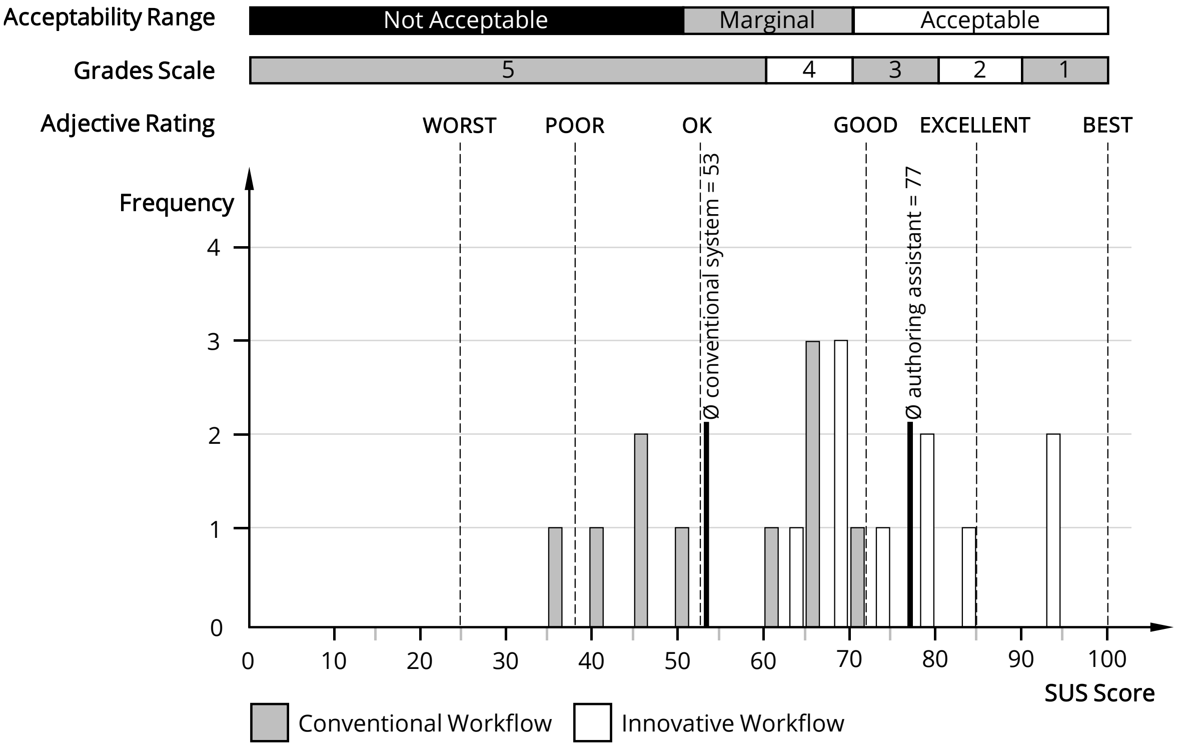


Figure 82: SUS evaluation result for commissioning implementation and documentation (n=10)

The second method used for usability assessment is the UEQ. Details about the UEQ, and the reason for using this method are discussed in Section 7.2.2. Figure 83 shows the result of the UEQ for both the conventional and the innovative workflows.

The results presented in Figure 83 demonstrate that the commissioning assistant received the highest ratings in terms of originality and stimulation. This suggests that the user found the interface of the system to be appealing and interactive in a way that promotes engagement and long use. Conversely, the commissioning assistant received lower ratings in terms of dependability and perspicuity. According to the statements of the participants, they felt that they required a longer time than planned to learn the system. The majority of the participants also commented that they felt the features for toggling different views such as the full screen view for 3D models and the view for OPC UA measurements could have been better implemented to save time and effort. These comments could be the reason of why the system was rated relatively low in terms of efficiency and perspicuity.

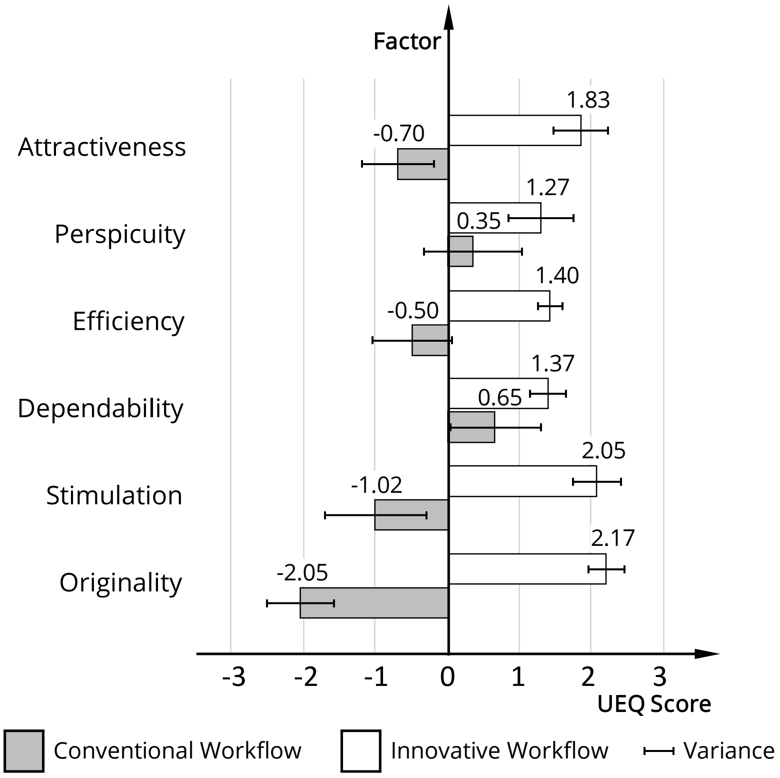


Figure 83: UEQ evaluation result – commissioning implementation and documentation (n=10)

The conventional workflow received its highest ratings in the factors of perspicuity and dependability. This result is logical because the conventional workflow incorporates paper documents, which the participants do not need to spend a long time to learn the structure of, as opposed to a system that employs a multimodal graphical user interface. That said, the ratings of these factors are still lower than these of the commissioning assistant. Moreover, the conventional workflow received the lowest ratings in terms of stimulation and originality, which is also comprehensible due to using paper documents.

Upon analyzing the commissioning assistant's UEQ results and comparing them to the benchmark results of software currently used in the industry, it is shown that the commissioning assistant demonstrates above-average results (see Appendix H). This outcome indicates that the developed commissioning assistant meets the requirements for user acceptance.

7.3.3 Discussion

The commissioning assistant has been evaluated through industry and laboratory assessments, which have showed that the innovative workflow outperforms the conventional workflow in terms of productivity and user acceptance.

Moreover, the laboratory experiments validate the conclusion made from the industry evaluation, which was based on analytical estimation. The conclusion can be summarized as follows: "*The commissioning assistant has the potential to improve productivity by reducing the time needed for information procurement and documentation"*. Nevertheless, both industry and laboratory assessments demonstrate that employing the commissioning assistant can lead to an increased time for performing the commissioning tests, particularly during installation testing. This is primarily due to the physical constraints imposed by introducing a physical device (hand-held tablet) to the workflow of the commissioning team. However, due to the lack of statistical significance in the laboratory experiment results, further investigation of this effect is necessary.

It is worth nothing that experts from the shipyard have affirmed that incorporating the commissioning assistant offers additional advantages, notably in attaining systematic and well-organized documentation and archiving of information, in comparison to the conventional workflow. To elaborate, the digital documentation, enabled by the commissioning assistant, offers new possibilities that were previously unavailable with conventional documentation methods. For example, the automated collection of measurement values allows for the potential implementation of *digital certification* for commissioning protocols during the final acceptance testing, involving both the client and regulatory representatives from classification societies. This means that using a commissioning assistant, equipped with IoT technology, facilitates running a sample of tests within a relatively short timeframe during the final acceptance stage to validate the measurement values captured from several systems on the ship. In summary, digital documentation provides more dependable results, ultimately increasing confidence in the captured data which promotes a digital certification process for commissioning test results.

Furthermore, uniform digital documentation data enables the application of advanced data analysis methods to systematically identify any deficiencies in the commissioning workflow and continuously take appropriate action to enhance the workflow. In addition, having a well-organized database of all testing results enables the efficient authoring of maintenance plans, which can be implemented using dedicated Digital Assistance Systems for maintenance.

The shipbuilding experts' remarks regarding the added benefits of digital documentation achieved using the commissioning assistant imply the experts' readiness to use the commissioning assistant, even if it leads to a longer duration for conducting the commissioning tests. To quantitatively assess these benefits, it is crucial to carry out extensive experiments in the shipyard over an extended period. These experiments can determine whether the digital documentation achieved through the commissioning assistant can ultimately contribute to an enhancement in the quality and productivity of the commissioning workflow.

8 Conclusion and Future Works

This chapter presents a concise overview of the key findings and contributions made in this dissertation and offers a perspective on potential future works.

8.1 Conclusion

Maritime commissioning is a highly complex process in shipbuilding in which all of the ship's systems and components undergo testing to ensure compliance to client specifications and regulatory standards before the ship can be put into operation. The analysis conducted in this dissertation revealed several shortcomings in the conventional commissioning process. These include extensive time and effort in preparing the commissioning plan due to the lack of automation, inefficient implementation and documentation procedures due to reliance on paper-based workflows, and suboptimal information management due to the lack of centralized information systems.

The objective of this dissertation was to develop a software solution that addresses the shortcomings of the conventional maritime commissioning process and enhances the workflow of the shipyard’s commissioning personnel. To develop a suitable solution that can resolve the previously mentioned shortcomings, systematic research had to be first conducted. Since the research focused on a problem within the shipbuilding industry, it was necessary to conduct the research with close contact to shipbuilding experts. Accordingly, three prominent shipyards in Germany were involved in the research work for a duration of three years. The shipyards took part in activities such as analyzing the conventional process, determining the necessary solution requirements, and evaluating the implemented solution. The research was conducted following the framework of the Design Science Research (DSR) methodology [Hevn04, P. 80]. As a result, the solution developed within the framework of this dissertation was a *Digital Assistance System* (DAS) comprising three products or artifacts: an *authoring assistant* for commissioning preparation, a *commissioning assistant* for implementation and documentation of commissioning tests, and a *Digital Twin* for centralized information management.

The DAS was set up at the shipyards and subjected to rigorous testing by experts in the field of maritime commissioning. Hence, evaluations were carried out in industrial and laboratory settings to determine the qualitative and quantitative advantages of using the DAS. The subsequent subsections provide a concise overview of each developed artifact and summarize the outcomes of the evaluation.

Authoring Assistant

The authoring assistant is a software application designed to assist commissioning personnel with creating the commissioning plan, which includes the necessary technical information for conducting testing procedures. The software's objective is to minimize the effort and time required to create the commissioning plan. This is achieved by automatically generating commissioning test specifications using a *template-based* authoring workflow. Furthermore, the authoring assistant addresses a significant issue in the conventional workflow, which is the inability to arrange commissioning tests in a viable sequence of execution. The authoring assistant employs a graph data structure and sorting algorithm to solve this problem by automatically organizing commissioning tests in a viable sequence. This sequence is determined based on factors such as *technical dependencies* between ship systems and components and *conflict avoidance* with ongoing production work.

The authoring assistant underwent systematic evaluation in both industry and laboratory settings, demonstrating a *significant reduction* in the time required to create the commissioning plan. The evaluation also demonstrated that the authoring assistant *significantly reduces* the number of errors and mistakes in the commissioning plan. Additionally, the authoring assistant obtained higher than average ratings in the usability and user acceptance assessment.

Commissioning Assistant

The commissioning assistant is a mobile software application specifically developed for on-board use, to assist commissioning personnel in executing the tests outlined in the commissioning plan. The commissioning assistant is used to substitute paper-based protocols by providing digital documentation capabilities. Accordingly, the software aims to minimize the effort and time needed for information procurement and documentation. To achieve efficient procurement of information, the approach of *context-awareness* is implemented, which eliminates the need for commissioning personnel to manually search for feasible work packages. To clarify, the commissioning assistant utilizes context-awareness to automatically search for appropriate tasks based on criteria such as fulfillment of technical dependency requirements and avoiding conflicts with ongoing production work. Additionally, the software utilizes the *Internet of Things* (IoT) technology to automatically capture measurement values from equipment, such as digital and analog sensors, resulting in reliable and efficient documentation.

The evaluation revealed that the commissioning assistant has the *potential to decrease* the overall time needed for commissioning test implementation and documentation. However, it is important to note that these findings lack statistical significance. Furthermore, the commissioning assistant achieves higher than average ratings in the usability and user acceptance assessment.

Digital Twin

The Digital Twin is as a backend server that acts as the central hub, connecting the DAS with the shipyard's IT-infrastructure. The aim of the Digital Twin is to achieve seamless transfer of information for processing and storage. A qualitative assessment conducted at the shipyards revealed the potential for successful integration of the DAS at the shipyards' infrastructure, as a result to the utilization of the Digital Twin.

8.2 Future Works

From the perspective of the *Design Science Research* (DSR) methodology, the conducted research in this dissertation contributes to the knowledge base of improving the maritime commissioning workflow through the utilization of a software artifact (the DAS). However, while the evaluation affirms the effectiveness of the artifact that was developed within this research, it also highlights areas that could be further explored through future works. Therefore, researchers aiming to add to the knowledge base should consider examining the following areas: extended industry evaluation, migration capability, and technical improvements.

Extended Industry Evaluation

Large-scale experiments to evaluate the DAS at the shipyards were not feasible due to time constraints. Instead, the productivity effects of implementing the DAS were evaluated using methods such as *analytical estimating* and *laboratory experiments*. The laboratory experiments results demonstrated statistical significance in enhancing the commissioning preparation process. However, for commissioning implementation and documentation, the DAS showed a *tendency* or *potential* for improving the workflow. That said, insights from expert interviews exposed further benefits arising from the structured digital documentation achieved with the use of the DAS. To elaborate, shipbuilding experts highlighted that maintaining organized and uniform documentation through the DAS can lead to long-term positive outcomes. These include the establishment of a more efficient and accurate digital certification process for commissioning protocols, continuous improvements in the commissioning process through advanced data analyses, and the development of effective maintenance plans.

Therefore, it is crucial to investigate the impact of utilizing the DAS for commissioning implementation and documentation on a broader scope, ideally by conducting experiments during an ongoing commissioning project at the shipyard. Moreover, when studying the effects of applying the DAS, it is crucial to take into account target variables other than just *time* and *error rate*.

Migration Capability

The integration capability of the DAS was evaluated by deploying the system at the shipyards and administering surveys to industry professionals at the shipyards. Nevertheless, for a complete transition from the conventional system to the DAS-based system, it is imperative to develop a systematic transition plan. The plan must incorporate strategies for efficiently handling substantial volumes of legacy shipyard data to make it usable with the DAS. Also, the transition plan should include strategies for implementing security measures to avoid data compromise.

Technical Improvements

This dissertation introduces the concept of *template-based authoring* for enhancing the authoring of commissioning tests. That said, using this method, the user must manually create a *template* for each class of components in the ship. These templates are required for the authoring assistant to be able to automatically generate the commissioning tests. It is crucial to explore the potential for improving this method in order to decrease the time and effort required for manual creation of such templates.

Furthermore, the algorithms designed in this work for the automatic generation of testing sequences do not take into account *time* as a determining factor. However, the DAS provides the initial stage of scheduling commissioning tests based on *technical dependency* constraints. Hence, researchers in the area of production planning and control aiming to incorporate time as a variable in automated scheduling of commissioning tasks should not find it conflicting to continue on the work presented in this dissertation.

Finally, the dissertation introduces a commissioning assistant that provides both 2D and 3D localization capabilities for accurately identifying the positions of systems and components on the ship. Nevertheless, as per the surveys conducted during the evaluation of the DAS, experts have emphasized the necessity of integrating *intelligent navigation* capabilities to calculate the most efficient routes and paths for reaching testing locations on the ship under construction. This functionality was considered essential for decreasing the initial time needed to prepare for conducting commissioning tests.

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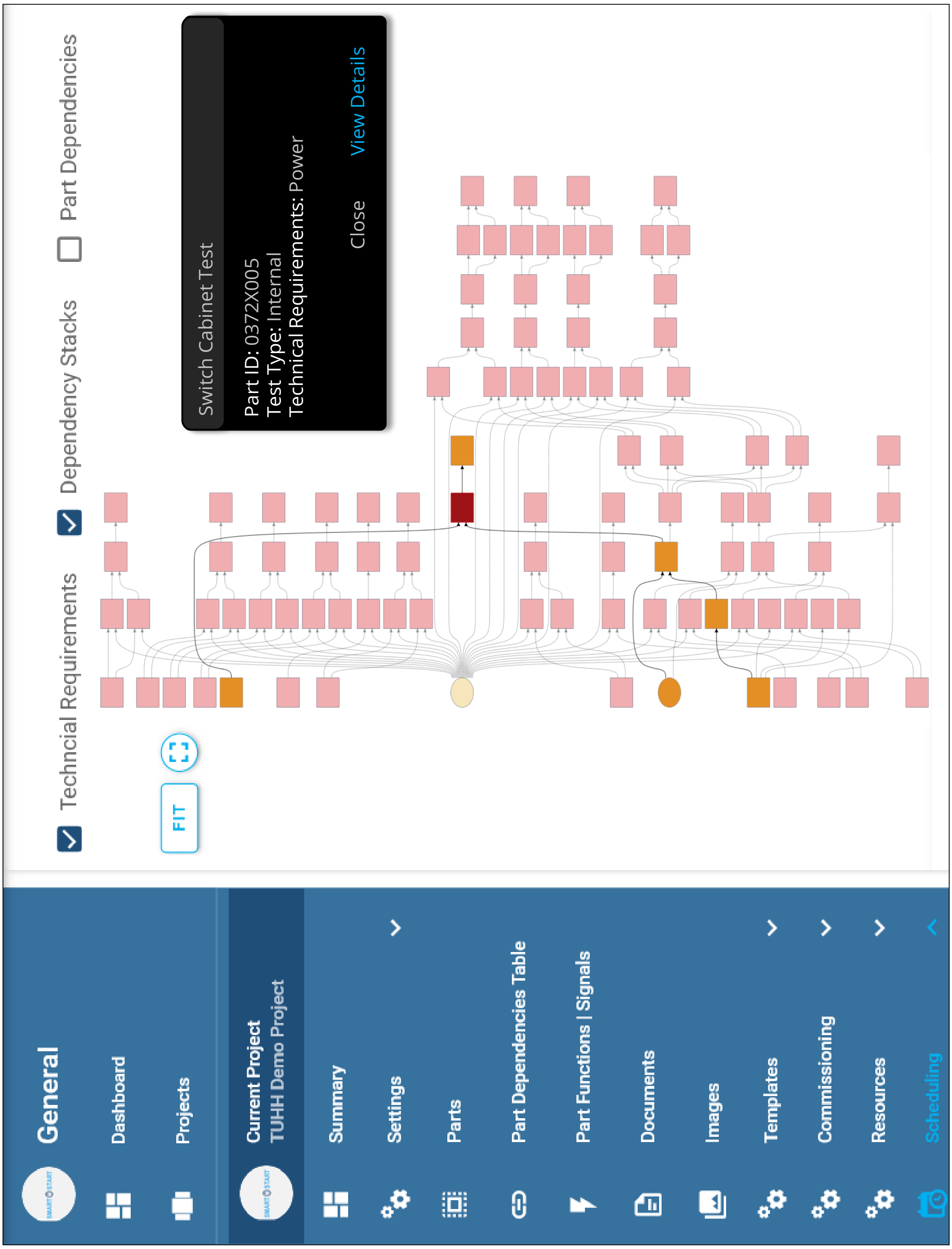
Appendix

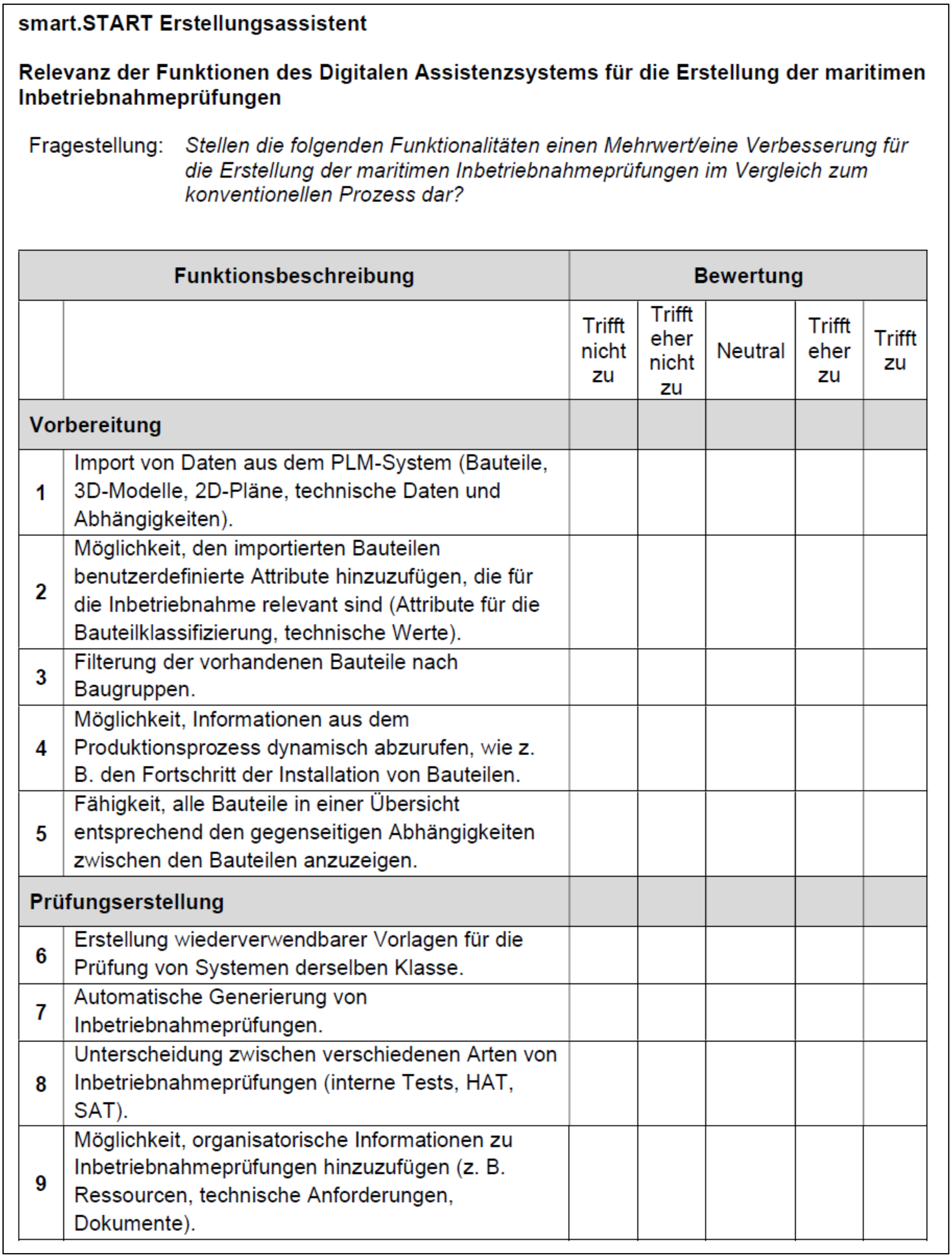
Appendix A – Dependency graph UI in the authoring assistant



Switch Cabinet Test

Part ID: 0372X005
Test Type: Internal
Technical Requirements: Power

Appendix B (1/4) – Functionality relevance survey – authoring assistant



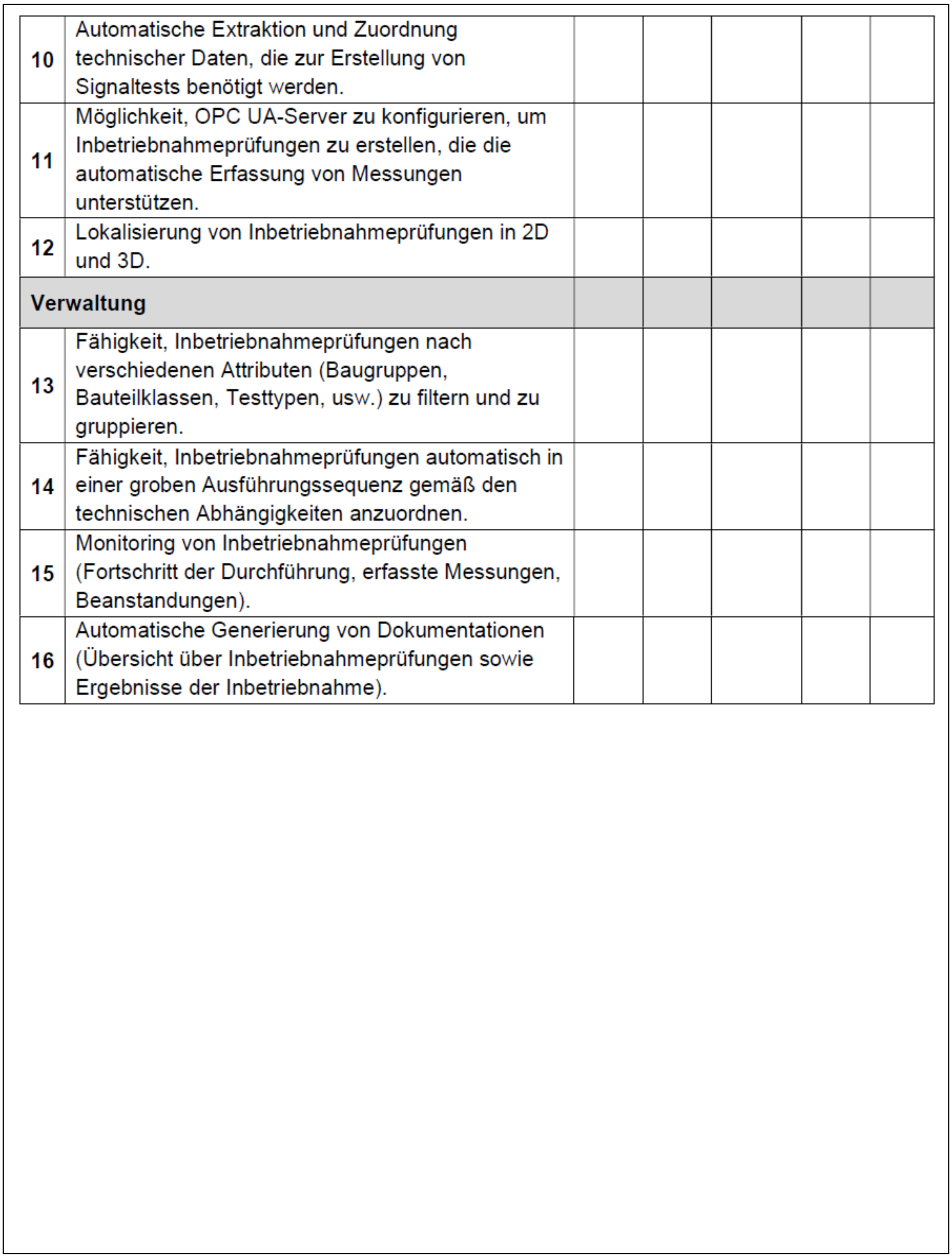
smart.START Erstellungsassistent

Relevanz der Funktionen des Digitalen Assistenzsystems für die Erstellung der maritimen Inbetriebnahmeprüfungen

Fragestellung: *Stellen die folgenden Funktionalitäten einen Mehrwert/eine Verbesserung für die Erstellung der maritimen Inbetriebnahmeprüfungen im Vergleich zum konventionellen Prozess dar?*

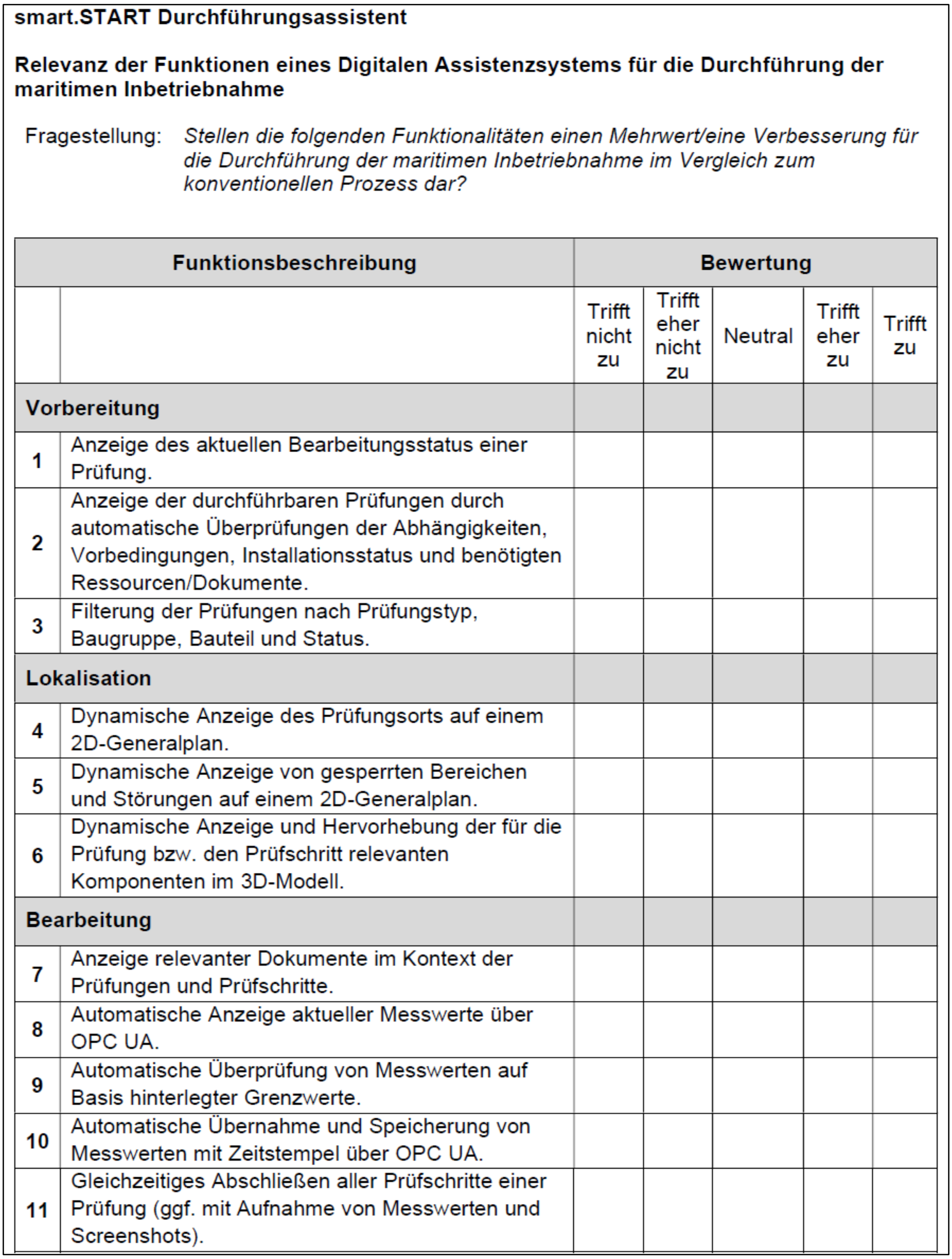
Funktionsbeschreibung		**Bewertung**				
		Trifft nicht zu	Trifft eher nicht zu	Neutral	Trifft eher zu	Trifft zu
Vorbereitung						
1	Import von Daten aus dem PLM-System (Bauteile, 3D-Modelle, 2D-Pläne, technische Daten und Abhängigkeiten).					
2	Möglichkeit, den importierten Bauteilen benutzerdefinierte Attribute hinzuzufügen, die für die Inbetriebnahme relevant sind (Attribute für die Bauteilklassifizierung, technische Werte).					
3	Filterung der vorhandenen Bauteile nach Baugruppen.					
4	Möglichkeit, Informationen aus dem Produktionsprozess dynamisch abzurufen, wie z. B. den Fortschritt der Installation von Bauteilen.					
5	Fähigkeit, alle Bauteile in einer Übersicht entsprechend den gegenseitigen Abhängigkeiten zwischen den Bauteilen anzuzeigen.					
Prüfungserstellung						
6	Erstellung wiederverwendbarer Vorlagen für die Prüfung von Systemen derselben Klasse.					
7	Automatische Generierung von Inbetriebnahmeprüfungen.					
8	Unterscheidung zwischen verschiedenen Arten von Inbetriebnahmeprüfungen (interne Tests, HAT, SAT).					
9	Möglichkeit, organisatorische Informationen zu Inbetriebnahmeprüfungen hinzuzufügen (z. B. Ressourcen, technische Anforderungen, Dokumente).					

Appendix B (2/4) – Functionality relevance survey – authoring assistant



10	Automatische Extraktion und Zuordnung technischer Daten, die zur Erstellung von Signaltests benötigt werden.					
11	Möglichkeit, OPC UA-Server zu konfigurieren, um Inbetriebnahmeprüfungen zu erstellen, die die automatische Erfassung von Messungen unterstützen.					
12	Lokalisierung von Inbetriebnahmeprüfungen in 2D und 3D.					
Verwaltung						
13	Fähigkeit, Inbetriebnahmeprüfungen nach verschiedenen Attributen (Baugruppen, Bauteilklassen, Testtypen, usw.) zu filtern und zu gruppieren.					
14	Fähigkeit, Inbetriebnahmeprüfungen automatisch in einer groben Ausführungssequenz gemäß den technischen Abhängigkeiten anzuordnen.					
15	Monitoring von Inbetriebnahmeprüfungen (Fortschritt der Durchführung, erfasste Messungen, Beanstandungen).					
16	Automatische Generierung von Dokumentationen (Übersicht über Inbetriebnahmeprüfungen sowie Ergebnisse der Inbetriebnahme).					

Appendix B (3/4) – Functionality relevance survey – commissioning assistant



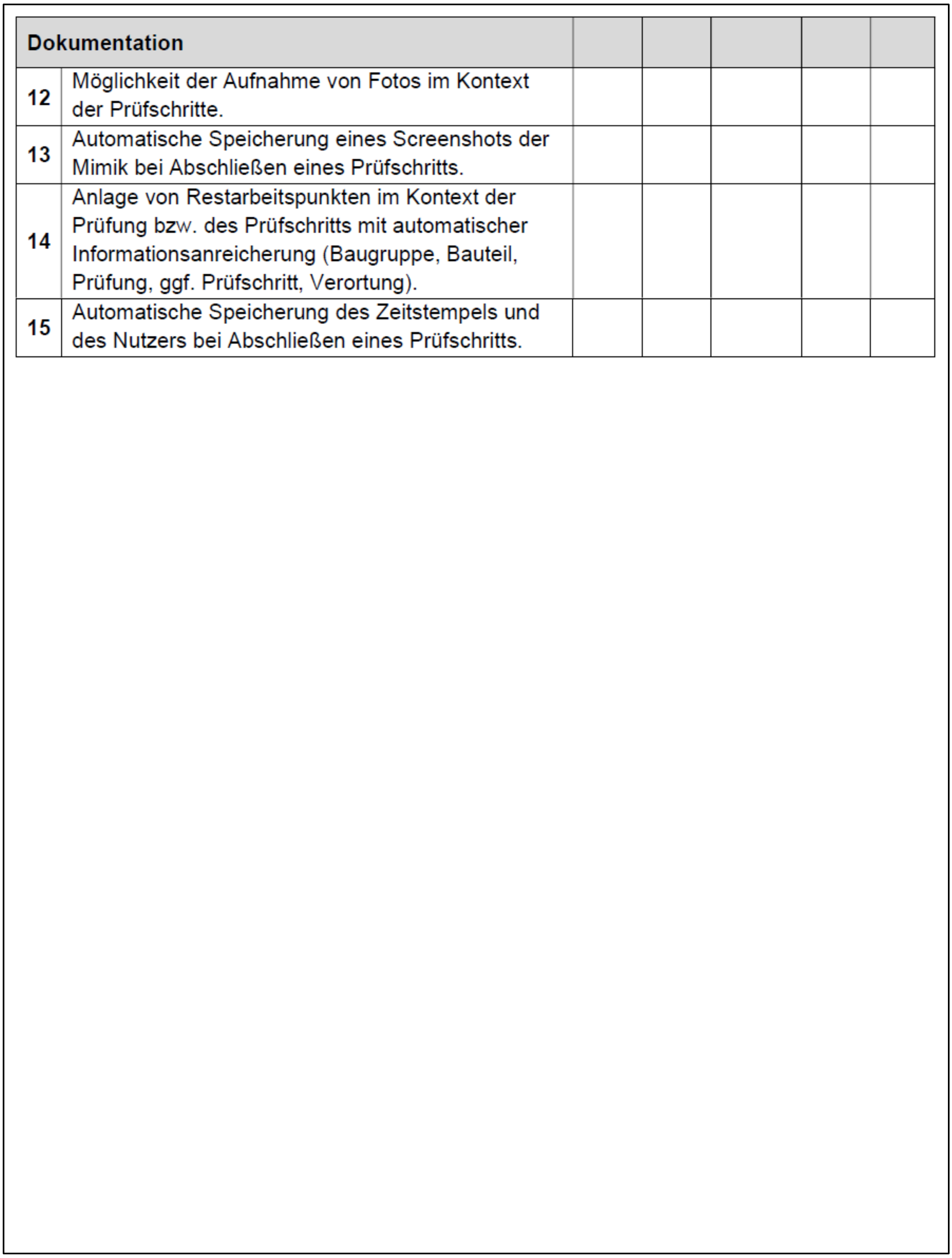
smart.START Durchführungsassistent

Relevanz der Funktionen eines Digitalen Assistenzsystems für die Durchführung der maritimen Inbetriebnahme

Fragestellung: *Stellen die folgenden Funktionalitäten einen Mehrwert/eine Verbesserung für die Durchführung der maritimen Inbetriebnahme im Vergleich zum konventionellen Prozess dar?*

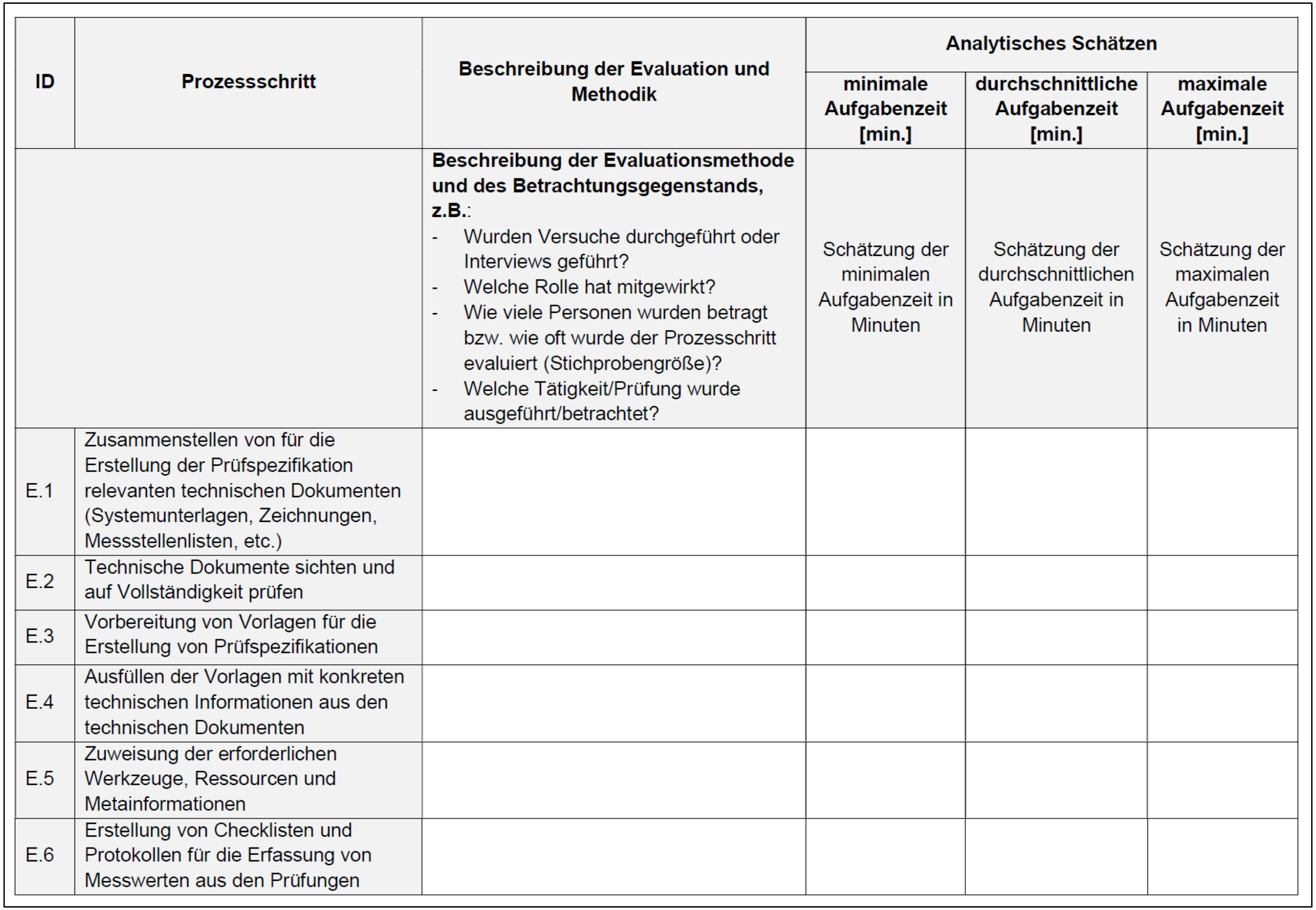
Funktionsbeschreibung		**Bewertung**				
		Trifft nicht zu	Trifft eher nicht zu	Neutral	Trifft eher zu	Trifft zu
Vorbereitung						
1	Anzeige des aktuellen Bearbeitungsstatus einer Prüfung.					
2	Anzeige der durchführbaren Prüfungen durch automatische Überprüfungen der Abhängigkeiten, Vorbedingungen, Installationsstatus und benötigten Ressourcen/Dokumente.					
3	Filterung der Prüfungen nach Prüfungstyp, Baugruppe, Bauteil und Status.					
Lokalisation						
4	Dynamische Anzeige des Prüfungsorts auf einem 2D-Generalplan.					
5	Dynamische Anzeige von gesperrten Bereichen und Störungen auf einem 2D-Generalplan.					
6	Dynamische Anzeige und Hervorhebung der für die Prüfung bzw. den Prüfschritt relevanten Komponenten im 3D-Modell.					
Bearbeitung						
7	Anzeige relevanter Dokumente im Kontext der Prüfungen und Prüfschritte.					
8	Automatische Anzeige aktueller Messwerte über OPC UA.					
9	Automatische Überprüfung von Messwerten auf Basis hinterlegter Grenzwerte.					
10	Automatische Übernahme und Speicherung von Messwerten mit Zeitstempel über OPC UA.					
11	Gleichzeitiges Abschließen aller Prüfschritte einer Prüfung (ggf. mit Aufnahme von Messwerten und Screenshots).					

Appendix B (4/4) – Functionality relevance survey – commissioning assistant



Dokumentation						
12	Möglichkeit der Aufnahme von Fotos im Kontext der Prüfschritte.					
13	Automatische Speicherung eines Screenshots der Mimik bei Abschließen eines Prüfschritts.					
14	Anlage von Restarbeitspunkten im Kontext der Prüfung bzw. des Prüfschritts mit automatischer Informationsanreicherung (Baugruppe, Bauteil, Prüfung, ggf. Prüfschritt, Verortung).					
15	Automatische Speicherung des Zeitstempels und des Nutzers bei Abschließen eines Prüfschritts.					

Appendix C (1/2) – Analytical estimating task catalog – authoring assistant

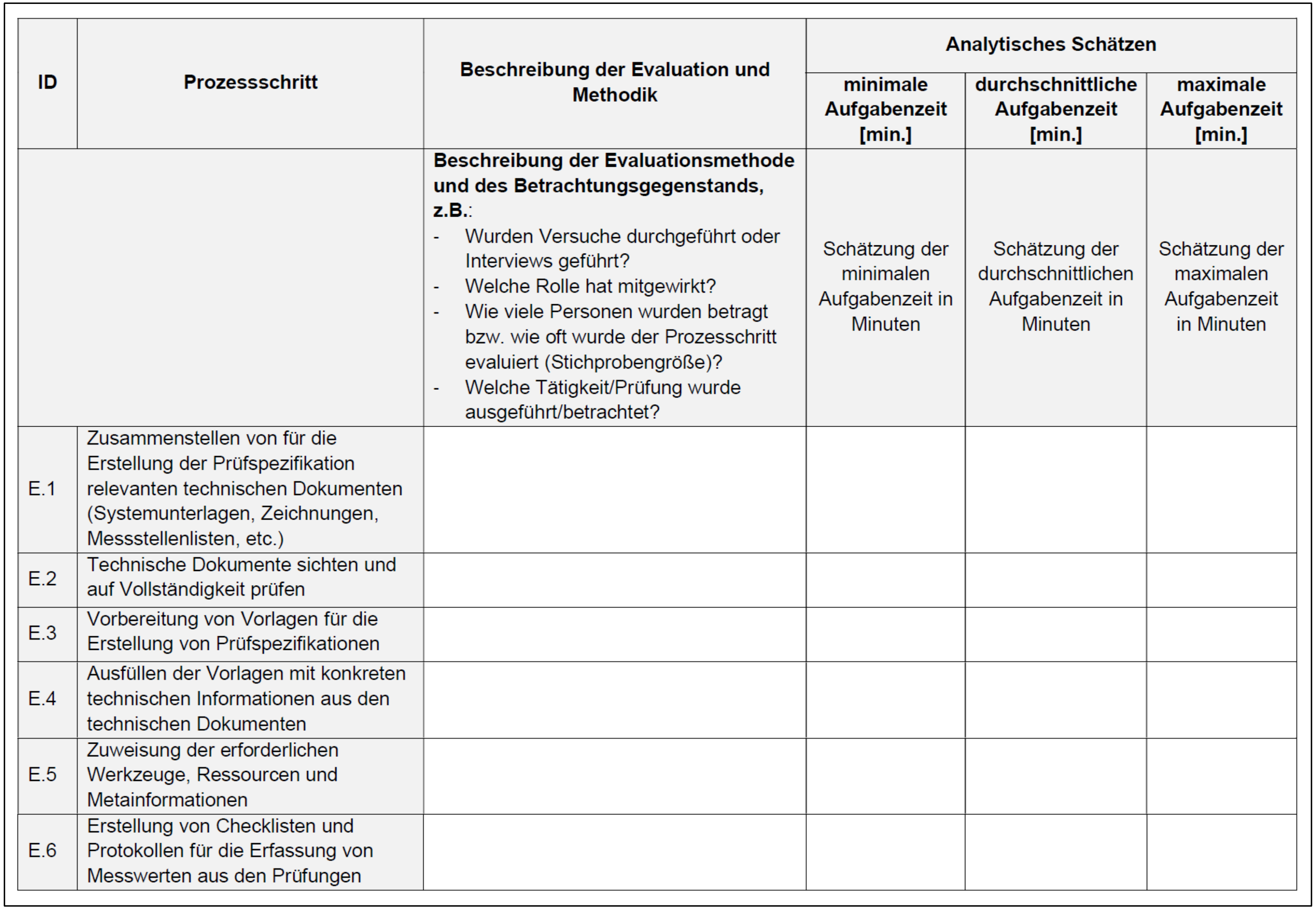


ID	Prozessschritt	Beschreibung der Evaluation und Methodik	Analytisches Schätzen		
			minimale Aufgabenzeit [min.]	**durchschnittliche Aufgabenzeit [min.]**	**maximale Aufgabenzeit [min.]**
		Beschreibung der Evaluationsmethode und des Betrachtungsgegenstands, z.B.: - Wurden Versuche durchgeführt oder Interviews geführt? - Welche Rolle hat mitgewirkt? - Wie viele Personen wurden betragt bzw. wie oft wurde der Prozessschritt evaluiert (Stichprobengröße)? - Welche Tätigkeit/Prüfung wurde ausgeführt/betrachtet?	Schätzung der minimalen Aufgabenzeit in Minuten	Schätzung der durchschnittlichen Aufgabenzeit in Minuten	Schätzung der maximalen Aufgabenzeit in Minuten
E.1	Zusammenstellen von für die Erstellung der Prüfspezifikation relevanten technischen Dokumenten (Systemunterlagen, Zeichnungen, Messstellenlisten, etc.)				
E.2	Technische Dokumente sichten und auf Vollständigkeit prüfen				
E.3	Vorbereitung von Vorlagen für die Erstellung von Prüfspezifikationen				
E.4	Ausfüllen der Vorlagen mit konkreten technischen Informationen aus den technischen Dokumenten				
E.5	Zuweisung der erforderlichen Werkzeuge, Ressourcen und Metainformationen				
E.6	Erstellung von Checklisten und Protokollen für die Erfassung von Messwerten aus den Prüfungen				

Appendix C (2/2) – Analytical estimating task catalog – authoring assistant

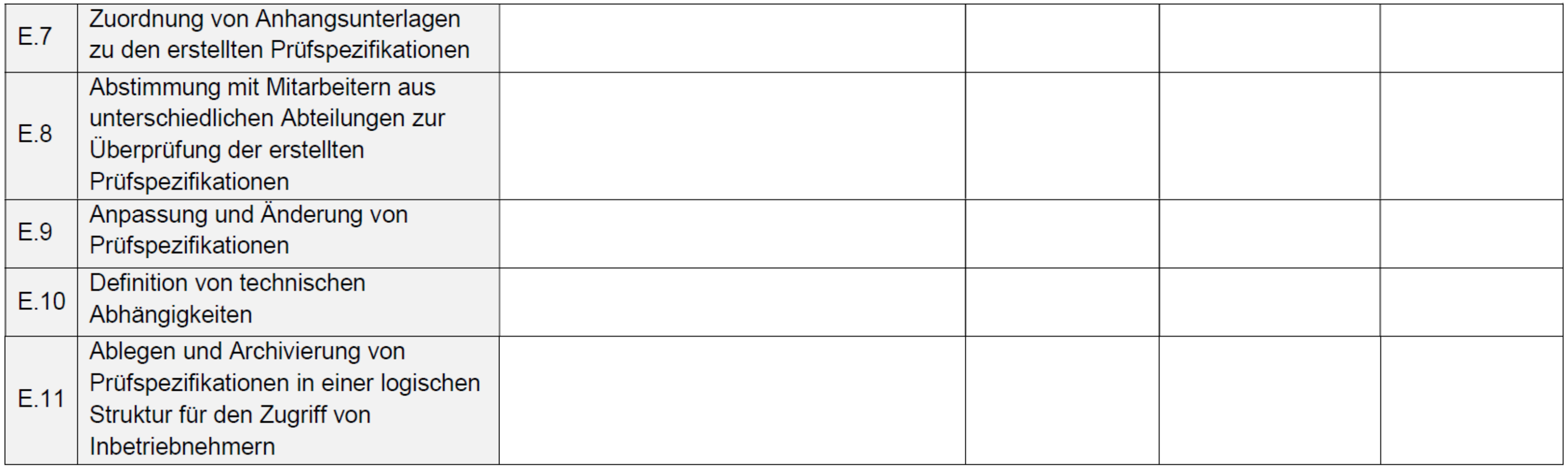
E.7	Zuordnung von Anhangsunterlagen zu den erstellten Prüfspezifikationen				
E.8	Abstimmung mit Mitarbeitern aus unterschiedlichen Abteilungen zur Überprüfung der erstellten Prüfspezifikationen				
E.9	Anpassung und Änderung von Prüfspezifikationen				
E.10	Definition von technischen Abhängigkeiten				
E.11	Ablegen und Archivierung von Prüfspezifikationen in einer logischen Struktur für den Zugriff von Inbetriebnehmern				

Appendix D (1/2) – Analytical estimating task catalog – commissioning assistant



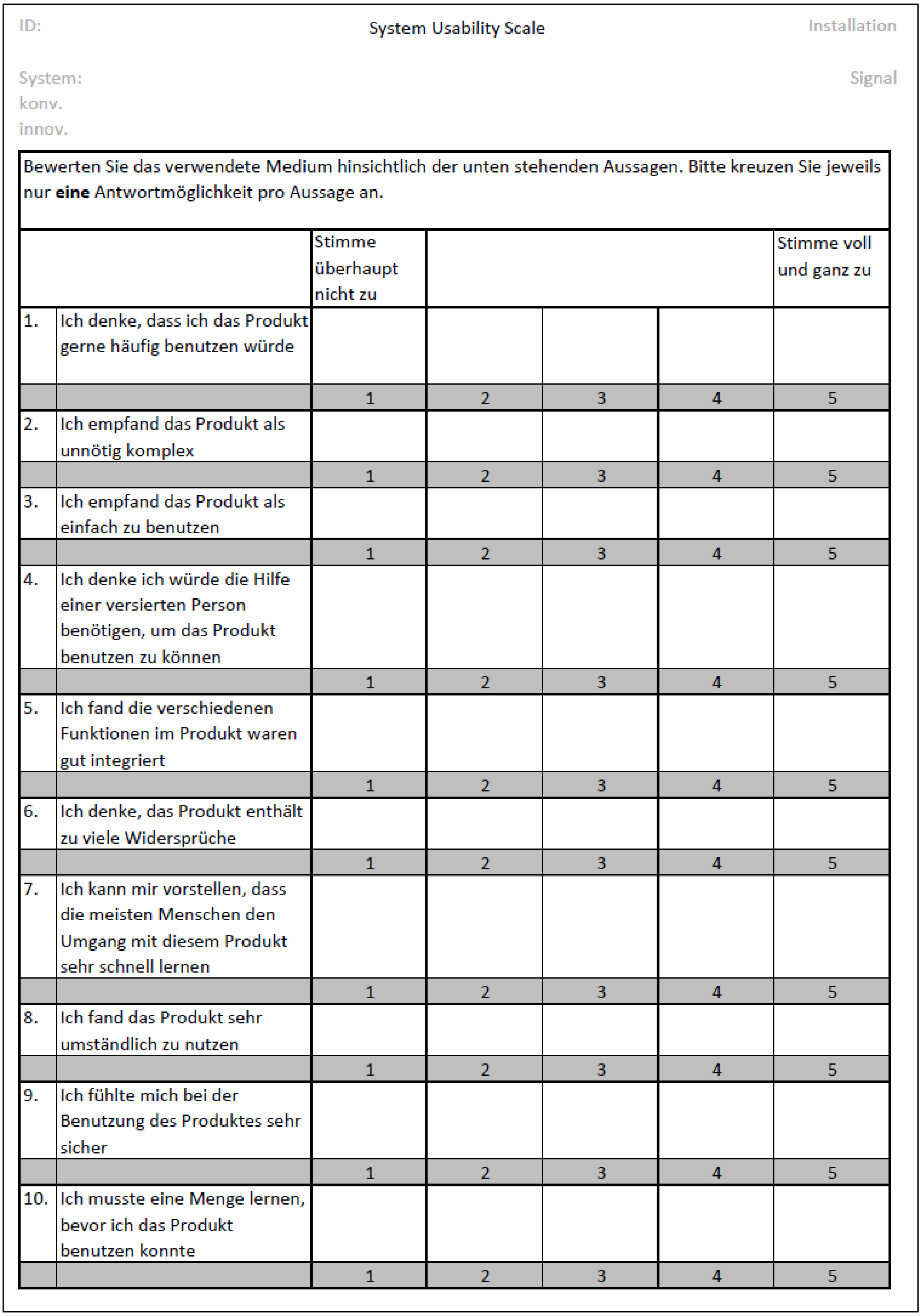
ID	Prozessschritt	Beschreibung der Evaluation und Methodik	Analytisches Schätzen		
			minimale Aufgabenzeit [min.]	**durchschnittliche Aufgabenzeit [min.]**	**maximale Aufgabenzeit [min.]**
		Beschreibung der Evaluationsmethode und des Betrachtungsgegenstands, z.B.: - Wurden Versuche durchgeführt oder Interviews geführt? - Welche Rolle hat mitgewirkt? - Wie viele Personen wurden betragt bzw. wie oft wurde der Prozesschritt evaluiert (Stichprobengröße)? - Welche Tätigkeit/Prüfung wurde ausgeführt/betrachtet?	Schätzung der minimalen Aufgabenzeit in Minuten	Schätzung der durchschnittlichen Aufgabenzeit in Minuten	Schätzung der maximalen Aufgabenzeit in Minuten
E.1	Zusammenstellen von für die Erstellung der Prüfspezifikation relevanten technischen Dokumenten (Systemunterlagen, Zeichnungen, Messstellenlisten, etc.)				
E.2	Technische Dokumente sichten und auf Vollständigkeit prüfen				
E.3	Vorbereitung von Vorlagen für die Erstellung von Prüfspezifikationen				
E.4	Ausfüllen der Vorlagen mit konkreten technischen Informationen aus den technischen Dokumenten				
E.5	Zuweisung der erforderlichen Werkzeuge, Ressourcen und Metainformationen				
E.6	Erstellung von Checklisten und Protokollen für die Erfassung von Messwerten aus den Prüfungen				

Appendix D (2/2) – Analytical estimating task catalog – commissioning assistant



E.7	Zuordnung von Anhangsunterlagen zu den erstellten Prüfspezifikationen				
E.8	Abstimmung mit Mitarbeitern aus unterschiedlichen Abteilungen zur Überprüfung der erstellten Prüfspezifikationen				
E.9	Anpassung und Änderung von Prüfspezifikationen				
E.10	Definition von technischen Abhängigkeiten				
E.11	Ablegen und Archivierung von Prüfspezifikationen in einer logischen Struktur für den Zugriff von Inbetriebnehmern				

Appendix E – System Usability Scale (SUS)



ID:

System Usability Scale

Installation

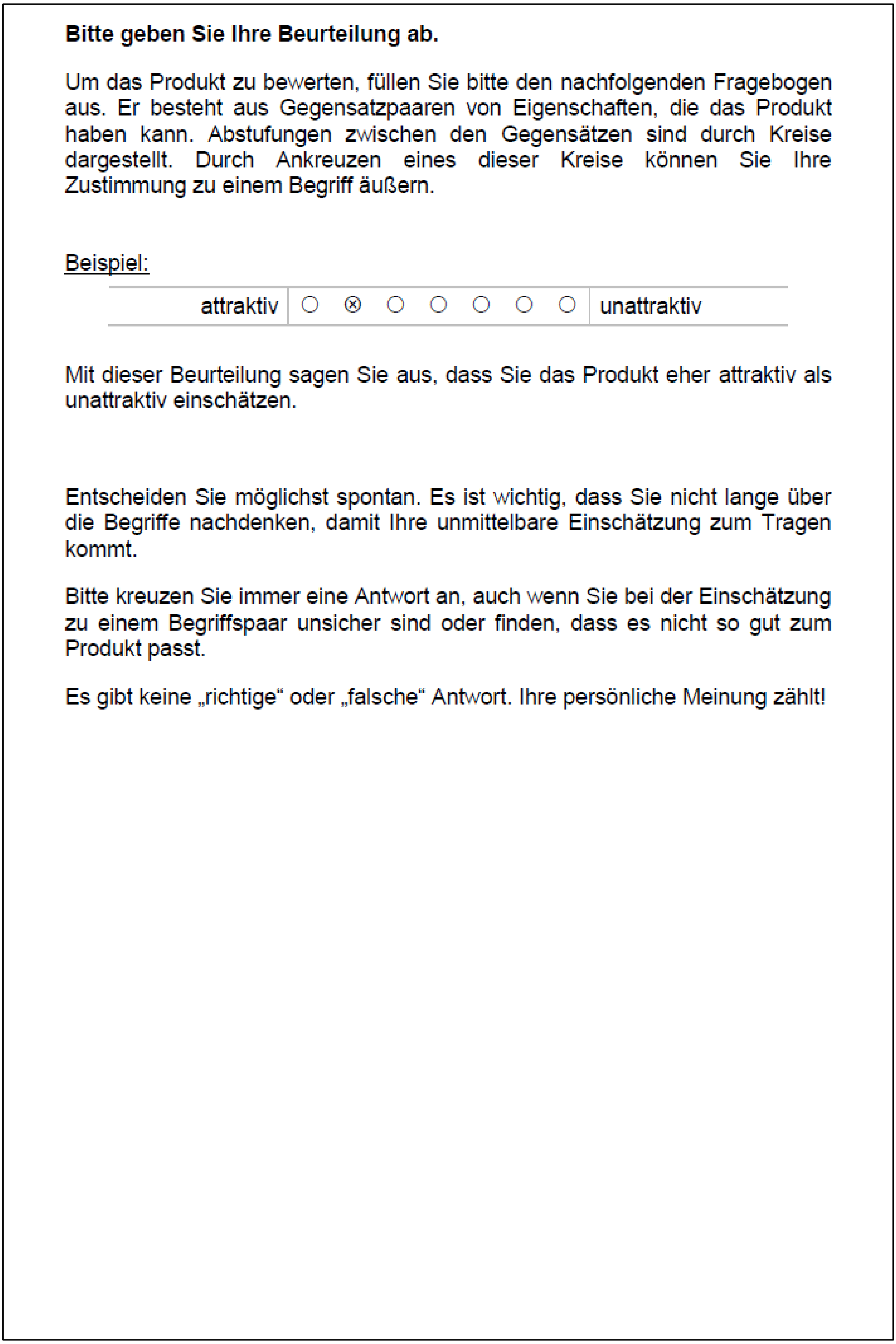
System:
konv.
innov.

Signal

Bewerten Sie das verwendete Medium hinsichtlich der unten stehenden Aussagen. Bitte kreuzen Sie jeweils nur **eine** Antwortmöglichkeit pro Aussage an.

		Stimme überhaupt nicht zu				Stimme voll und ganz zu
1.	Ich denke, dass ich das Produkt gerne häufig benutzen würde					
		1	2	3	4	5
2.	Ich empfand das Produkt als unnötig komplex					
		1	2	3	4	5
3.	Ich empfand das Produkt als einfach zu benutzen					
		1	2	3	4	5
4.	Ich denke ich würde die Hilfe einer versierten Person benötigen, um das Produkt benutzen zu können					
		1	2	3	4	5
5.	Ich fand die verschiedenen Funktionen im Produkt waren gut integriert					
		1	2	3	4	5
6.	Ich denke, das Produkt enthält zu viele Widersprüche					
		1	2	3	4	5
7.	Ich kann mir vorstellen, dass die meisten Menschen den Umgang mit diesem Produkt sehr schnell lernen					
		1	2	3	4	5
8.	Ich fand das Produkt sehr umständlich zu nutzen					
		1	2	3	4	5
9.	Ich fühlte mich bei der Benutzung des Produktes sehr sicher					
		1	2	3	4	5
10.	Ich musste eine Menge lernen, bevor ich das Produkt benutzen konnte					
		1	2	3	4	5

Appendix F (1/2)– User Experience Questionnaire (UEQ)



Bitte geben Sie Ihre Beurteilung ab.

Um das Produkt zu bewerten, füllen Sie bitte den nachfolgenden Fragebogen aus. Er besteht aus Gegensatzpaaren von Eigenschaften, die das Produkt haben kann. Abstufungen zwischen den Gegensätzen sind durch Kreise dargestellt. Durch Ankreuzen eines dieser Kreise können Sie Ihre Zustimmung zu einem Begriff äußern.

Beispiel:

attraktiv	○	⊗	○	○	○	○	○	unattraktiv

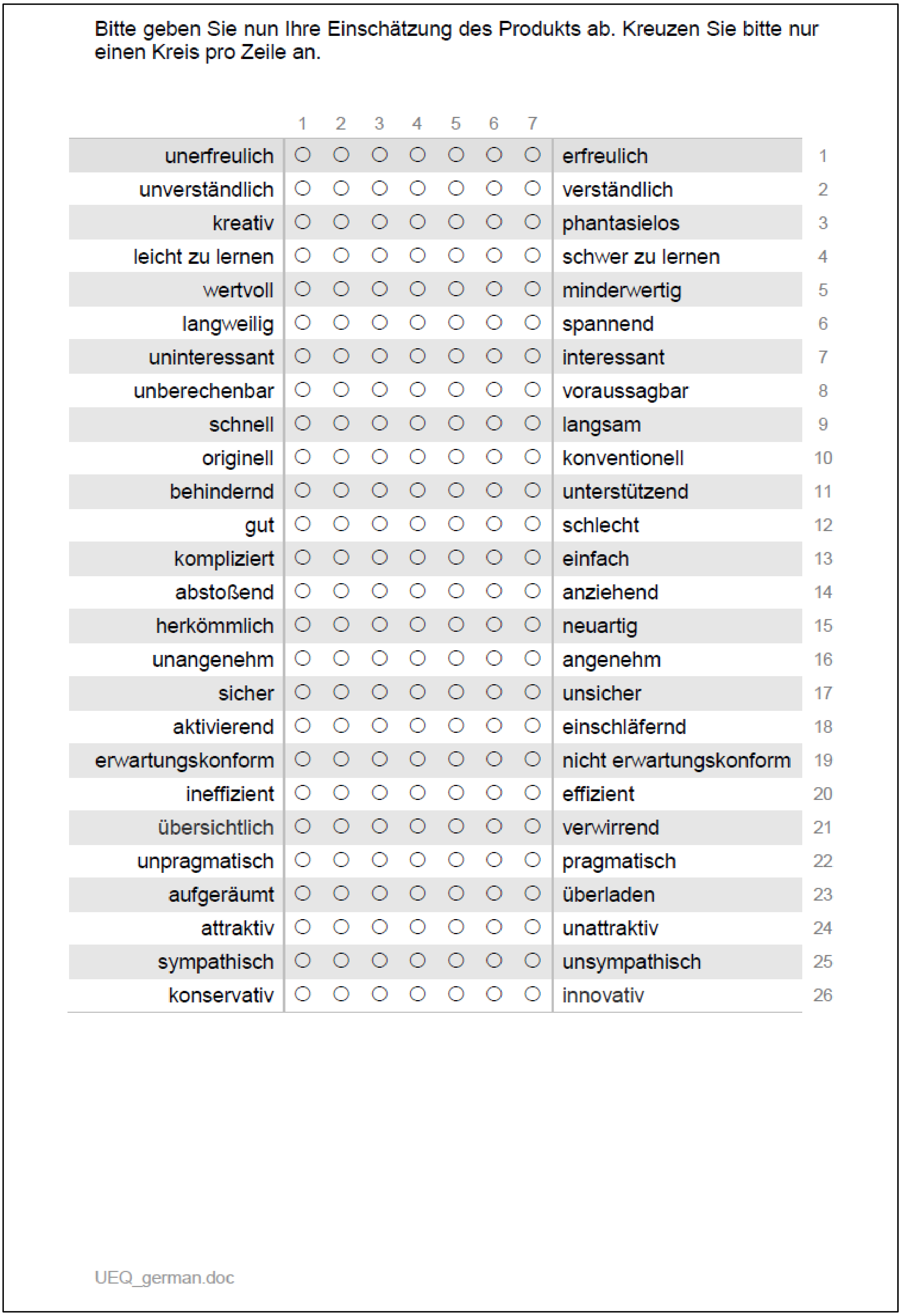
Mit dieser Beurteilung sagen Sie aus, dass Sie das Produkt eher attraktiv als unattraktiv einschätzen.

Entscheiden Sie möglichst spontan. Es ist wichtig, dass Sie nicht lange über die Begriffe nachdenken, damit Ihre unmittelbare Einschätzung zum Tragen kommt.

Bitte kreuzen Sie immer eine Antwort an, auch wenn Sie bei der Einschätzung zu einem Begriffspaar unsicher sind oder finden, dass es nicht so gut zum Produkt passt.

Es gibt keine „richtige“ oder „falsche“ Antwort. Ihre persönliche Meinung zählt!

Appendix F (2/2)– User Experience Questionnaire (UEQ)

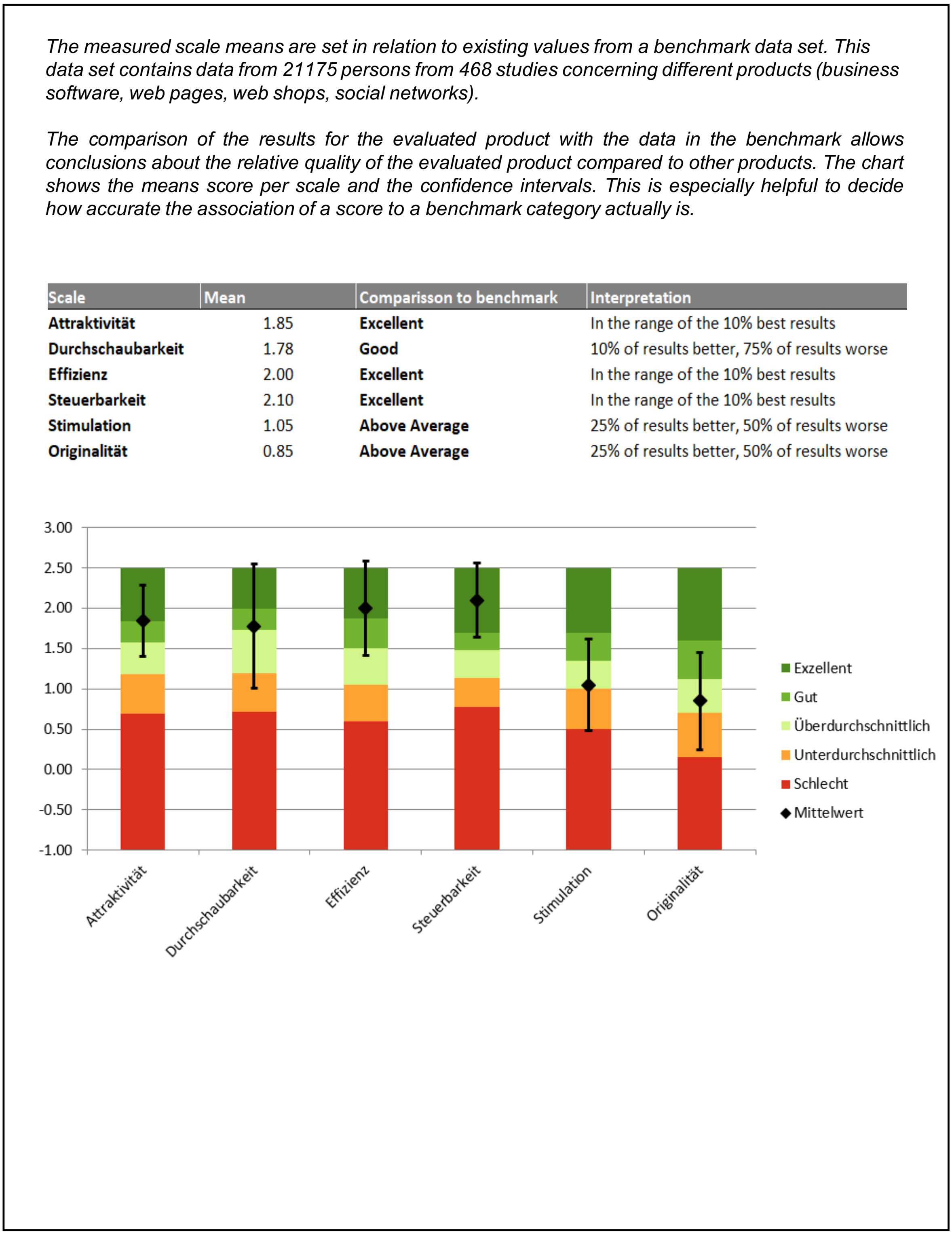


Bitte geben Sie nun Ihre Einschätzung des Produkts ab. Kreuzen Sie bitte nur einen Kreis pro Zeile an.

	1	2	3	4	5	6	7		
unerfreulich	○	○	○	○	○	○	○	erfreulich	1
unverständlich	○	○	○	○	○	○	○	verständlich	2
kreativ	○	○	○	○	○	○	○	phantasielos	3
leicht zu lernen	○	○	○	○	○	○	○	schwer zu lernen	4
wertvoll	○	○	○	○	○	○	○	minderwertig	5
langweilig	○	○	○	○	○	○	○	spannend	6
uninteressant	○	○	○	○	○	○	○	interessant	7
unberechenbar	○	○	○	○	○	○	○	voraussagbar	8
schnell	○	○	○	○	○	○	○	langsam	9
originell	○	○	○	○	○	○	○	konventionell	10
behindernd	○	○	○	○	○	○	○	unterstützend	11
gut	○	○	○	○	○	○	○	schlecht	12
kompliziert	○	○	○	○	○	○	○	einfach	13
abstoßend	○	○	○	○	○	○	○	anziehend	14
herkömmlich	○	○	○	○	○	○	○	neuartig	15
unangenehm	○	○	○	○	○	○	○	angenehm	16
sicher	○	○	○	○	○	○	○	unsicher	17
aktivierend	○	○	○	○	○	○	○	einschläfernd	18
erwartungskonform	○	○	○	○	○	○	○	nicht erwartungskonform	19
ineffizient	○	○	○	○	○	○	○	effizient	20
übersichtlich	○	○	○	○	○	○	○	verwirrend	21
unpragmatisch	○	○	○	○	○	○	○	pragmatisch	22
aufgeräumt	○	○	○	○	○	○	○	überladen	23
attraktiv	○	○	○	○	○	○	○	unattraktiv	24
sympathisch	○	○	○	○	○	○	○	unsympathisch	25
konservativ	○	○	○	○	○	○	○	innovativ	26

UEQ_german.doc

Appendix G – UEQ benchmark - authoring assistant



The measured scale means are set in relation to existing values from a benchmark data set. This data set contains data from 21175 persons from 468 studies concerning different products (business software, web pages, web shops, social networks).

The comparison of the results for the evaluated product with the data in the benchmark allows conclusions about the relative quality of the evaluated product compared to other products. The chart shows the means score per scale and the confidence intervals. This is especially helpful to decide how accurate the association of a score to a benchmark category actually is.

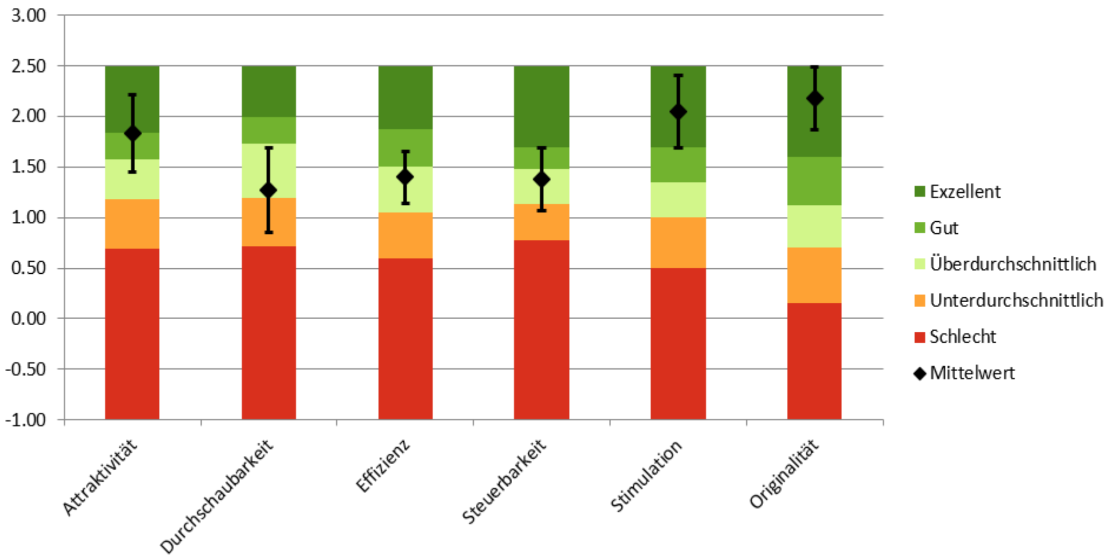
Scale	Mean	Comparisson to benchmark	Interpretation
Attraktivität	1.85	**Excellent**	In the range of the 10% best results
Durchschaubarkeit	1.78	**Good**	10% of results better, 75% of results worse
Effizienz	2.00	**Excellent**	In the range of the 10% best results
Steuerbarkeit	2.10	**Excellent**	In the range of the 10% best results
Stimulation	1.05	**Above Average**	25% of results better, 50% of results worse
Originalität	0.85	**Above Average**	25% of results better, 50% of results worse

Appendix H – UEQ benchmark - commissioning assistant

The measured scale means are set in relation to existing values from a benchmark data set. This data set contains data from 21175 persons from 468 studies concerning different products (business software, web pages, web shops, social networks).

The comparison of the results for the evaluated product with the data in the benchmark allows conclusions about the relative quality of the evaluated product compared to other products. The chart shows the means score per scale and the confidence intervals. This is especially helpful to decide how accurate the association of a score to a benchmark category actually is.

Scale	Mean	Comparisson to benchmark	Interpretation
Attraktivität	1.83	**Good**	10% of results better, 75% of results worse
Durchschaubarkeit	1.28	**Above Average**	25% of results better, 50% of results worse
Effizienz	1.40	**Above Average**	25% of results better, 50% of results worse
Steuerbarkeit	1.38	**Above Average**	25% of results better, 50% of results worse
Stimulation	2.05	**Excellent**	In the range of the 10% best results
Originalität	2.18	**Excellent**	In the range of the 10% best results



Appendix I – Authoring assistant's laboratory experiment data and interpretation

Experiment data:

Test Participant Number	Educational Background of Test Participant	Experiment Type*	Previous Experience of Test Participant with Authoring Tool**	Target Variable: Duration of Authoring in Seconds
1	Logistics	A	Yes	1381
		B	Yes	308
2	Mechanical Engineering	A	Yes	1655
		B	Yes	371
3	Mechanical Engineering	A	Yes	1810
		B	No	312
4	Mechanical Engineering	A	Yes	1790
		B	No	238
5	Medical Engineering	A	Yes	1429
		B	No	321
6	Mechanical Engineering	A	Yes	1394
		B	Yes	357
7	Mechanical Engineering	A	Yes	1326
		B	No	273
8	Mechanical Engineering	A	Yes	970
		B	No	389
9	Mechanical Engineering	A	Yes	1658
		B	Yes	315
10	Industry Mechanics Technical Training	A	Yes	1738
		B	No	399

* **Experiment Type**:
A: Authoring using the conventional workflow
B: Authoring using the innovative workflow

** **Authoring Tool**:
Conventional: Microsoft Word and Excel
Innovative: Authoring Assistant

Parameters for implementing paired t-test:

Sample size: $N = 10$

Degree of freedom (DoF): $N - 1 = 9$

Significance level: $\alpha = 0.05$

Mean duration (A): $\mu_A = 1515.1$

Mean duration (B): $\mu_B = 328.3$

Mean difference: $\mu_d = 1186.8$

Sample standard deviation of difference: $\sigma_d = 281.6$

Sample standard error of difference: $\sigma_M = 89.05$

t-Value: $t = \frac{\mu_d}{\sigma_M} = 13.3$

Interpretation:
With a degree of freedom of 9 and a significance level of 5%, consulting the t-value distribution table yields a critical value of 1.83. The calculated t-value of 13.3 surpasses the critical value, suggesting statistical significance. Therefore, it is safe to reject the null hypothesis which states that *there is no difference in terms of authoring time between the authoring assistant and the conventional tools*.

Appendix J (1/2) – Commissioning assistant’s laboratory experiment data and interpretation

Experiment data (raw):

Test Participant Number	Educational Background of Test Participant	Experiment Type*	Previous Experience of Test Participant with Tool**	Measurements ***		
				T_1	T_2	T_3
1	Mechanical Engineering	C	Yes	123	393	18
		D	Yes	93	38	82
2	Mechanical Engineering	A	Yes	141	227	42
		B	Yes	51	8	62
3	Mechanical Engineering	C	Yes	79	183	48
		D	Yes	109	25	105
4	Mechanical Engineering	A	Yes	351	175	52
		B	Yes	83	5	96
5	Electronics Engineering	A	Yes	379	232	18
		B	No	134	47	99
6	Process Engineering	C	Yes	125	268	99
		D	Yes	88	17	286
7	Process Engineering	A	Yes	369	169	15
		B	Yes	133	34	110
8	Mechanical Engineering	C	No	177	185	44
		D	Yes	148	16	157
9	Mechanical Engineering	A	Yes	295	211	32
		B	No	98	6	82
10	Mechanical Engineering	C	Yes	245	290	23
		D	Yes	200	17	206

*** Experiment Type:**
A: Implementing installation test using the conventional workflow
B: Implementing signal test using the innovation workflow
C: Implementing installation test using the innovative workflow
D: Implementing signal test using the conventional workflow

**** Tool:**
Conventional: Paper Documents
Innovative: Commissioning Assistant

***** Measurements (in seconds):**
T1: Duration of information procurement
T2: Duration of performing commissioning test
T3: Duration of documenting test results

Appendix J (2/2) – Commissioning assistant's laboratory experiment data and interpretation

Experiment data (consolidated):

Test Participant Number	Target Variable: Duration of completing a test (seconds)			
	Installation test		Signal test	
	Conventional	Innovative	Conventional	Innovative
1	-	534	213	-
2	410	-	-	121
3	-	310	239	-
4	578	-	-	184
5	629	-	-	280
6	-	492	391	-
7	553	-	-	277
8	-	406	321	-
9	538	-	-	186
10	-	558	423	-

Two-sample t-test:

Parameter	Installation Test		Signal Test	
	Conventional	Innovative	Conventional	Innovative
Sample size	$N = 10$		$N = 10$	
Degree of freedom	$N - 2 = 8$		$N - 2 = 8$	
Significance level	$\alpha = 0.05$		$\alpha = 0.05$	
Mean duration	$\mu_1 = 541.6$	$\mu_2 = 460$	$\mu_1 = 317.4$	$\mu_2 = 209.6$
Mean difference	$\mu_d = 81.6$		$\mu_d = 107.8$	
Sample variance	$\sigma_1^2 = 6606.3$	$\sigma_2^2 = 10380$	$\sigma_1^2 = 8406.8$	$\sigma_2^2 = 4640.3$
Pooled variance	$\sigma^2 = \frac{\sigma_1^2 + \sigma_2^2}{2} = 92.2$		$\sigma^2 = \frac{\sigma_1^2 + \sigma_2^2}{2} = 80.8$	
Standard error	$\sigma_M = \sqrt{\frac{4}{N}\sigma^2} = 58.3$		$\sigma_M = \sqrt{\frac{4}{N}\sigma^2} = 51.1$	
t-value	$t = t_{critical\ at\ DoF=8} * \sigma_M = 134.4$		$t = t_{critical\ at\ DoF=8} * \sigma_M = 117.8$	
95% confidence interval of the difference	$(\mu_d - t,\ \mu_d + t)$ = $(-52.8,\ 216)$		$(\mu_d - t,\ \mu_d + t)$ = $(-10,\ 225.6)$	
Statistical significance	Not statistically significant		Not statistically significant	

Interpretation:
With a degree of freedom of 8 and a significance level of 5%, the confidence intervals for differences in both installation and signal tests include the zero, indicating that there is no significant difference. Therefore, the null hypothesis cannot be rejected.

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