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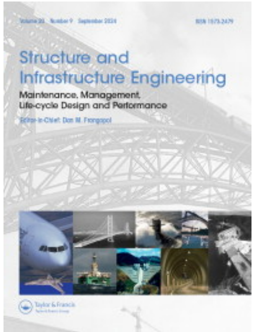

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Asset management for storm surge barriers: how and why?

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ABSTRACT

Due to increasing flood risks, storm surge barriers become crucial for the socioeconomic continuity of coastal areas. They provide flood protection, especially against extreme events, by operating under specific circumstances. This imposes high-performance requirements for storm surge barriers and their asset management during their lifetime and emphasises the role and criticality of their asset management. For this purpose, the research investigates asset management for storm surge barriers by focusing on the approach in the Netherlands and analysing it relative to distinctive characteristics of storm surge barriers. Based on thematic analysis, the study unfolds that barriers' characteristics: (1) clarify the vital motives for the asset management approach, (2) confront the approach with challenging conditions, resulting in further maturation of the approach, and (3) require ongoing support from the approach, enforcing continuous improvement and resilience of the asset management approach. These findings demonstrate the strong influence of barriers' characteristics on their asset management approach and provide a fundamental understanding of asset management for storm surge barriers. This supports flood defence authorities in the development and improvement of asset management for storm surge barriers and underpins associated complexities for future designs and research. Furthermore, the study assists in tailoring approaches for other assets.

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Asset management; climate change; coastal hazards; flood protection; sea-level rise; storm surge barriers

1. Introduction

Coastal areas are vital in their social and economic development but are also among the most vulnerable areas to climate change (Nguyen, Bonetti, Rogers, & Woodroffe, 2016). A tenth of the global population and assets in low-lying regions are exposed to coastal hazards from climate change (Pörtner, Roberts, Adams, et al., 2022). This combination of environmental conditions and socioeconomic development increases the risk of flooding (Du et al., 2020) with (1) higher probability due to extreme rainfalls, sea level rise (SLR), and storm surges (Pörtner, Roberts, Poloczanska, et al., 2022) and (2) more severe consequences due to the increase in intense storm surges threatening developed coastal cities (Dong, Cao, & Liu, 2022; Du et al., 2020).

With this flood risk being inevitable and accelerating beyond 2050 and 2100, hard infrastructure and soft nature-based protections become essential (Pörtner, Roberts, Adams, et al., 2022). For the 2100 flood risks, hard protections, such as storm surge barriers (SSBs), are necessary (Du et al., 2020). Cities such as Götenborg and New York are actively considering SSBs in their development plans to reduce flood risk and adapt to SLR (Mooyaart & Jonkman, 2017).

SSBs are gated and moveable infrastructures essential in flood risk management and adaptation of populated delta regions. They help in dealing with climate change effects and maintaining strict safety requirements without compromising the connection to the sea (Jonkman, Hillen, Nicholls, Kanning, & van Ledden, 2013). Accordingly, they are designed to close during extreme flood events to prevent devastating damages, as witnessed in the 1953 flood in the Netherlands (Battjes & Gerritsen, 2002) and the United Kingdom (Lavery & Donovan, 2005). This imposes high safety requirements on SSBs such as protection against 500-year flood events in New Bedford (Morang, 2016) and a 10000-year flood event in Rotterdam (Mooyaart & Jonkman, 2017). Having such high-reliability requirements with intermittent operation, asset management of SSBs becomes vital and complex (Jordan, Manojlovic, & Fröhle, 2019).

Asset management (AM) ensures the asset functions when needed, during its lifetime. It supports organisations in achieving strategic plans and objectives (Goforth, Yosri, El-Dakhakhni, & Wiebe, 2022) and in synchronising efforts at different levels to create value throughout the lifecycle of assets (Maletič, Maletič, Al-Najjar, & Gomišček, 2020). For assets with strict requirements, organisations create value cost-effectively while complying with regulations and delivering highly reliable service. Thus, AM is performed with a

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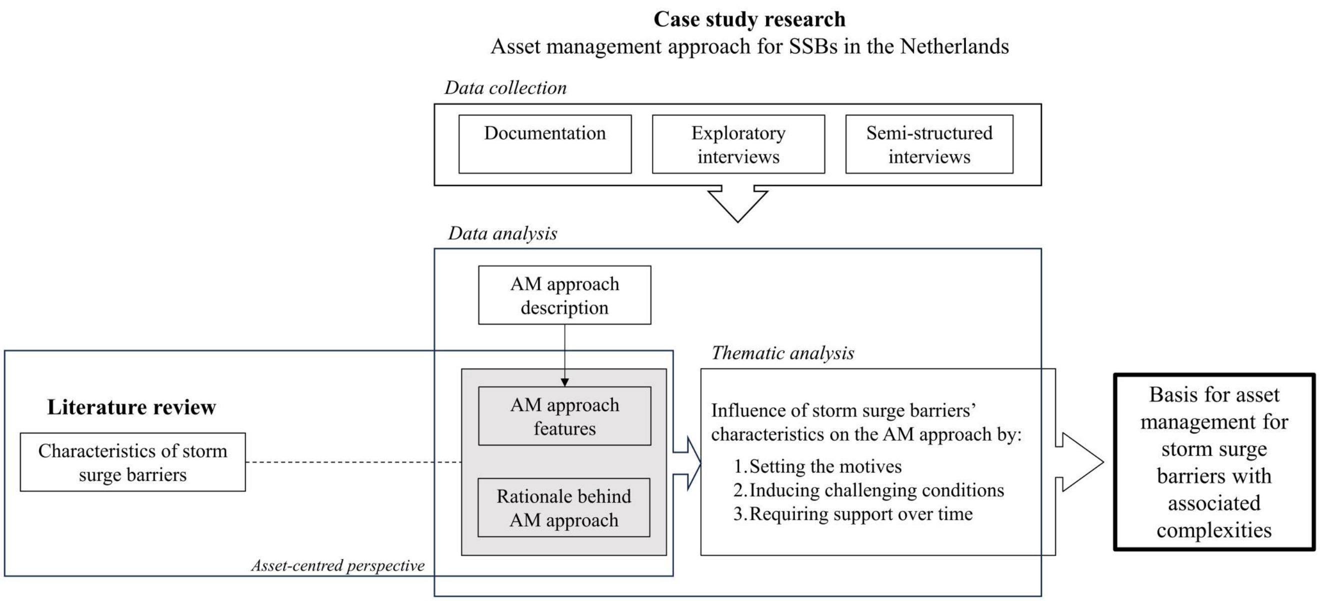

Figure 1. Research methods and steps.

complex model (Lima & Costa, 2019) dependent on each organisation and the context in which the asset operates. In the case of flood defences, AM is considered to have severe technical, financial, and safety complications (den Heijer, Rijke, Bosch-Rekveldt, de Leeuw, & Barciela-Rial, 2023). For SSBs, AM is confronted with various complications due to, for example, structural uniqueness and limited information (Walraven, Vrolijk, & Kothuis, 2022) and future challenges due to climate change (Haasnoot et al., 2020; Trace-Kleeberg, Haigh, Walraven, & Gourvenec, 2023).

Despite the importance of AM to sustain flood safety, current literature inadequately addresses AM for SSBs. Recent studies addressed the complexities of AM for flood defences with cooperation between organisations (den Heijer, Podt, Bosch-Rekveldt, de Leeuw, & Rijke, 2023; den Heijer, Rijke, et al., 2023). Others focused on dealing with uncertainties with adaptative AM (Gersonius et al., 2020; Jordan et al., 2019; Sayers et al., 2021). Furthermore, the latest studies investigated specific topics in AM of SSBs, such as the influence of SLR on maintenance strategies (Trace-Kleeberg et al., 2023), the remaining life of SSBs (Vader et al., 2023), and economic optimisation in relation with the closure reliability of SSBs (Mooyaart, Bakker, van den Bogaard, Rijcken, & Jonkman, 2023). These studies concede that SLR and ageing SSBs set more stringent requirements for AM to sustain SSBs' functions. To combat future requirements with AM, the past and current AM of SSBs must be understood.

Addressing the AM of SSBs persists even with international standards and AM from other assets. ISO 5500x series (ISO, 2014a, 2014b, 2018) is generic and applicable to a wide portfolio of assets, which gives it a strategic perspective without elaboration on 'how' to fulfil them. There is a need to focus on AM models for assets to reflect on the interpretation and application of the ISO requirements in practice (Konstantakos, Chountalas, & Magoutas, 2019). Studying such cases is helpful for SSBs and other assets especially while considering their special characteristics that influence AM (Herder & Wijnia, 2012).

Therefore, it is vital to explore the AM for SSBs due to its challenging context and increasing importance for flood protection (Du et al., 2020; Orton et al., 2023). This current study aims to: (1) provide a foundational understanding of AM for SSBs for its broader development, application, and investigation and (2) disclose the complexity of AM for SSBs to support the design of SSBs and future research on the evolution and adaptability of AM for SSBs, in a continuously changing context. These objectives are achieved by investigating the AM for SSBs in the Netherlands and its evolution with a focus on the role of SSBs' characteristics during this process. Following this introduction, Section 2 explains the materials and methods to conduct the case study and analyse the data. Section 3 elucidates the characteristics of SSBs from the literature. Hereafter, Sections 4 and 5 present the results of the AM approach and its evolution, respectively. Lastly, Section 6 discusses the results to conclude the research in Section 7.

2. Materials and methods

The research methodology encompasses several stages for data collection and analysis, illustrated in Figure 1 and elaborated in this section.

2.1. Literature review

A comprehensive literature study was conducted to identify SSBs' characteristics. This review supported establishing an asset-centred perspective for the researched case and provided a broader context for the study.

2.2. Case study research

Given the study's objective to investigate the application and development of AM for SSBs, case study research was

Figure 2. Locations of SSB in The Netherlands.

identified as the most suitable approach. It aligns with authors exploratory and explanatory goals, as it is well-suited for addressing 'how' and 'why' questions and comprehensively studying a phenomenon within its real life (Yin, 2017). Furthermore, the focus on a specific case enhances the investigation of obscured explanations of a phenomenon (Ridder, 2017). For this purpose, the AM for SSBs in the Netherlands is thoroughly studied to explain the approach and to unveil its evolution and the reasons behind its development. Furthermore, SSBs in Europe and the United States were examined, in Section 6, as part of exploratory research to support the findings.

2.2.1. Case of The Netherlands

The research is centred on AM practices for SSBs in the Netherlands, a country known for its experience and approaches to flood defences. The geographical positioning of the Netherlands in the delta of the Meuse, Rhine, and Scheldt rivers, where large areas of land are below sea level, has necessitated the development of flood protection mechanisms, including dikes, dunes, and SSBs (illustrated in Figure 2). These flood defences were completed based on safety requirements and are constantly assessed against strict national safety standards (Jorissen, Kraaij, & Tromp, 2016).

For SSBs, the Flood Defence Act specifies performance requirements that shall be met and demonstrated (Webbers, van den Bogaard, van Manena, & van Akkeren, 2008). Compliance with these requirements is maintained using 'ProBO: Probabilistic Operations and Maintenance' approach, implemented by Rijkswaterstaat (RWS), the organisation responsible for the management and maintenance of SSBs (Jorissen et al., 2016).

2.3. Data collection

To perform the research, data was collected from the following sources:

- Documentation: This encompassed organisational reports and operational guidelines on ProBO. The studied documentation provided background on ProBO, methods used, work processes, and encountered challenges. This paved the way for studying ProBO over time and scope.
- Exploratory interviews: During site visits, meetings, and office interactions, data was collected and recorded on various topics of the approach in practice, such as operational processes, quality control, and maintenance challenges.
- Semi-structured interviews: 10 participants, representing various roles (e.g. reliability expert, maintenance manager, asset manager, and director) and periods of involvement with ProBO, were interviewed. The interviews were recorded and transcribed verbatim. All interviewees gave informed consent and approved the transcripts. These interviews followed a protocol with questions covering the following topics:
  1. History of the AM approach and its change over time.

2. Current AM approach with different subjects of AM as provided in IAM (2015).
3. Influence of characteristics on the AM approach.
4. Challenges and improvements of ProBO.

2.4. Data analysis

Hereafter, the data to investigate ProBO and its evolution are analysed. First, the different sources were consulted to describe ProBO, explain its application, identify its features, and understand the rationale behind it. Then, ProBO was interpreted relative to SSBs' characteristics by analysing the interviews using Atlas.ti software and conducting a Thematic Analysis. This led to identifying three main themes detailing the role of SSBs' characteristics in the evolution of ProBO. Finally, the case study's outcomes were further examined by comparing them with other SSBs and linking the findings to the literature on AM and SSBs.

3. Characteristics of storm surge barriers

To set the asset-centred perspective for analysing the case study, the characteristics of SSBs are identified from the literature (Figure 3). First, SSBs are considered *systems within a system* since they belong to the flood defence system (Jonkman et al., 2013) while being themselves a system of sub-systems that are studied together to assess the sole failure of the SSB system (Mooyaart & Jonkman, 2017). They are *public infrastructures* constructed and managed with public funds to provide specific safety levels as specified for the USA (Morang, 2016) and the Netherlands (Jonkman, Voortman, Klerk, & van Vuren, 2018). To reach these safety levels, *high investment costs* are associated as recorded for constructed barriers (Mendelsohn, Fairbank, & Rajaoberison, 2022; Miller, Desoto-Duncan, & Hertzler, 2013). Their operation and maintenance (O&M) costs can also be high depending on the length and quantity of moveable parts (Aerts, 2018).

Furthermore, SSBs are subject to *political processes* and *long lead times until their construction*. Such long processes occur due to stagnation in policy and socio-economic response to flood protection defences (Hanson et al., 2011). This is witnessed in Sint Petersburg Russia for financial, ecological, and political reasons (Lavrov & Sementsov, 2015) and in the Netherlands where intensive technical analysis, long discussions on the closure of the Eastern Scheldt estuary (Taebi, Kwakkel, & Kermisch, 2020), and political opposition and debates are observed (Meijerink, 2005). Another characteristic of SSBs is *critical infrastructure* (NCTV, 2017). Such assets have nationwide disruptions in case of failure (Alcaraz & Zeadally, 2015) and international effects due to interdependencies (Pörtner, Roberts, Adams, et al., 2022). By protecting growing urban areas and their economies (Aerts, 2018), failure to operate during extreme weather events can be disastrous. SSBs are found in major cities with a high economic role, such as Rotterdam (Zhong, Van Overloop, Van Gelder, & Rijcken, 2012), and London (McRobie, Spencer, & Gerritsen, 2005). Moreover, SSBs are proposed for central cities such as New York to prevent tens of billions of damages (Morang, 2016).

In addition to their main protection role, SSBs are *multi-functional* with socioeconomic functions including:

- reducing the risk of failure and costs of strengthening defences behind them (Nogueira & Walraven, 2018), enabling less strict standards for flood defences in the hinterland and fewer disruptions of the landscape in the hinterland (Walraven et al., 2022);
- resuming navigation in port cities and supporting the growth of deltas (Meyer & Nijhuis, 2013);
- providing the opportunity to generate renewable energy using tidal flow turbines (Basco, 2020); and
- regulating the water discharge to minimise salt intrusion (Ysebaert et al., 2016).

To consider these various functions and their influence, an *integrated approach* to the lifecycle management of SSBs is necessary (Jonkman et al., 2013) because flood protection

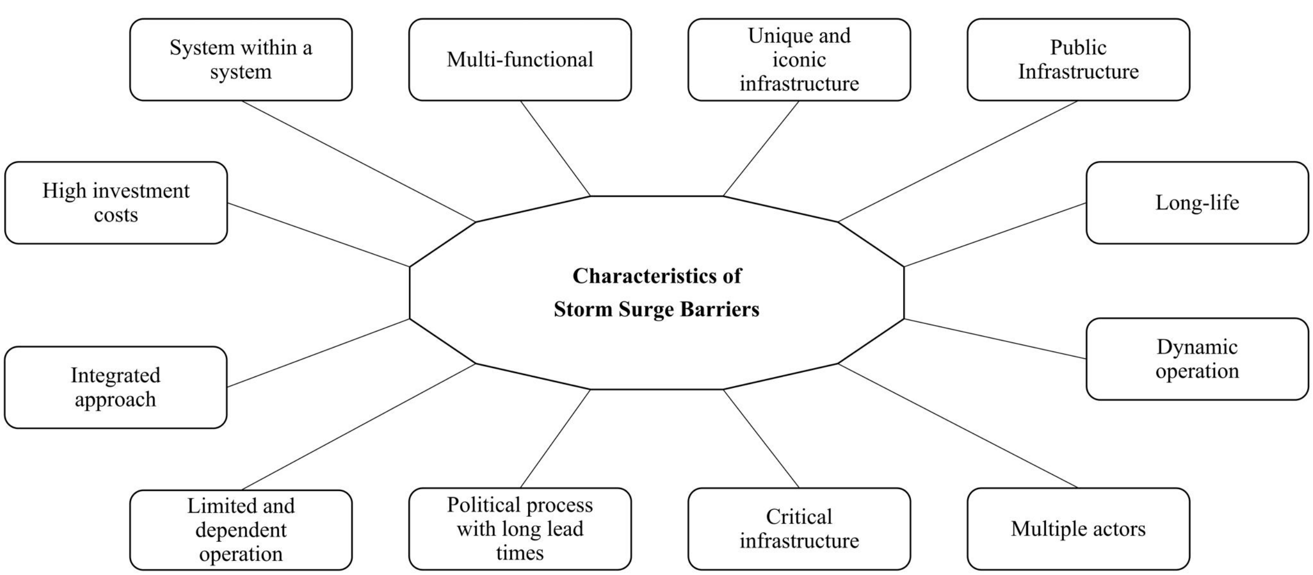

Figure 3. Characteristics of SSBs.

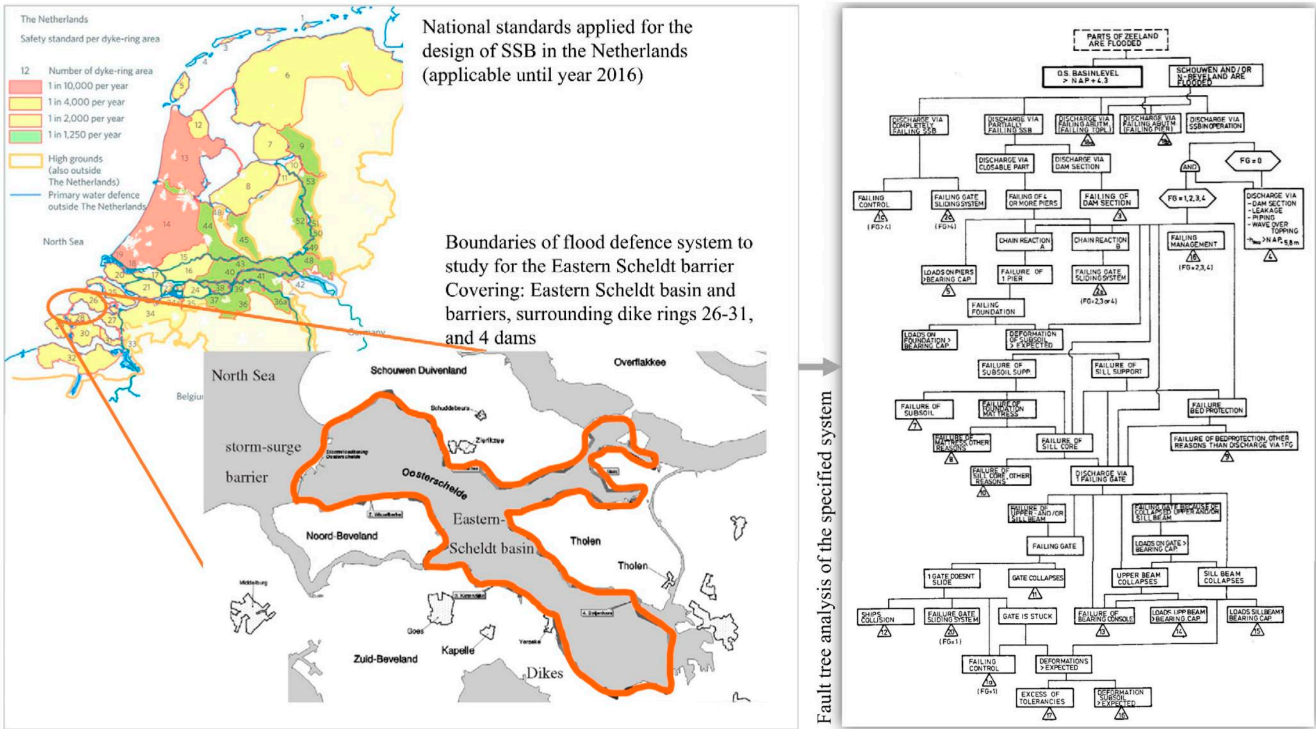

Figure 4. An illustrative example of how FTA was used in the design of the Eastern scheldt barrier to assess the reliability requirements (sources: (Willems & Webbers, 2003) and (Rijkswaterstaat, 1994)).

interacts with urban development, economic progress, and environmental issues (Meyer & Nijhuis, 2013). These aspects are covered with the involvement of *multiple actors* with different interests, as in the Dutch National Delta plan (Meijerink, 2005). With such an integrated approach, *unique and iconic* SSBs are designed with customised subsystems and components. Each SSB is considered a prototype having a distinct physical environment, specific requirements, and individual design (Mooyaart & Jonkman, 2017). Furthermore, innovations enable the design of SSBs, as was the case in the Netherlands and the United States, and their success creates an international image (Meyer & Nijhuis, 2013).

After the construction of these unique SSBs, they are expected to have a *long life* for periods reaching 200 years for the Eastern Scheldt barrier (McRobie et al., 2005). During this long life, changes occur, influencing the SSBs. This is seen in the study by Haasnoot et al. (2020), who highlighted that the design of existing coastal defences accounted for lower magnitudes of SLR which reduces their original design lifetime. In this long life, SSBs have *limited and dependent operations.* Their closure depends on water level thresholds or annual exceedance probability constants (Chen, Orton, & Wahl, 2020). Their operation is also limited since SSBs are designed to close in case of rare storm surges. Existing barriers in the USA did not operate yet at or close to their design peaks (Morang, 2016), and those in the Netherlands have a low closure frequency (Nogueira & Walraven, 2018).

Having limited and dependent operations with a long life, the operation of SSBs is *dynamic*. Due to SLR, SSBs are expected to have more frequent and longer closures (Chen et al., 2020) to comply with the standards (Jonkman et al., 2018). Furthermore, the operation of SSBs can be influenced by high precipitation since their closure may result in freshwater flooding behind the gates (Mendelsohn et al., 2022).

4. Asset management approach in The Netherlands - ProBO

In this section, the AM approach employed in the Netherlands, known as ProBO, is studied. First, the design basis focusing on the safety requirements for SSBs and their transfer to the AM approach is explained. Then, the application of ProBO to monitor and manage SSBs is detailed and the guiding principle for decision-making is clarified.

4.1. Design basis

SSBs in the Netherlands are subject to specific requirements dependent on the national safety standards and the flood defence system they belong to Mooyaart and Jonkman (2017). After the 1953 flood, safety standards were initiated based on a cost-benefit analysis motivated by the work of Van Dantzig and Kriens (Jorissen et al., 2016; Van Dantzig, 1956; van Dantzig & Kriens, 1960). These safety standards identified exceedance probabilities of hydraulic load conditions for enclosed areas protected by a flood defence system known as dike rings. These standards governed the realisation of SSBs and became a reference for annual reliability assessments relative to the Water Act (Jorissen et al., 2016).

As a result, the design of SSBs was accomplished relative to safety standards for the flood defence system protecting a

Table 1. Performance requirements and operating conditions for SSBs in The Netherlands (source: Rijkswaterstaat public information, dutch water act).

SSB	Target performance requirements *(acceptable failure probability)*	Operating conditions *(forecasted water level for closure)*
Hollandse IJssel barrier	1:200 per closure	+2.25 m above NAP (Amsterdam Ordnance Datum)
Maeslant barrier	1:100 per closure	+ 3 m above NAP near Rotterdam or more than + 2.9 m above NAP near Dordrecht
Eastern Scheldt barrier	1:10000 per year	+3 m above NAP
Ramspol barrier	1:100 per closure	+0.50 m above NAP and a strong northwest wind
Hartel barrier	1:10 per closure	+ 3 m above NAP near Rotterdam or more than + 2.9 m above NAP near Dordrecht
Haringvliet sluices	1:1000 per year	+2.2 m above NAP and closed for daily operation for river discharge

dike ring, as shown in Figure 4. At the design stage of SSBs, Fault Tree Analysis (FTA) was conducted to assess the probability of flooding while considering different structures, their elements, and failure mechanisms (Battjes & Gerritsen, 2002; Vrijling, 2001). This analysis was applied to the design and construction of the Eastern Scheldt barrier and the Maeslant barrier (Vrijling, 2001). The design plan of the Eastern Scheldt barrier explained the translation from national safety requirements to system analysis and functional analysis and the compliance with the Water Act (Rijkswaterstaat, 1994). For the Maeslant barrier, an additional requirement on closing frequency was considered due to the presence of Rotterdam Harbour as presented by Janssen and Jorissen (1991). As such, the Water Act defined the design requirements and operating conditions for SSBs while the FTA facilitated the design and the demonstration of compliance with requirements.

Hereafter, reliability and risk considerations were transferred to the O&M phases (Vrijling, 2001), such as reliability of maintained and repairable components, software reliability, human reliability, and operational reliability. Furthermore, the FTA dedicated to SSBs was constructed to demonstrate that the requirements imposed by the Water Act were met by O&M throughout the lifetime of SSBs (Walraven et al., 2022). Table 1 presents the current operating conditions and target performance requirements, with acceptable failure probabilities being the unavailability of SSB per closure or the protection level for SSBs with a chain of gates.

4.2. Monitoring and managing SSB

To continuously monitor the performance of SSBs, ProBO was designed as a risk-based approach centred around the FTA of a SSB. ProBO aims to maintain SSBs such that the target performance requirements are sustained, fulfilled, and demonstrated. This is achieved by connecting O&M with risks influencing performance and integrating three core aspects in ProBO: technical, organisational, and contractual.

Technical aspects focus on analysing the system and its requirements to achieve an FTA assessing the risk of failure during O&M. Organisational and contractual aspects translate this risk analysis to O&M processes and outsourcing schemes, respectively. Then, these three aspects are integrated into an overarching process (called ProBO) following a Deming cycle with Plan-Do-Check-Act (PDCA) phases (Bogaard & Akkeren, 2011), as depicted in Figure 5 and Table 2. Therefore, the expected tangible outcomes of ProBO are:

- a risk model (FTA) to assess performance levels;
- O&M requirements, plans, and guidelines;
- management strategies for quality assurance, outsourcing, and knowledge management among others; and
- assessment of the actual current situation relative to targets.

4.2.1. ProBO in practice

Starting with the technical aspects, the FTA of an SSB was developed to the component level based on:

- design information and field explorations to decompose the SSB system accurately;
- review sessions with suppliers and contractors to estimate the necessary parameters (such as failure frequencies, maintenance interventions, and repair times); and
- research studies on human reliability and software reliability.

The defined parameters in the FTA were set as requirements for the maintenance process. In current practice, these requirements are managed in a maintenance planning tool (RCMCost) to analyse maintenance options and optimise plans (Figure 6). This is performed in connection with the FTA to assess the maintenance scenarios' influence on the unavailability of the SSB. From this analysis, the maintenance requirements along with short and long-term plans are set and stipulated in work instructions and contracts. Furthermore, contractors are trained to work with these strict requirements and ProBO in general, such as reporting the Root Cause Analysis (RCA) of failures for the continuous understanding and improvement of the SSB.

Furthermore, human-related errors are analysed with the OPSCHEP model that was customised to the SSBs from the THERP method (Gertman & Blackman, 1993) for HRA in the nuclear industry. This model helped quantify human errors' contribution to the unavailability of the SSB for: (1) maintenance actions resulting in components in undesired condition, (2) repair or restoration actions of failed components during operations, and (3) operating actions during manual operations.

Based on these analyses, the necessary support was prepared, such as operational scenarios, manuals for emergency closure and urgent repairs, and operating instructions.

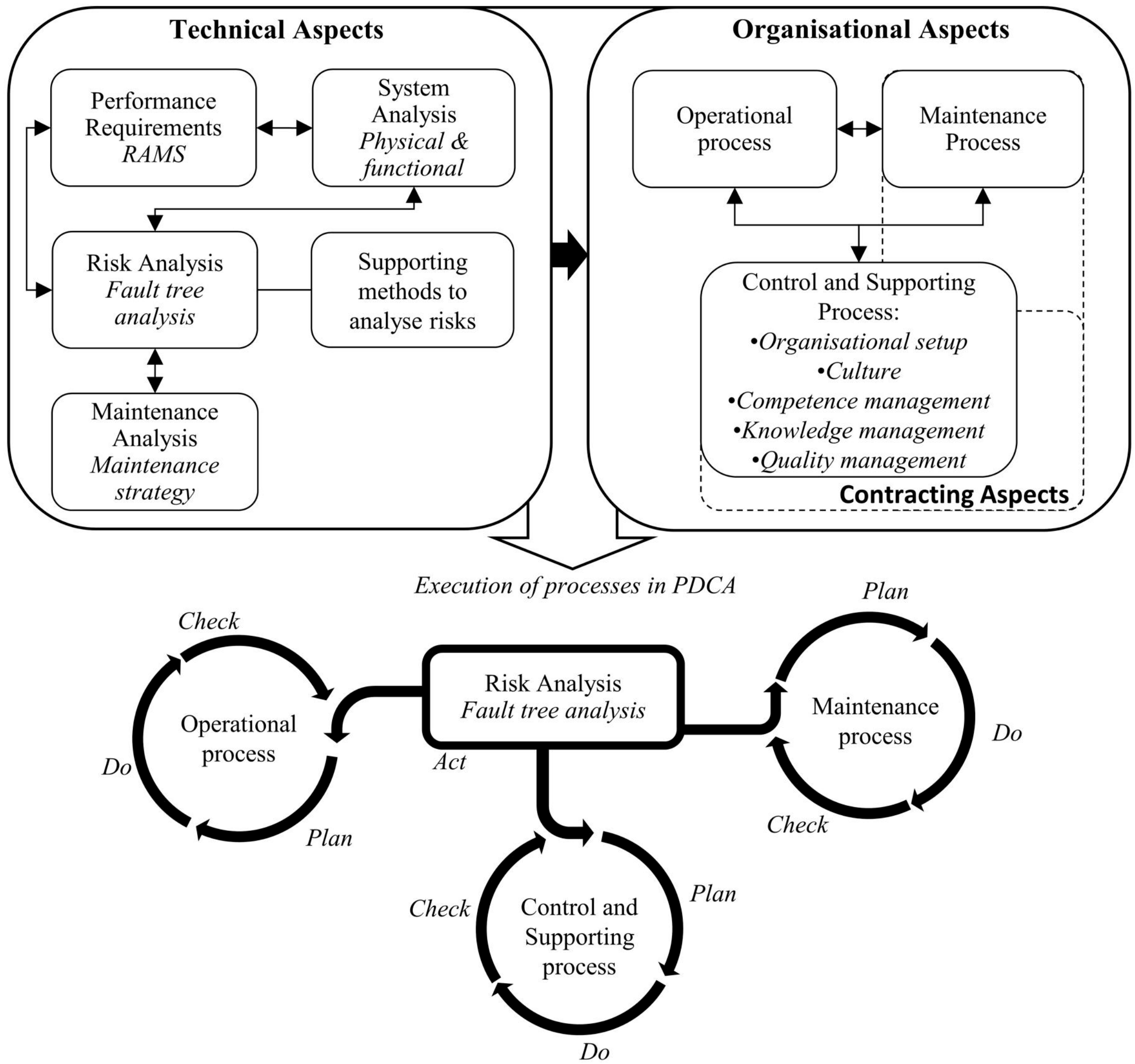

Figure 5. Overview of ProBO as depicted by kharoubi et al. (2023).

These workable guidelines are part of the control and supporting process that also considers organisation setup and training for O&M, among others. The processes of ProBO are executed in a PDCA cycle shown in Figure 7. In the plan phase, schedules and contracts are prepared along with the required instructions. In the Do phase, O&M is executed by its personnel and contractors. In the Check phase, the performed activities are evaluated relative to their original planning and requirements. Furthermore, the collected data is analysed to determine trends, deviations, improvements to plans, or optimisation of components/systems. In the Act phase, the SSB's performance is assessed against the reliability requirements based on collected data and the underlying assumptions of the risk analysis are validated. This is performed twice a year, before and after the defined storm season from October to April.

The actual performance is analysed relative to the model and the validation covers: (1) the quantitative assumptions for the calculations of the FTA, such as repair times, and (2) the qualitative pre-conditions, such as trained personnel. The former utilises the FTA while the latter relies on ProBO Compass which is an internal self-audit developed to address topics, such as control quality, resources, and knowledge levels. By analysing the collected data, the following are provided:

- overview of performed activities, encountered disturbances, and changes in the system or FTA model;
- discussion of the influence of these changes, follow-up actions, and improvements;
- assessment of the current failure probability with actual data, where possible;
- rationalisation of future issues with potential influence on performance; and
- presentation of the internal audit results with elaboration on non-conformities along with their possible short or long-term influence on the performance.

Based on the act phase, the evaluations guide the short and long-term decision-making that aims to ensure flood safety with fulfilled performance requirements. They provide evidence along with an explanation of factors influencing performance and consequences relative to the requirements. Furthermore, they provide a transparent

Table 2. Explanation of ProBO's aspects and processes.

Aspect	Process	Description
Technical aspects	Performance requirements	Identify performance requirements from legislation and policies in terms of: • Quantitative RAMS (Reliability, Availability, Maintainability, Safety) • Other qualitative requirements
	System Analysis	Provide, based on design information, an overview of relationships between physical elements and components and their functions with: • System Breakdown Structure • Functional Breakdown Structure
	Supporting methods to analyse risks	Perform the following analyses as a prerequisite for the risk analysis: • Failure Mode & Effects Analysis (FMEA) to interpret failures to the component level that can be linked to RAMS specifications from available data, calculations, or expert opinions • Software reliability analysis to decompose coding into modules and quantify their failures • Common Cause Failure analysis (CCF) to quantify dependencies in the failure of components and software modules • External events analysis to identify causes and effects of external events influencing the system's performance • Human Reliability Analysis (HRA) to analyse human errors during O&M activities influencing the system's performance
	Risk analysis	Assess the performance level of the barrier system with information from the previous steps in an FTA quantifying the undesired event (unreliability or unavailability) to reflect the current performance level and compare it with requirements
	Maintenance analysis	Determine based on the risk analysis: • Maintenance strategies using the concept Reliability Centred Maintenance (RCM) and information from the risk analysis such as test intervals and repair times • Maintenance, test, and inspection activities with frequencies estimated while considering the former maintenance strategy, acceptable failure probability, expected and required performance
Organisational aspects	Operational process	Set the operational process while considering performance requirements, human errors, and repair work to conclude: • Operational scenarios and preconditions • Operational activities • Procedures and instructions • Necessary resources for operation
	Maintenance process	Prepare this process based on performed risk and maintenance analyses to specify: • Maintenance plans and activities • Maintenance procedures to facilitate repairs and reduce human errors and common cause failures from maintenance faults
	Control and supporting process	For each of the operational and maintenance processes, define the following: • Organisational setup • Organisational tasks, responsibilities, and roles clarifying communication lines • Knowledge levels, competencies, and skills for the different positions along with development plans and training • Human Resource Management (HRM) plan to retain knowledge and set methods for documentation and transfer of knowledge • Quality management to maintain processes and their quality with audits • Culture management promoting a safety culture
Contracting aspect	Contracting process	Prepare for outsourcing with: • Decisions on activities to outsource • Clarifications of responsibilities of the contractor • Plans and processes to prepare contractors to work at the SSB with ProBO • Contracts specifying activities, performance requirements, training levels, and documentation requirements • Competencies and knowledge preparation of contractor and contracting organisation

assessment of the status of the SSBs with a holistic view covering the technical reality, O&M processes, organisation, and contracts. In this manner, the necessary information is provided for management review and governmental decisions on SSBs.

5. Role of characteristics in the evolution of ProBO

As described earlier, ProBO is composed of various interacting analyses and processes, leading to an approach with features defined in Table 3. These features support the investigation of the development of ProBO. By analysing these features relative to the SSBs' characteristics in Figure 3, the study provides an understanding of how SSB characteristics have influenced the evolvement of the AM approach with three main themes:

1. Setting the motives at the initiation.
2. Inducing challenging conditions that cause the AM approach to mature.
3. Requiring support over time which enforces continuous improvement and resilience of the AM approach.

These themes enable understanding the evolution of ProBO with the influence of characteristics as depicted in Figure 8 and explained in the subsequent sections.

5.1 Initiation: setting the motives

In this phase, the characteristics of SSBs had a role in setting the following two major motives for ProBO, requirements and social responsibility.

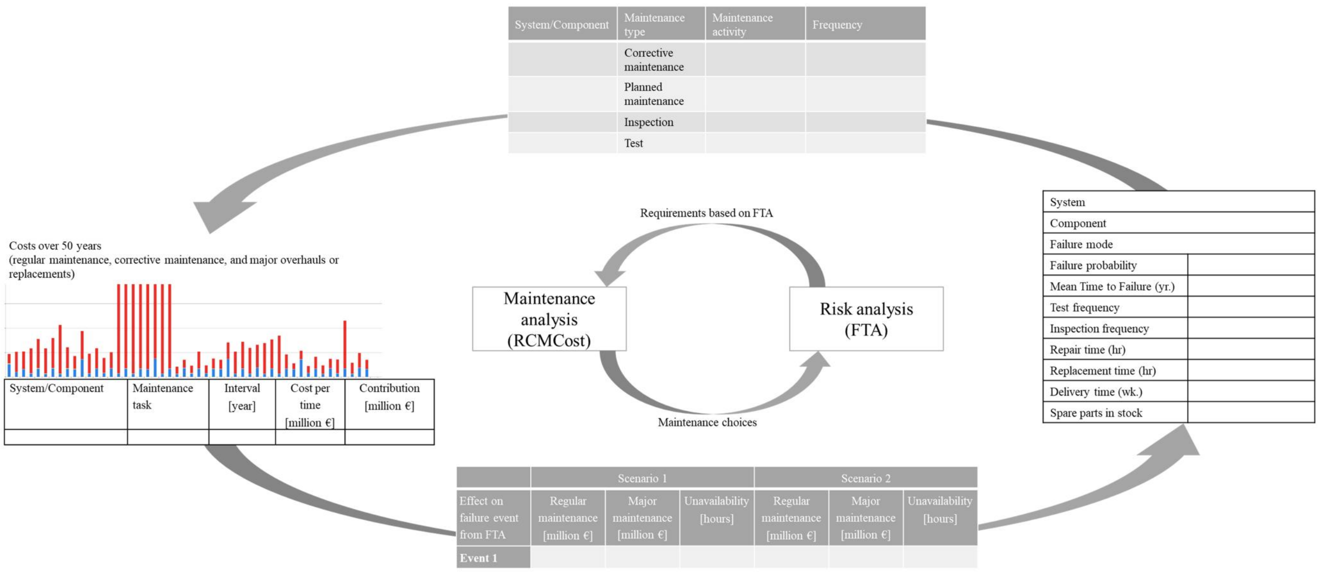

Figure 6. Connection between maintenance and the SSB's FTA.

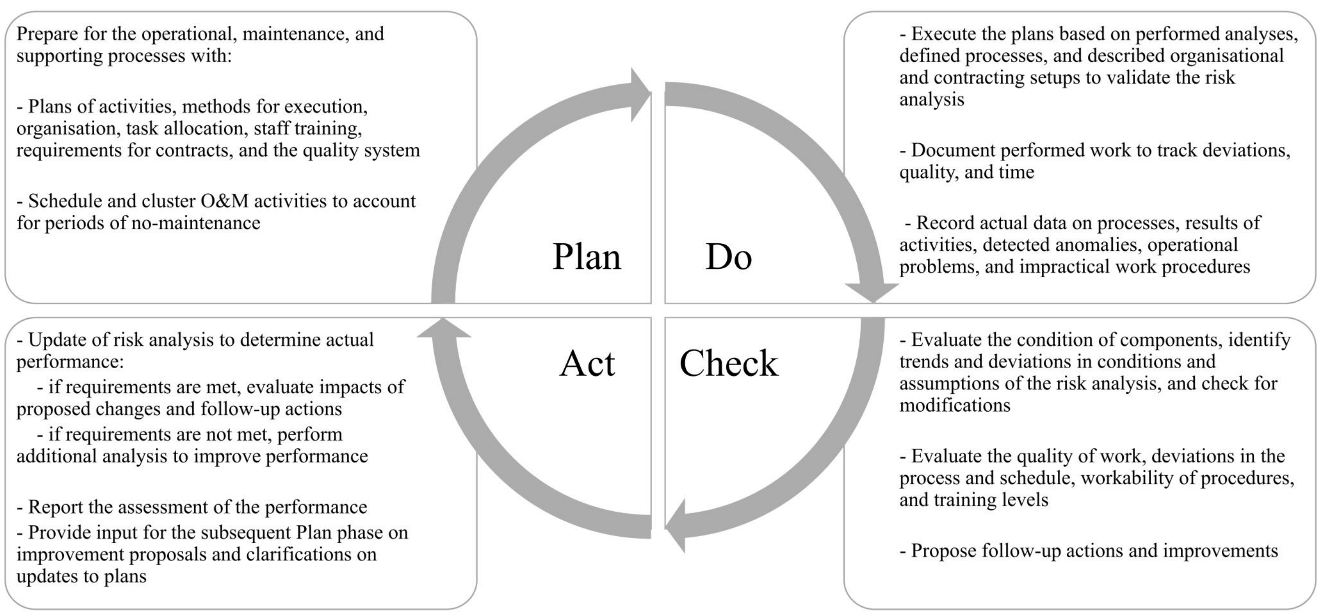

Figure 7. PDCA explained.

5.1.1. Requirements

In addition to the design basis (in section 4.1), various characteristics of SSBs have led ProBO to focus on the requirements. Being a critical and public infrastructure designed and completed to meet stringent reliability requirements, the Maeslant barrier, operating since 1997, required an AM approach to showcase its reliability requirements. This was the primary trigger for a quantitative approach linking maintenance to design reliability requirements. However, such a link was not accounted for in the design phase nor was it common at that time (2002). Consequently, a suitable approach had to be tailored to the uniqueness of the barriers.

Due to the combination of high-reliability requirements, limited operation, and components unique in design or operating conditions, the tailored approach was developed with the features risk-based, comprehensive, and holistic. The approach relied on detailed risk analysis to assess and monitor performance levels, plan and evaluate maintenance interventions, and demonstrate compliance with reliability requirements. Henceforth, ProBO became holistic, connecting the risk analysis to organisational and contracting aspects to manage their influence on the barrier's performance of the barrier. In this manner, the organisation gains the necessary control over the performance. This is emphasised since SSBs belong to the flood defence system that is also subject to high-performance requirements.

Furthermore, the multi-functionality of the barrier was addressed in the comprehensive approach with agreements with stakeholders on operating conditions. For example, discussions with the Port of Rotterdam fixed agreements on the conditions under which the barrier can close the

Table 3. Features of ProBO.

Features	
Holistic Approach	Covering and connecting technical, organisational, and contracting aspects with the risk analysis
Comprehensive approach	Thorough preparation and assistance to execute the work
Strict approach	Following planning and procedures to validate the risk analysis
Risk-based approach	Having the risk analysis as the basis for all three processes (Operation, Maintenance, Control and support)
Quantitative approach	Providing evidence of compliance with performance requirements
Constant control	Assessing regularly the system's performance and checking with PDCA-based execution
Continuous improvement	Improving continuously at different levels (with PDCA cycles, progress strategies and training for personnel, and quality management)
Connection between risks and people	Connecting internal and external parties to risks (with the contracting aspect connected to the risk analysis, and human error, expertise, and culture covered in the control and supporting process
Transparency	Proving that the necessary work is done and the required performance is sustained
Creating a specific culture	Having a culture looking beyond planning and doing to continuously improve and be in control
Tailored approach	Tailoring an approach to the specific SSB depending on various influencing factors

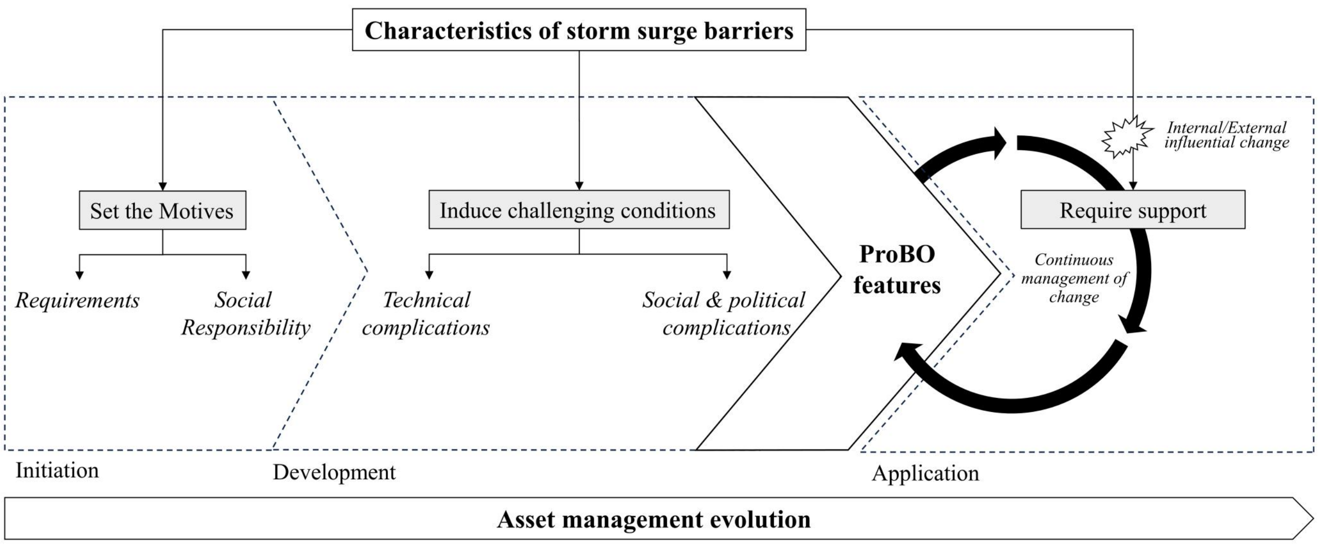

Figure 8. Evolution of ProBO with the influence of SSBs' characteristics.

waterway and allocated a time slot for annual testing. Such agreements were added to the Dutch Water Act and were considered in ProBO to avoid discussions on closure during critical times and account for other functionalities and interests of stakeholders. After implementing ProBO at the Maeslant barrier, other SSBs in the Netherlands adopted it. Each barrier tailored ProBO to its specific requirements, unique shape, operating conditions, and flood defence system.

5.1.2. Social responsibility

Another crucial motive for the development of ProBO was social responsibility. This started with a newspaper article (de Vreede, 2006) on the low reliability of the Maeslant barrier. Due to this claim, the government initiated a task force to assess, improve, and sustain the required performance. Since then, the fulfilment of the regulation became a political process with regular reporting to the minister and continuous proof of protection to the people. Therefore, the barrier's criticality and the political demand to demonstrate compliance with the quantitative requirements triggered transparency.

This transparency depended on extensive work and calculations due to the limited operation of the critical asset. Barrier teams have to perform O&M as prescribed and prove 'on paper' that the barriers meet the required reliability and are ready to operate upon request. Furthermore, transparency warrants the necessary maintenance for operation in uncontrolled environments and extreme events. This is also connected to social responsibility in using public money which becomes evident with the risk-based and holistic view of ProBO. Furthermore, the pressure from authorities and the role of maintenance in providing safety triggered strict rules towards contractors. This required ProBO to incorporate the preparation of contractors, training, and detailed procedures.

5.2. Development: Inducing challenging conditions

After setting the motives, the development of ProBO entailed dealing with technical complications and social and political pressure.

5.2.1. Technical complications

Technical complications occurred due to specific characteristics of SSBs and were resolved in ways that enriched ProBO with more details. The technical complications were first witnessed at the Maeslant barrier. The contractor proved that the barrier was sufficiently reliable and provided a maintenance guide. However, it did not provide confidence that the maintenance would lead to the required performance. Furthermore, unrealistic assumptions were detected regarding software reliability and human's role in operations. This commenced investigations to assess the barrier's performance and improve the maintenance guidelines.

An initial challenge to this investigation was the lack of calculations for assessing the SSB's reliability during the maintenance phase and incorporating it in the reliability assessment of the dikes in the hinterland. Thus, a quantitative approach was crucial to respond to the latter and the Water Act specifying protection levels in terms of probabilities.

Another major challenge surfaced during the reliability assessments. SSBs are '*sleeping giants*' hindering the ability to assess performance in operating conditions. As a solution, the performance of the barrier is evaluated with an FTA, performed and detailed to the component level for which data can be collected from tests and inspection. Based on this information, various models, and analysis of SSBs' subsystems, the performance of the barrier was eventually concluded. This FTA of the SSB became the tool for regular assessment to monitor performance.

Furthermore, the previously disregarded human reliability was introduced in ProBO with its necessary support, including:

1. Accounting for the role of humans in correcting failures during operations and improving the barrier's performance.
2. Setting instructions to reduce failure rates due to human error.
3. Training to prepare the teams, especially with limited experience from few operation opportunities.
4. Training contractors to understand the unique asset and the risk-based approach.
5. Assessing regularly the human's role.

In this manner, ProBO gained further details, became a strict approach, and created a specific culture focusing on risks influencing performance.

5.2.2. Social and political pressure

In addition to technical complications, social and political pressure accompanied the teams due to the responsibility of protecting against flooding. The criticality of the barrier created pressure to keep the barrier in a perfect state. This requested constant awareness and analysis of the situation (components, failures, root causes) to ensure safety and operability. Also, a specific working culture dominated by high awareness ('*We do it with four eyes*'), continuous improvement, perfection, and transparency. Such a culture is needed since '*You can't say the barrier doesn't work*'.

Social and political pressure was also encountered in relation to budget discussions and governmental decisions and demands. To support the political process, the risk-based approach facilitated assessing the influence of decisions on the barrier's performance and explaining the needed budgets. Then, the effects of fluctuations and misalignments between budget plans and maintenance programs are discussed, based on risks, to support maintenance and replacement decisions. Similarly, the influence of decisions on O&M processes can be analysed with the holistic and comprehensive approach of ProBO. Therefore, ProBO enables the handling of the political process and ensures flood safety is not compromised.

5.3. Application: requiring support over time

The addressed motives and challenging conditions led to specific features of ProBO. Over time, these features support the management of influential changes, stimulating cycles of continuous improvement. The strict and comprehensive features of ProBO support knowledge retention during the long life of SSBs. Furthermore, ProBO provides constant control with regular assessments and trend analyses that inform top management of changes in the barriers and their influence on performance. This clarifies when and where to intervene.

In connection with stakeholders, ProBO facilitates collaboration with risk-based and quantitative features. For example, stakeholders optimised budget allocation to meet the requirements of the flood defence system by improving the barrier instead of heightening the dikes in the hinterland. Furthermore, ProBO can assist future discussions, for example, to reach new agreements with stakeholders on operating conditions in case of frequent closures of the waterway due to climate change.

In addition, ProBO has a role in identifying external changes that might influence the performance of the barrier. In practice, the threats from climate change are being addressed by specialised teams collaborating with universities to research the future conditions and the influence on O&M. Based on such research, the barrier teams can prepare to adapt O&M processes and maintenance strategies as suitable for future challenges. In summary, ProBO was shaped by the unique characteristics and needs of SSBs, evolving from its initiation, through its development, and into its ongoing application to ensure consistent performance.

6. Discussion

The case study investigates ProBO, its application in practice, and its evolution. To discover the underlying reasons for this specific approach, the developments of ProBO were analysed relative to SSBs' characteristics. The results of the case study show that SSBs' characteristics have significantly influenced the evolution and maturation of ProBO.

SSBs' characteristics not only initiate, shape, develop and mature the AM approach, but they also provoke awareness of future changes, inducing resilience in the AM approach. The AM evolution does not resemble a top-down process produced by the organisation, based on standards. In contrast, it resembles the growth of a living system with a context or environment represented by SSBs' characteristics. While these findings are specific to ProBO, they are given a broader perspective in the following discussion, relative to the literature and in comparison with other cases, where similar findings are observed.

6.1. Initiation: setting the motives

In the early stages, the characteristics of SSBs influenced ProBO by setting the motives, requirements and social responsibility. The requirements defined ProBO as a risk-based and quantitative approach. Likewise, social responsibility led to incorporating additional features to prove readiness, ensure successful operations, and guarantee public safety.

In comparison with AM for SSBs in Europe and the United States, the leading motive was social responsibility. These cases have the possibility of more frequent operations. This led to AM approaches relying on operations to assure that the system would operate and prove that to the public. Accordingly, the AM approach focused on frequent testing, redundancies in operational procedures (such as automatic, manual, and external support), and training in real situations to acquire knowledge and experience. Despite that, features from ProBO are being considered to improve performance, optimise investments, and facilitate communication with public authorities.

Based on this comparison, it is concluded that the combination of SSB's characteristics sets, early on, specific motives for the AM approach. The focal role of the motives in the case of AM for SSBs is in line with standards stating that (1) requirements are key for any asset and form one of the objectives of AM (IAM, 2015; ISO, 2018) and (2) social responsibility is vital for setting objectives for AM (Almeida, Trindade, Komljenovic, & Finger, 2022; ISO, 2018).

With the motives in sight, the characteristics guide tailoring the AM approach as seen in the addressed cases:

1. In the case of limited operations of SSBs, the focus is on requirements and social responsibility with an AM approach having ProBO-like features, such as risk-based and transparent.
2. When more operations are possible, social responsibility remains crucial and the AM approach shifts to focus on operations and aims to improve with additional features from ProBO.

Therefore, it is evident that SSB's characteristics have a dominant role in defining the AM motives and direction from the beginning. This supposition is supported by previous studies and the results build on their propositions to:

- Rely on probabilistic models to deal with the complexity of O&M of SSBs (Jonkman et al., 2018).
- Tailor maintenance and management to avoid an increased risk of failure (Chen & Alani, 2012; Jonkman et al., 2013).
- Cover in the AM approach means to align maintenance efforts while continuously satisfying requirements (Vonk et al., 2020).

6.2. Development: inducing challenging conditions

In the case study, ProBO was further shaped with necessary features to deal with technical complications and social and political pressure. These features offset the complications with analysis, procedures, and training, among others. Despite that, not all complications are resolved with ProBO but become noticeable over time. For example, loss of knowledge and insufficient information in archives were mentioned as current struggles arising from the uniqueness and long life of SSBs. Furthermore, barrier-specific complications influence ProBO. Complexity increases with issues in technology, such as at the Maeslant barrier, in comparison with simpler designs of the Hollandse IJssel barrier and the Eastern Scheldt barrier.

In comparison with other SSBs, challenges also influenced the development of the suitable AM approach. Technical complications, due to a lack of knowledge, information, and experience, are tackled with frequent operations and tests. Furthermore, other SSBs consider solutions such as building archives, accrediting personnel, setting and updating manuals and procedures, working closely with contractors, and building partnerships with continuous communication, between the Design & Build party and O&M party. Similarly, social and political complications led to embedding in the AM approach solutions, such as communicating frequently with stakeholders to facilitate the closure procedure, keeping knowledge in-house, focusing only on flood-related activities, and informing and educating the public. Therefore, the characteristics of SSBs cause general or barrier-specific challenges to achieving objectives. The AM approach is shaped by addressing these challenges. Furthermore, challenges emerge with time as witnessed during and after the development of the AM approach.

6.3. Application: requiring support over time

Building on the previous notion, this theme focused on changes that are addressed, during application, with the existing AM approach or its adaptation. The case study showed that changes influencing SSBs' performance surface due to characteristics: (1) inducing different conditions over time, such as multi-functional, long-life, and dynamic operation, or (2) increasing the vulnerability of SSBs to changes, such as critical and public infrastructure. To manage these changes and sustain the required performance, ProBO features (such as risk-based, continuous improvement, and constant control) assist in capturing, communicating, assessing, and adapting.

Similarly, AM approaches of other SSBs and their development address changes related to the SSBs' characteristics, dynamic operation, long life, unique, and critical infrastructure. These include: (1) improving based on lessons learned about the barrier and its O&M, (2) future-proofing with early preparations for modifications to SSBs or their systems, and (3) adapting maintenance plans due to SLR influencing O&M. Therefore, SSBs are vulnerable to changes, requiring the adaptation of their AM approach to sustain the required performance. This theme builds on Section 6.2 and implies the constant adjustment of the AM approach to deal with changes over the lifetime of SSBs. This conclusion is aligned with the AM requirements of ISO (2018) on addressing risks and opportunities that impact the asset or its AM approach and improving accordingly.

Furthermore, recent studies addressed changes related to the dependent and dynamic operation of multi-functional SSBs. For example, Trace-Kleeberg et al. (2023) investigated the pressure from SLR on the Maeslant barrier's maintenance strategies and proposed changes to the current approach to preserve the required reliability. Vader et al. (2023) proposed a framework to assess the remaining life (technical, functional, and economic) which in turn supports strategy planning and decisions by asset managers and van Alphen, Haasnoot, and Diermanse (2022) examined the impacts of accelerated SLR on the maintenance of SSBs.

6.4. Limitations and further application

The previous sections discussed each theme explaining the role of SSBs' characteristics in the evolution of the AM approach. These themes form the basis for establishing and developing an AM approach for SSBs while being bounded for the following reasons. First, the studied AM approach for SSBs has a specific context. Second, the interviews provided evidence of the influence of SSBs' characteristics on the AM approach with some characteristics prevailing over others. Third, the discussion revealed that SSBs can have certain characteristics from the identified list, in Section 3, due to the governing uniqueness of SSBs. Thus, these limitations hinder the ability to generalise and directly apply the findings to SSBs worldwide or other asset types.

Nonetheless, the research has implications for SSBs in particular and AM in general. The study supports: (1) developing and applying an AM approach with 'how' and 'why', (2) tailoring the suitable AM approach to the asset's characteristics, requirements, and context, and (3) employing the AM approach to capture, analyse, and respond to changes. Furthermore, the research shows the complexity created by characteristics, complicating or facilitating the AM approach. This encourages early consideration of the AM approach, especially maintainability, in the design of SSBs or other assets. This raises the questions for future research of whether the earlier consideration of the characteristics of SSBs (on maintainability, operation frequency, and others) facilitates AM for these assets and whether cultural and organisational differences have a dominating influence on the AM and its effectiveness.

In addition, the research contributes to the literature with a case study unveiling the evolution process of an AM approach and its complexity. This enabled determining the careful choices and rationale for tailoring the AM approach. Therefore, the study explains the influence of the characteristics of an asset on its AM approach as addressed by Herder and Wijnia (2012), provides evidence of the continuous evolution of AM in line with the studies (Masood et al., 2016; Pathirana, Heijer, & Sayers, 2021; Sinha, Labi, & Agbelie, 2017), and proves the complexity of forming a suitable AM approach as indicated by Lima and Costa (2019); Schraven, Hartmann, and Dewulf (2011); Wijnia and Croon (2015).

This was achieved by having a holistic perspective of the AM approach. Consequently, this study responds to the call for attention from researchers and practitioners to the overall AM approach (Maletič, Marques de Almeida, Gomišček, & Maletič, 2022) when research focuses on specific topics, such as infrastructure assets' condition assessment, optimisation models, and information management (da Silva & de Souza, 2021). Furthermore, the AM for SSBs as addressed in this study becomes an initial step for studies on AM in its entirety and future research shall consider cases from other sectors to enable the sharing of knowledge and experience with AM and identifying common challenges and success factors.

7. Conclusions

This study explained AM for SSBs in the Netherlands, traced the evolution of the AM approach, and highlighted the role of SSBs' distinctive characteristics throughout this evolution. An in-depth study reviewed the AM in practice from historical data and real-life experiences. Then, it was interpreted, from initiation to application, with an asset-centred perspective and thematic analysis to conclude that SSBs' characteristics:

1. set the motives in the initial phase to clarify the objectives of AM and guide its development;
2. induce challenging conditions that are tackled during its development, maturing the AM approach;
3. require support from the AM approach throughout the life of an asset, incorporating continuous improvement and resilience to the AM approach.

These insights provide the basis for developing and applying AM for SSBs and assets of different industries and sectors. Furthermore, the study presented an AM approach in detail and explained its complexity relative to its characteristics. Understanding this complexity facilitates developing AM and future-proofing for these assets and considering AM earlier in the design phase. Thus, the study provides valuable information for organisations with SSBs or planning to build new SSBs.

Besides practical applications, this research enriches the growing literature on SSBs by covering AM, which is critical for their operation and flood protection. It also builds on AM literature by providing evidence for previous claims on the influence of characteristics, complexity of AM, and continuous evolution of AM. Furthermore, the research provides a holistic case study of AM which encourages similar studies in other fields to share knowledge and advancements.

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Declaration of competing interest

The authors declare that they have no known competing financial or personal relationships that could have appeared to influence the work reported in this paper.

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