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Navigating dynamics with a sociotechnical perspective to asset management performance

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Abstract

Organisations aim to create value from infrastructure assets under varying circumstances with asset management. Asset management is inherently complex with multiple interacting actors and processes, varying asset stages, and evolving contextual conditions. While performance management should enable the evolution and improvement of asset management, conventional approaches often neglect its complexity and dynamic nature. In this study, we adopt a sociotechnical system perspective to asset management performance to (i) explain how performance results from interdependencies across social and technical elements and their alignment and (ii) embed adaptation to contextual change as intrinsic to performance management. We developed and demonstrated this perspective with an abductive research approach based on an in-depth study of asset management for storm surge barriers, providing a unique and safety-critical infrastructure context. We iterated between theory and field data to code interdependency associated with performance pathways and consolidated them into sociotechnical alignments. Based on these empirical results, we developed a conceptual model for monitoring and managing asset management performance over time, connecting it to leading indicators and performance outcomes. We made the model actionable by linking contextual signals to the alignments they disturb and directing targeted sociotechnical adjustments. By integrating sociotechnical systems into asset management performance, this study contributes to the theory with a contemporary approach to performance, while emphasising adaptation. The findings provide context-specific insights while demonstrating a methodological approach that can be adapted to other infrastructure domains operating under dynamic governance and operational conditions.

Keywords Asset management · Sociotechnical systems · Performance management · Adaptation · Resilience · Storm surge barriers

1 Introduction

Asset management (AM) is the coordinated activities to realise value from assets (ISO, 2014a). AM must sustain required service levels of public and private infrastructure assets during their long lifecycles (Lima et al. 2021) while dealing with limited and changing budgets, regulatory performance requirements, stakeholder demands, uncertain and evolving environments (Almeida et al. 2022; Maletič et al. 2022), technological advancements, and organisational context and changes (Ruitenburg and Braaksma 2017). AM adapts to shifting service demands and mitigates ageing and obsolescence risks (Le Gat et al. 2025). It increasingly incorporates social responsibility, sustainability, and environmental concerns into long-term plans (Gavrikova et al. 2020).

Being impacted by changing internal and external contexts (ISO, 2014a), AM must evolve continuously (Chabane et al. 2023) to counter challenges and maintain effectiveness over time (Lima and Costa 2019). Monitoring and evaluating the performance of the AM processes, which is hereafter referred to as AM performance, is central to this evolution,

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as it informs responses and improvement (IAM 2015; ISO, 2014b, 2018). Standards (IAM 2015; ISO, 2018) and prior research (Arthur et al. 2016; Attwater et al. 2014; da Silva et al. 2020; Roda et al. 2022; Wang et al. 2016) have predominantly framed AM performance through hierarchical indicator-based approaches or by examining individual processes in isolation. While these studies have offered valuable insights, they have not systematically addressed how interdependencies, social interactions, and contextual influences shape performance.

The present study brings these elements together, treating AM in its complexity. AM complexity stems from multidisciplinary topics and their couplings across lifecycle stages, functions, stakeholders, and organisational levels (IAM 2015; ISO, 2018; Sandu et al. 2023). Consequently, AM performance emerges not only from discrete activities but from interactions among social, technical, and contextual elements. Making these interactions explicit helps managers see how performance is generated, built up, and propagated through the system. This thereby indicates where to act and how to keep performance on track as conditions change.

Addressing this complexity calls for a systems perspective that examines AM in its context (Diop et al. 2022; Komljenovic et al. 2016). Infrastructure assets are inherently sociotechnical and interact with their environment. Their management should therefore reflect these properties (Osman and Nikbakht 2014). We adopt a sociotechnical systems (STS) perspective to AM of infrastructure assets to investigate how social elements (actors, roles, governance) and technical elements (tools, data, methods) work together, depend on one another, interact with the broader environment, and evolve over time. With this STS perspective, we treat performance as a dynamic outcome of ongoing interactions (Baxter and Sommerville 2011). Recent work likewise stresses coupling STS to manage infrastructure transitions under global pressures such as digitalisation (Diop et al. 2022; Manny et al. 2022).

Complex and dynamic AM with emergent performance is salient for AM of storm surge barriers (SSBs). SSBs are critical public infrastructures with long lifespans and high-reliability requirements. They rarely operate as they are mostly designed to protect against extreme flood events. This led to the development of a dedicated AM for SSBs' characteristics, with different interconnected processes, and its evolution over time for successful operation and continuous assurance of safety to society (Kharoubi et al. 2024). SSBs are subject to internal (e.g. dynamics in organisations, knowledge, and skills) and external (e.g. environment and climate, socio-economic, technological, regulatory, and political) contextual changes highlighted by Walraven et al. (2022) and addressed in various studies, including (Kamps et al. 2024; Vader et al. 2023; van Alphen et al. 2022). The combination of high stakes, occasional operation, and shifting context makes SSBs a pertinent setting to study AM performance.

This study investigates how AM performance emerges over time and how this understanding can support AM adaptation to changing contexts. We develop and apply STS perspective on AM performance that explicates interdependencies, assesses alignment at key interfaces, and considers adaptation to changes. With in-depth case study research for the AM of SSB, we demonstrate STS perspective to AM, complementing indicator-based AM performance evaluation.

2 Literature review

In this section, we elaborate on AM performance in Subsection 2.1. Subsection 2.2 delves deeper into the overlooked AM complexity in reviewed AM performance studies and highlights contemporary performance management theories. In Subsection 2.3, we explain the study's approach to embrace AM complexity with STS perspective to AM performance.

2.1 AM performance

Performance evaluation informs the current and prospective state of assets and their AM, supports monitoring them over time, and guides their adaptation and improvement (IAM 2015; ISO, 2014b, 2018). Lima et al. (2021) relate AM performance to business performance to assist investment prioritisation. Roda et al. (2022) promoted AM improvement decisions by prioritising based on AM processes, their maturity, and their contribution to value creation. Too (2012) frames AM as a dynamic capability, arguing organisations must, for example, develop cross-functional coordination, relational capacity, and technology absorptive capability, to adapt and sustain performance in changing environments.

To evaluate AM performance, most studies draw on hierarchical performance measurement traditions (Bititci 2015; Kaplan 2009; Neely et al. 2002). Performance is tied to objectives and operational outputs. It is assessed either via the overall Performance Indicators (PIs) that appraise activities or through cause-and-effect deployments that link actions to PIs to estimate influence on overall results (Bititci 2015). Attwater et al. (2014), Arthur et al. (2016), and Wang et al. (2016) adopted such approaches to AM. These approaches clarify what to measure and how to align indicators with strategy. However, they generally assume linear static cascades and pay less explicit attention to AM complexity and dynamics.

2.2 AM complexity: rethinking AM performance

AM evolved from maintenance-focused practices to an integral approach (Alquraidi and Awad 2024; Sandu et al. 2023). This shift amplifies complexity as evolving internal and external conditions (including regulatory, technological, environmental, social, and organisational factors) continuously shape the achievement of intended outcomes (ISO, 2018). Consequently, AM performance requires a dynamic, holistic perspective that makes interactions and context explicit.

Recent performance management research calls for approaches that are responsive to uncertainty, complexity, and social dynamics (Bourne et al. 2018; Mackenzie and Bititci 2023, 2024; Pavlov and Micheli 2022). Mackenzie and Bititci (2024) argue that control and predictability are unsuitable to manage complex organisational performance. They adopted complexity theory, focusing on the social aspects (including leadership, communication, and trust) to improve performance and shape behaviour (Mackenzie and Bititci 2023). Pavlov and Micheli (2022) highlight the dynamic environments and emergent performance, focusing on interactions generating performance instead of aggregating indicators to conclude performance. They recommend systems thinking methods (e.g. system dynamics to consider interactions with feedback loops and non-linearity with indirect, unpredictable, and disproportionate influence). Similarly, Bourne et al. (2018) question the suitability of cascaded Key Performance Indicators (KPIs) under turbulence and propose a shift towards learning and adaptation, with a holistic focus on objectives and relationships.

The complexity-aware performance literature recommends systems thinking and learning-oriented governance that complement indicator hierarchies. AM research can build on this by explicitly addressing interfaces, interdependencies, feedback, and dynamic environments through which AM performance is produced and maintained.

2.3 Embracing complexity: STS perspective to AM

Trist and Bamforth (1951) first introduced the interplay between technical and social subsystems in the coal mining industry. It was then formalised as STS for organisational design, recognising both subsystems for improved performance (Emery and Trist 1960).

STS treats systems as interacting social and technical subsystems: the technical (processes, tasks, technologies) and the social (structures, skills, relationships, norms). These subsystems interact with each other and with their context, producing outcomes (Bostrom and Heinen 1977; Trist 1981). The context includes the broader organisation and the external environment, for example, social systems (institutions, markets, socio-political dynamics, stakeholders), technological changes, and the natural environment (Chappin and van der Lei 2014; Davis et al. 2014). Drawing on general systems theory, STS perspective adopts interconnectedness, emergence, and limited predictability in evolving contexts (Kleiner et al. 2015). Accordingly, STS aims for joint optimisation or alignment between the social and technical subsystems and adaptability to turbulent environments (Trist 1981). This is necessary to analyse performance as emerging from dynamic interactions between various STS elements (Baxter and Sommerville 2011).

STS application initially focused on new technologies, then extended to heavy industry (Trist and Bamforth 1951), organisational performance (Bostrom and Heinen 1977), manufacturing, management and services (Clegg 2000), information systems, safety and accident analysis (Leveson 2004; Salmon et al. 2012), management of broader topics such as environmental sustainability, resilience (Davis et al. 2014), infrastructure transformation for sustainable energy systems (Bolton and Foxon 2015), and coordinating and aligning actors and technical systems for better long-term infrastructure performance (Osman and Nikbakht 2014).

Researchers advocate broader use of STS thinking to complex systems (Davis et al. 2014). STS was proposed for high-reliability domains (e.g. nuclear power) to integrate technical functions, human behaviour, inter-organisational collaboration, and multi-level context. This aimed to shift from relying only on probabilistic risk assessment and compliance that can oversimplify operational realities and mislead decision-making (Aven and Ylönen 2018). For future-focused dynamics, researchers propose STS perspective for adaptation, especially for organisations and infrastructure assets exposed to transformative changes, such as climate change (Chappin and van der Lei 2014) and exponential advances in technology and AI (Pasmore et al. 2019). This is the case for AM, as it is complex and subject to risks and uncertainties (Diop et al. 2022), especially with AM transition to Industry 5.0 with a human-machine system perspective and resilience to dynamics (Chabane et al. 2023).

This theoretical grounding motivates our shift from static indicators to STS of AM performance. We consider STS perspective to AM performance, contributing to system-oriented studies with attention to dynamics and complexity. We also extend on studies with attention to dynamics, such as adaptive capabilities of AM (Masood et al. 2016; Too 2012) and resilience engineering (Hollnagel 2014), aiming to sustain operations under varying conditions. We complement these studies with explicit coupling of social and technical elements, examining how performance emerges and how alignment and adaptability can be governed over time.

3 Methods

The research takes STS perspective to understand how AM interacting processes, actors, tools, and other constituents of AM shape its performance. This is explored with a case study of the AM for SSBs in the Netherlands. Subsection 3.1 explains how we adopted the theoretical STS perspective to AM. Subsection 3.2 describes the case study, and Subsection 3.3 clarifies the data collection and analysis procedures followed.

3.1 STS for AM performance

Considering STS for AM performance, we adopted the classic STS framework by Bostrom and Heinen (1977) based on the theory of Trist and Bamforth (1951). This is sufficient to: (1) articulate how we see AM as STS and (2) analyse AM performance while remaining tractable for data collection and analysis.

Figure 1 presents AM as STS connected to its internal and external environment and assets. We show generic social and technical subsystem components derived from and supported by clauses from (ISO, 2024b). We allocate all human-focused aspects in the social subsystem and all processes, tools, and information in the technical subsystem. At the outer shell, we set the environment influencing the STS, including the external and internal organisational context. Furthermore, the infrastructure asset is added as a separate component of the system to highlight the relationship between the asset and its AM and the impact of the environment on the asset. Lastly, the AM STS representation shows the reciprocal influences between (1) the social and technical components and (2) AM, with its asset and context, highlighting the mutual shaping and adaptation of the AM STS.

Following STS theory, AM performance emerges from interactions. We study AM performance through these interactions by analysing the main socio-technical mechanisms defined below, based on (Baxter and Sommerville 2011; Bostrom and Heinen 1977; Clegg 2000; Trist 1981):

- *Interdependence*: Performance emerges from the interactions between STS elements, such that a change in one part propagates to others and system performance reflects their joint effects, not the parts in isolation.
- *Alignment (Joint optimisation)*: Performance is maximised only when the technical subsystem and the social subsystem are co-designed and tuned together. The compatibility between social and technical subsystems influences AM performance.
- *Adaptability*: STS senses change, learns, and reconfigures structures/practices fast enough to stay fit for

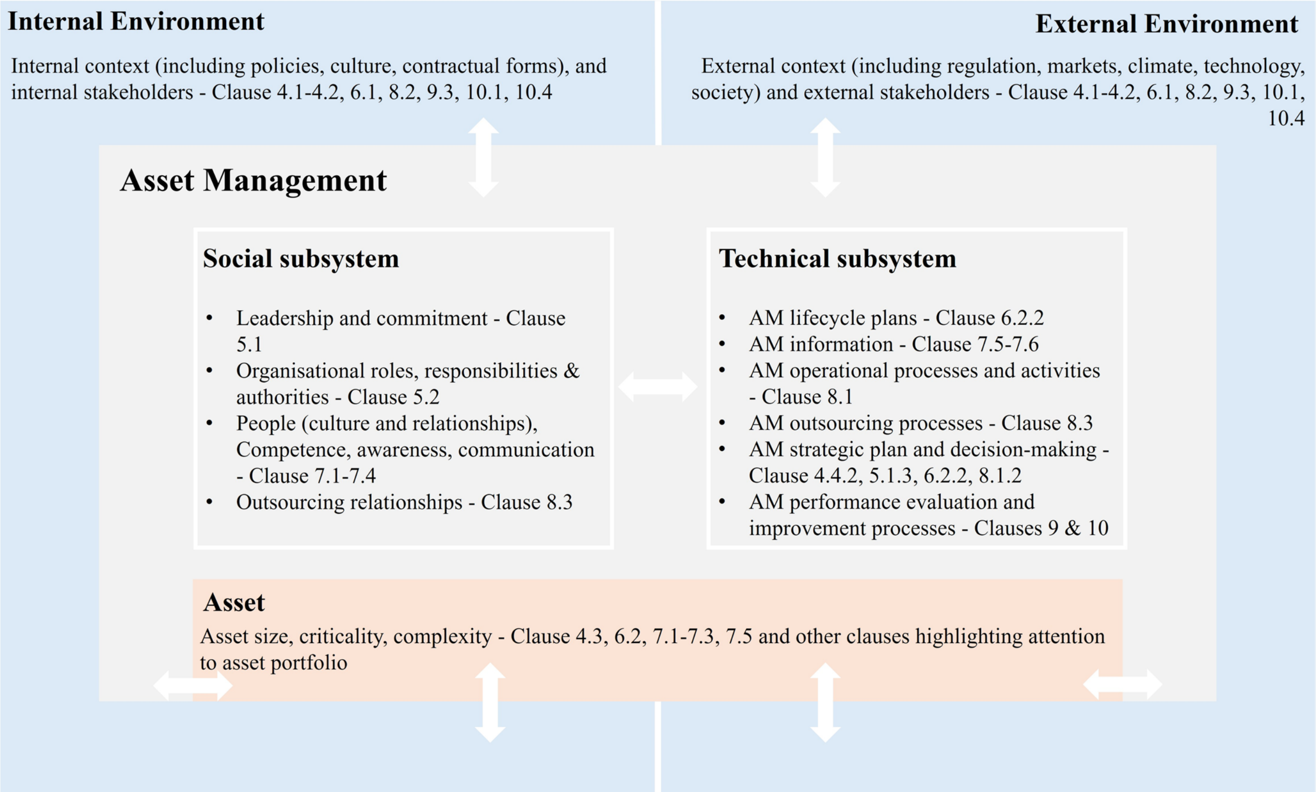


Fig. 1 AM as STS based on Baxter and Sommerville (2011); Bostrom and Heinen (1977); and ISO (2024b) with supporting clauses as examples

context. This focuses on the ability of the system to adapt and respond to changes to realign with the context.

3.2 Case study description

Performance emergence is contextual, processual, and mechanism dependent. This aligns with "how/why" phenomenon that case studies are designed to explain. Case study research is especially suitable when the borders between the phenomenon and context are indistinct. It enables considering the context (e.g. political budgets, procurement rules) and case specifics (Yin 2018). We study in-depth a case offering access to rich insights into interactions inducing performance. We focus on the AM specifically designed for SSBs in the Netherlands, known as ProBO ("Probabilistic operation and maintenance") (Kharoubi et al. 2024; van den Bogaard and van Akkeren 2011).

ProBO focuses on meeting requirements for flood protection through a risk-based approach. It aims to satisfy and demonstrate SSBs' performance requirements, link O&M to risks influencing SSB performance, provide control over the system's performance level, and constantly improve the system and processes. To achieve these objectives, ProBO integrates technical, organisational, and contracting aspects. The approach is structured around a central risk analysis based on fault tree analysis, three core processes (operations, maintenance, and support and control processes) and supporting activities (e.g. contracting, quality management, and knowledge management, among others). Risk is then governed through the Plan-Do-Check-Act (PDCA) cycle of the three processes; further details can be found in the cited references (Kharoubi et al. 2024; van den Bogaard and van Akkeren 2011). Accordingly, ProBO in practice is enacted by multiple actors, from different disciplines, hierarchy levels, and organisations, within the organisational setting, external context, and specific SSB context.

Given ProBO's breadth, a comprehensive performance assessment is beyond scope. The maintenance of SSBs is consistently reported as a primary concern by practitioners working on SSBs worldwide. This is due to the limited operation to provide data, the uniqueness of custom components difficult to replace, tight windows for executing maintenance, among other challenges (Haigh et al. 2024). For this reason, we focus on the efforts to maintain SSBs, considering the contributions and interactions of different disciplines and processes. We investigate the sociotechnical interactions that drive maintenance performance over time while remaining framed within the broader ProBO system and avoiding an isolated analysis.

3.3 Data collection and analysis

We collected data from three sources, semi-structured interviews, documents, and informal site discussions (elaborated in Table 1), to capture interactions between the different STS components. These sources provide rich, contextual evidence about how processes are executed and how interactions unfold in real settings. They help establish a chain of evidence (Bowen 2009; Yin 2018). We conducted 10 semi-structured interviews with experts: (1) directly involved in SSB maintenance, (2) involved in strategic and tactical discussions, and (3) working on research and projects related to external changes. We covered the core questions (clarified in Table 1) while having probes to allow in-depth questions.

We applied a hybrid, abductive thematic analysis in multiple steps, iterating between data and STS theory (Fereday and Muir-Cochrane 2006). First, interviews were open-coded, focusing on interactions between STS elements (Fig. 1), misalignments, proposals for alignment, and performance impacts. For each interview, we assigned codes to clarify which STS elements interact with each other, why (the outcome or goal to achieve), and how. These codes enabled identifying and defining interdependencies. Second, we associated coded interdependencies with performance impacts from interactions in practice. Third, we consolidated interdependencies and impacts referring to the same situations, clarifying interacting STS elements. Fourth, we performed a cross-analysis that enabled matching and temporal ordering of the interdependencies. Then, we reviewed clustered interdependencies to abstract alignments from identified (mis-)fit of STS elements. We defined these alignments and associated them with PIs and re-alignment proposals from interviewees. Together, the results of previous steps informed the development of a conceptual model explaining how maintenance performance emerges from STS interactions over time. Last, we focused on adaptation analysis based on contextual changes, their influence on alignments, and possible re-alignments to remain fit to context.

4 Results: empirical and analytical

In this section, we analyse ProBO performance based on the STS perspective. In Section 4.1, we present the empirical results on interdependencies and alignments between the elements of the AM STS. In Sections 4.2 and 4.3, we present the analytical results with the former defining the conceptual model for managing performance and the latter utilising the model to investigate contextual changes, impacts and adaptations. Supplementary material is provided to show the detected patterns and their effects on performance.

Table 1 Focus of data collection and its aim for different sources

Data sources, their collection and utilisation	
Semi-structured interviews	*Addressed 3 main topics*: *1. Maintenance practice: Explored how maintenance is enacted in practice and how it affects SSB performance over time.* a. How is the maintenance process currently organised and executed in practice? b. Where do recurrent problems occur in the maintenance process, and why do they occur? c. How do these issues affect SSB performance in the short and long term? d. What interventions have been implemented or are considered to enhance maintenance and SSB performance? *2. Vertical and horizontal organisational interactions: Examined coordination, decision-making, and interface management across organisational boundaries.* a. How are interactions between organisational levels and units structured in practice? b. How do information and decisions flow vertically (top-down and bottom-up) and horizontally? c. How do these interactions support or constrain maintenance planning and execution? d. How are maintenance-related decisions made in practice, and who is involved at different stages? *3. Short- and long-term connections and change initiatives: Focused on perceived impactful changes and ongoing projects with their implications for SSB management and system evolution.* a. What are the main circumstances perceived to influence SSBs' management? b. How do they influence SSBs and their management over time? c. How are they being further studied? d. How are they connected with SSBs' operational teams? and how will they be integrated?
Documents	- *Strategic asset management plan*: Clarified organisational and AM objectives, strategic, tactical, and operational division of roles and connections, and major feedback loops. - *ProBO quality management system report*: Clarified maintenance process and its connection with other teams and departments in the organisation. - *SSBs' remaining life analysis*: Clarified main concerns pressuring maintenance over time. - *SLR and sand hunger affect the Eastern Scheldt*: Clarified future threats on operational closure and maintenance, and possible scenario solutions discussed between teams.
Informal site discussions	- *Visit SSBs to discuss asset management long-term plans*: Showed long-term plans and explained how and why maintenance plans are challenged now and in the future. - *Visit Deltares, the scale model for the Eastern Scheldt barrier*: Explained the project, why it was initiated, what the main threats being studied are, and how the information support SSBs team.

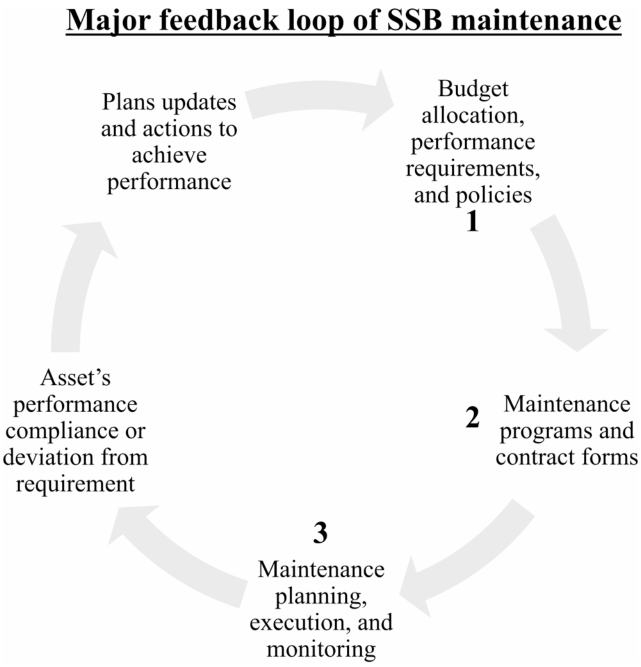


Fig. 2 ProBO feedback loop highlighting SSB maintenance

4.1 Interdependencies and their alignment shaping performance

The maintenance of SSBs undergoes a major feedback loop depicted in Fig. 2, connecting the planning and execution of maintenance to budget allocations and agreements. Interviewees reflected on the interdependencies and their alignment across the successive three phases: (1) Agreements and budget allocation, (2) Maintenance contracting coordination, and (3) Maintenance planning, execution, and monitoring. From the interviews, we explored how the social, technical, and contextual elements of the STS AM are interdependent in concept and how they interact in practice to shape performance based on observed performance outcomes:

- Progress of maintenance plans: percentage of planned maintenance projects completed on time.
- Maintenance plans verification and update over time: percentage of maintenance tasks and projects assessed and analysed to integrate with actual insights.

4.2 Agreements and budget allocation

This phase is mainly associated with the interaction between strategic, tactical, and operational levels, leading to decisions impacting the progress of maintenance plans. In principle, the strategic level sets direction from a societal political perspective. It provides input to the tactical level, with a network view, which translates strategic intent into coordinated multi-year planning programmes and contract preparations. Operational teams then execute, monitor, and evaluate plans at the asset level, acting with high urgency and ownership to keep the assets within requirements. Results and evidence from operations flow back to tactical for network-level performance assessment, which in turn feeds strategic decision-making on budget allocations, performance requirements, and policies.

The central interdependency concerns actors and information, specifically how information is framed, interpreted, and mobilised across levels. Alignment between actors and information is therefore critical and directly linked to the performance indicator decision latency. Figure 3 depicts the interdependencies and performance effects elaborated below.

The need for alignment stems from actors' differences in perspectives, responsibilities, and languages. Currently, the translations at the tactical level leave gaps in interpreting information. Strategic actors have a different mindset, looking for certainty and accuracy in predictions, while technical experts communicate probabilistic evidence and asset-condition nuance. Strategic attention to visible SSB closures and reported compliance can, in the view of operational teams, divert focus from maintenance issues and their impact on the long-term viability of achieving the performance requirement. At the same time, technically detailed compliance reports from operations do not always support the scenarios, plans, and decisions. This misalignment between actors and information distorts risk perception and urgency, increases communicative effort, delays decisions, and slows maintenance progress.

Furthermore, contextual dynamics amplify decision latency. Internally, management turnover disrupts shared risk understanding and perception built through experience, triggering repeated cycles of learning, knowledge sharing and discussions. Externally, political budget cycles and competition with more visible ageing assets (e.g., highways, tunnels) undermine long-term funding stability for SSB maintenance. The limited public visibility of SSBs, despite their national safety priority, further weakens prioritisation. Together, these contextual influences create fluctuating urgency and agreement on resource allocation, leading to deferred decisions, postponed projects, and cascading delays.

Consequently, the necessary alignments for this maintenance phase are cross-level information fit and leadership continuity. These are essential for timely decision-making to facilitate subsequent planning and execution phases.

4.3 Maintenance contracting coordination

This phase coordinates maintenance plans and prepares contracts following agreements and budget allocations. Contracting and SSB teams jointly translate asset knowledge into contract requirements. This is especially necessary for defining the scope of major overhauls and improving the requirements for data collection of regular maintenance. This creates interdependencies between actors, knowledge, and information to prepare contracts. The degree of alignment among these sociotechnical elements governs the timeliness of contracts, reflected by the performance indicator contract queue length, preparation duration, and overall lead time. The analysis of this phase is presented in Fig. 4.

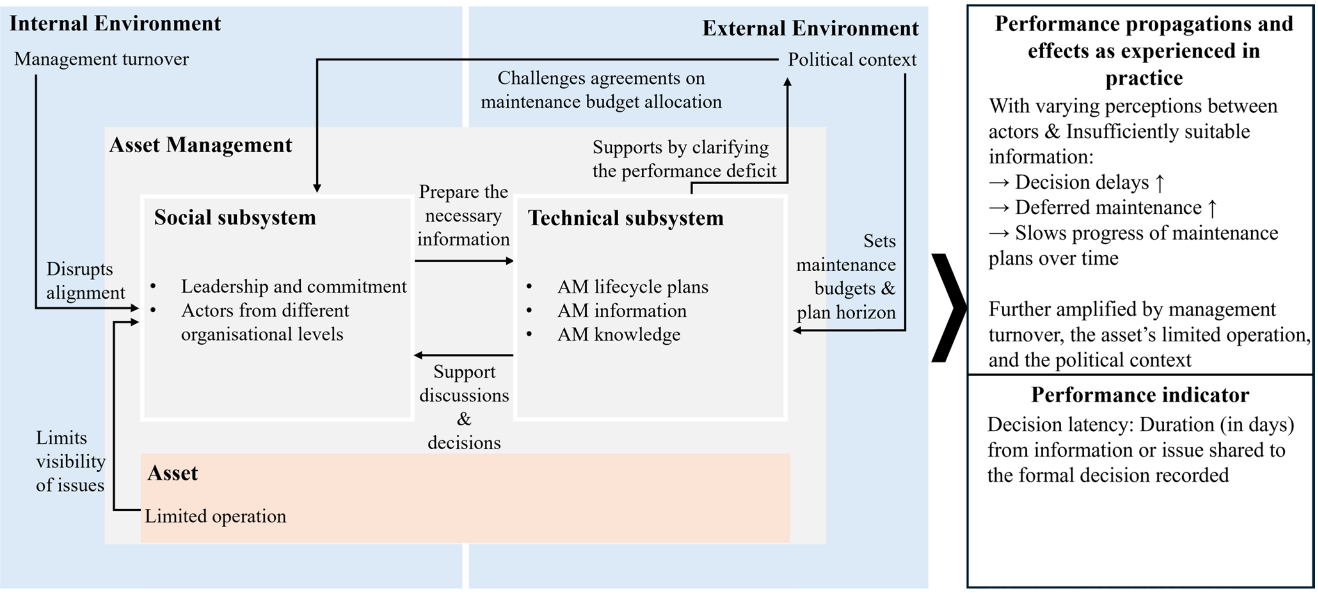


Fig. 3 Interdependencies and associated performance effects of the agreements and budget allocations phase

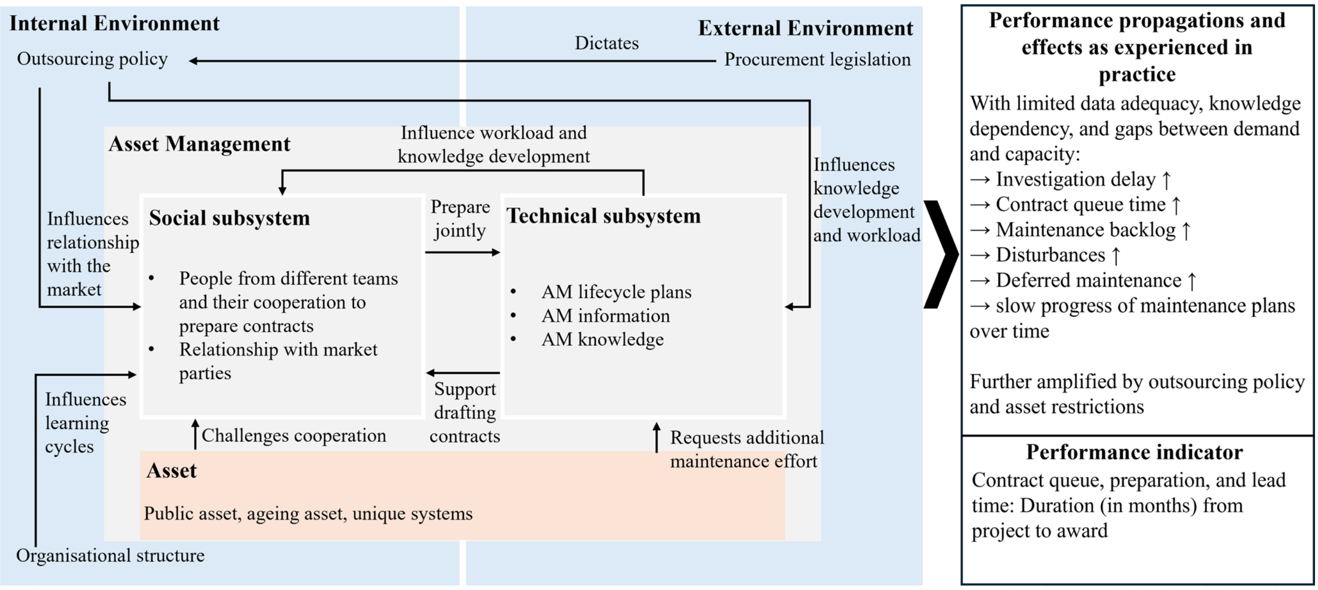


Fig. 4 Interdependencies and associated performance effects of the maintenance coordination phase

The alignment is vulnerable to the availability of human resources, the availability of knowledge and data, and dependency on specialised expertise. These are generated or amplified by the internal and external environment and asset specifics.

The involved contracting and SSB teams report a persistent mismatch between capacity and demand, which in turn disrupts coordination and preparation of contracts. Contributing factors include (i) more projects as SSBs age, (ii) lowest bid selection (due to tax money responsibility pressure) while undermining quality, leading to rework from non-compliant contract execution (e.g., limited expertise, quality issues, divergent interpretations), (iii) shortages of specialised skills and hiring challenges, and (iv) turnover among contracting staff, which forces SSB teams into repeated cycles of knowledge sharing. These complications contribute to longer contract queue times and ultimately increase the maintenance backlog with fewer projects prepared and completed to plan. As backlogs grow with late overhauls, disturbances increase, which in turn increase unplanned maintenance, further disrupt progress of plans, and worsen the workload of teams.

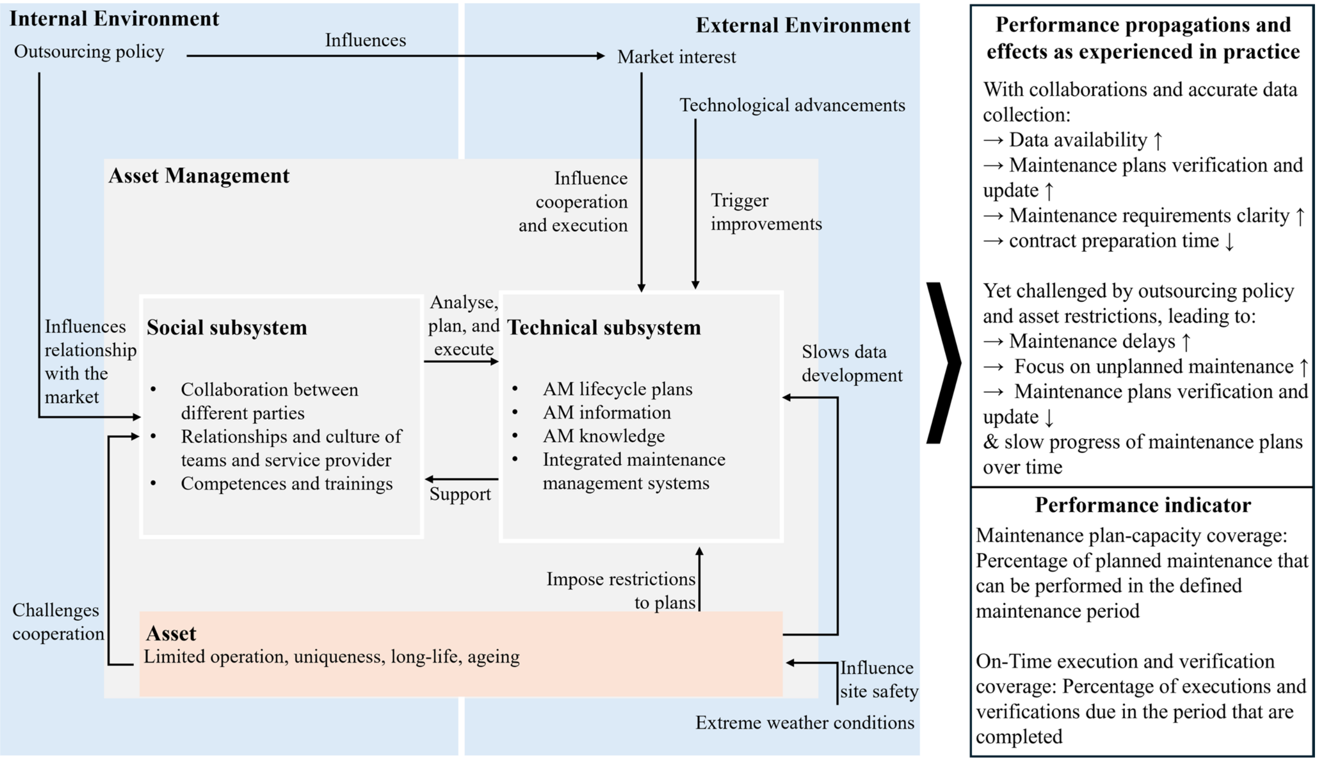
Data limitations further exacerbate delays. Data adequacy for major overhauls is often insufficient because of infrequent usage, prompting pre-contract investigations (e.g., condition-assessment steps in two-phase contracts) that extend lead times. Furthermore, investigation periods increase with the erosion of tacit knowledge. Interviewees reflect on decreasing tacit knowledge among the team or their collective memory, as maintenance is mainly outsourced and internal employee turnover is high. This creates dependency on a small number of experts, amplifying search and bottleneck delays and reinforcing investigation workload. The knowledge dependency is influenced by the suitability of contract forms, standardised within national and European procurement rules (i.e. limited contract duration).

Consequently, the coordination of contracts requires collaborative capacity alignment to reflect the congruence between the necessary joint effort of teams to prepare contracts, the available human resource capacity, and the adequacy of data and dependency on knowledge. Knowledge preservation-contract alignment is also essential for easing the contract preparation time.

4.4 Maintenance planning, execution, and re-calibration

This phase applies the adopted contract forms in the previous phase and contracted maintenance projects. The operational team and service providers execute maintenance and collect data to re-calibrate plans. This depends on contract forms, actors and their relationships, collaboration, resource availability, and SSBs' constraints, depicted in Fig. 5.

For major overhauls, current contract forms are perceived to deter relationships and cooperation for feedback on maintenance projects and plans. They tend to have a strict attitude towards service providers and transfer too much risk to them. This is reducing market interest to work for SSBs, already witnessed as an issue delaying maintenance projects. For regular maintenance, SSB maintenance plans start as model-based, assumption-driven strategies derived from asset, system, and failure analysis. As inspection data accrue, those assumptions are tested and revised in plans,



Performance propagations and effects as experienced in practice

With collaborations and accurate data collection:
→ Data availability ↑
→ Maintenance plans verification and update ↑
→ Maintenance requirements clarity ↑
→ contract preparation time ↓

Yet challenged by outsourcing policy and asset restrictions, leading to:
→ Maintenance delays ↑
→ Focus on unplanned maintenance ↑
→ Maintenance plans verification and update ↓
& slow progress of maintenance plans over time

Performance indicator

Maintenance plan-capacity coverage: Percentage of planned maintenance that can be performed in the defined maintenance period

On-Time execution and verification coverage: Percentage of executions and verifications due in the period that are completed

Fig. 5 Interdependencies and associated performance outcomes of the maintenance planning, execution, and re-calibration phase

contract requirements, and major overhaul scopes. Effective re-calibration depends on clear information models, accurate data collection and registration, agreed reporting standards, timely verification, and integrated maintenance information systems. Collaboration between service providers and SSB teams is critical to closing feedback loops. However, interviewees indicate that data quality varies with service providers' culture, commitment, and attitude. Commitment is strengthened when system condition interpretation and deviation analysis are conducted jointly, enhancing contract compliance rate and deliverable quality essential for progressing and updating maintenance plans.

Asset-specific constraints further affect execution and re-calibration timeliness. These include:

- Specific short maintenance periods (during summer non-stormy season) are disrupted by weather conditions (high winds or water levels hindering site safety).
- Complex site interfaces between different subsystems (e.g. blocking projects and restrictions on gates out of service).
- Safety training of service providers before site access.
- Service provider availability during the specific short maintenance period.
- Obsolete components requiring new designs, research, and testing, especially witnessed with rapid technological advances, adding projects (e.g. operating system change every 5–10 years) and,
- Slow data and knowledge development due to uniqueness and limited operation ("it takes a lot of time to recognise a failure").

Given these restrictions, SSB teams are challenged with delays in execution and alterations in maintenance plans. The limited maintenance period triggers a firefighting state to ensure the SSBs are ready for operation. This is especially witnessed as the asset is ageing, coupled with postponed maintenance, leading to increased disturbances. This shifts effort to unplanned maintenance, reducing capacity for planned maintenance and verifications.

Therefore, it is important to consider the alignments: (1) provider relationship-contract fit to enable collaboration, cooperation, and knowledge preservation, (2) capacity-task fit for workload availability for timely analyses, (3) data integration congruence between different elements, including tools (models with assumptions), plans, actors, contract requirements, information management systems, and (4) asset restriction-plan flexibility to facilitate maintenance execution under restrictions.

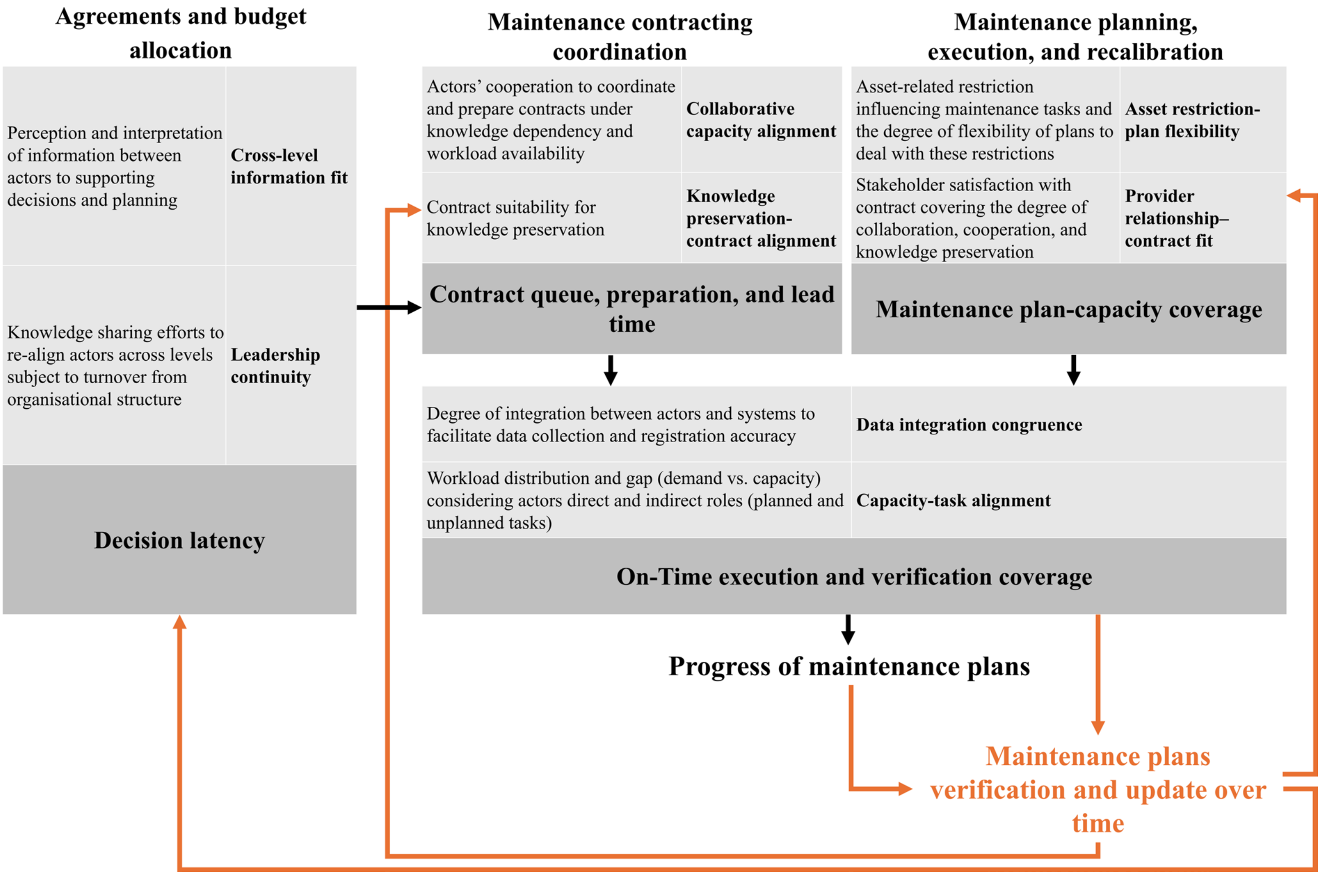


Fig. 6 Conceptual model concluding performance based on STS perspective

4.5 Performance based on STS perspective: the conceptual model

After analysing the interdependencies and clustering them into alignments shaping performance, we conclude the conceptual model based on STS perspective to performance in Fig. 6. The model clarifies how performance emerges from the alignments and propagates between the three studied phases of maintenance, associated with performance indicators, and connected to performance outcomes. This model acts as a tool for monitoring and managing performance.

To support managing alignments, we propose variables to trigger action for re-alignment along with targeted interventions grounded in interview evidence.

1. Cross-level information fit: This alignment can be monitored with, for example, the percent of information fit based on reviewing an agreed-on checklist and perception variability between actors based on short surveys. For drifting alignment, interviewees suggested strengthening the tactical layer to translate between strategic and operational needs. We also recommend co-designing reports, so they include the information requested by the different actors.
2. Leadership continuity: Re-alignment cycles can monitor the management turnover and its impact. To ensure alignment, introduce a joint shadowing transition period when key positions change to preserve shared perspectives and support this with an on-/off-boarding management knowledge booklet to retain assumptions, contact networks, and recent decisions. This involves monitoring the continuity of decisions beyond specific actors.
3. Collaborative capacity alignment: We propose monitoring this alignment with, for example, demand-capacity gap check, synchrony-window overlap between dependent actors, and degree of knowledge dependency (e.g. high for reliance on a single expert). Re-alignment proposals include (a) pairing juniors with specialists to rebuild collective memory and reduce single-expert dependence, and (b) clarifying the knowledge dependencies and difficulty of maintenance projects while matching them with the workload distribution of the needed experts.
4. Knowledge preservation-contract alignment: Interviewees indicate monitoring this alignment by checking knowledge handover clauses in contracts and time

allocation for review, feedback, and integration of generated knowledge. This follows with the re-alignment proposals: (a) insert knowledge-handover clauses and (b) use cooperative learning-oriented contracting forms (e.g. alliancing, two-stage) so knowledge is carried throughout the asset lifetime and the SSB team is involved in reviving collective memory.

5. Asset restriction-plan flexibility: For this alignment, we can investigate the share of restricted maintenance projects and the repeated constraint-induced reschedules without mitigation solutions. This helps trigger re-alignment by developing technical and operational solutions to recurring restrictions (for example, operational designs that limit evacuations as being studied for the Maeslant barrier) and setting pre-agreed workarounds, ensuring earlier permit or interface clearing, and having rescheduling protocols to keep plans executable.
6. Provider relationship-contract fit: For this alignment, interviewees propose monitoring qualified bids per tender, non-conformance recurrence, and SSB team and provider satisfaction and cooperation level. To re-align relationships and contracts, interviewees note cooperative and learning-oriented contract forms (e.g. alliance-type) that enable joint problem-solving under uncertainty and shared reviews to reflect on relationship quality and identify improvements.
7. Data integration congruence: The integration between actors and systems can be monitored with registration error rate, data adequacy and accessibility, and analysis time. It can then be managed with realignments, such as clarifying actors' data needs and reporting requests so that contract requirements and system fields match practice and protecting time for integration and analysis so collected data can actually be used to recalibrate plans.
8. Capacity-task alignment: For this alignment, we also need to monitor demand-capacity gap with attention to different factors such as time spent on unplanned tasks, overtime hours, uncompleted tasks, and employee turnover. For re-alignment, we suggest rebalancing workload and agreeing on clear prioritisation rules and making hidden workload visible by considering the complexity of tasks, rework, knowledge transfer, restrictions, and other driving workload, not only the planned tasks.

4.6 Adaptation–fit to context

AM performance, in terms of progress against planned work and the verification and update of plans, emerges from the alignments identified in our analysis. These alignments are, however, susceptible to drift under external contextual change. This section, therefore, uses the performance monitoring and management insights developed earlier to examine adaptation.

Consistent with STS, adaptation is conceived as sensing change, learning from its implications, and reconfiguring system elements to restore fit. We operationalise sense-learn-reconfigure, defined below, as a proactive qualitative governed cycle for stabilising sociotechnical alignments fit to context so that performance holds:

- Sensing surfaces external signals and their observable traces in maintenance work,
- Learning interprets which alignments are vulnerable or have already drifted, and why, and.
- Reconfiguring adjusts social and technical elements at the affected interfaces until there is evidence of restored fit.

We apply this cycle to the risks and opportunities reported by interviewees and documented in organisational records while employing the alignments and proposed conceptual model of the previous sections. We distinguish between near-term and longer-term contextual changes.

Interviewees communicate near-term contextual changes on technological advances (e.g. sensors for big data and digital twins) and procurement legislation (e.g. sustainability-focused). While digital technologies (e.g. sensors, data platforms) offer opportunities to improve data collection and analysis, limited involvement of SSB teams in their development creates risks of misalignment between systems and actors. Early co-design that accounts for user needs, skills, and knowledge is therefore critical to preserve data-integration congruence.

Procurement, sustainability, and environmental legislation introduce both risk/opportunity and uncertainty into maintenance planning, requiring the STS perspective to adapt, i.e., to realign roles, asset subsystems or components, and routines. Interviewees described concrete effects on execution (e.g., the transition of surroundings from asphalt to higher dunes, protected by nature regulations, impeded deformation measurements and triggered an additional compliance project). Such changes expand the definition of work (with more investigations and analyses), lengthen contract preparation and lead times, and depress on-time execution. Sociotechnical adaptation, therefore, targets the interfaces where misfit arises in collaborative capacity and capacity-tasks fit with rebalanced workload and roles (additional specialists) and resequencing of plans (e.g. to bring investigations forward or add contingencies). Provider relationship-contract alignment further supports adaptation by enabling joint problem-solving under regulatory uncertainty. These desirable changes can be used to inform the management early on for cross-level information alignment. This translates new legal clauses into implications, options, and residual uncertainty for timely decisions.

Longer-term contextual changes concern budget stability and Sea Level Rise (SLR). Political and economic dynamics in context create uncertainty of the budget horizon and stability, influencing commitments and decisions. Accordingly, this dynamic is linked to cross-level information alignment with a trigger to adapt actors and information to the changing context. Interviewees, for instance, note the need for information on performance deficiencies and scenarios to facilitate decision-making. They also reflect on the importance of their involvement in co-designing an organisation-wide value matrix to support decision-making across ageing assets, considering SSB specifics. Early involvement and discussions on arising risks of budget shifts can help to avoid decision latency propagating to maintenance delays. Budget instability also propagates to the alignment between capacity and tasks already pressured with ageing SSBs. Sociotechnical adaptation to political context shall also consider timely re-configuration of capacity-tasks alignment with rebalanced workload and roles, along with proactive resequencing of maintenance (e.g. bringing forward critical investigations).

In the case of SLR, the organisation engages in various studies to investigate the impact of SLR on SSBs functionality. For example, how SLR and sand hunger affect the Eastern Scheldt, covering the barrier's structural failure probability, tipping points for performance levels, and options to reduce closure frequency or modify closure thresholds (Duits et al. 2024). Another study is using scale modelling techniques to test the Eastern Scheldt barrier to its limits in a special basin. The work supports an upcoming multi-decade renovation, worth hundreds of millions, by reevaluating the original design against today's flood safety requirements (in the Water Act) and projected SLR (Deltares, 2025). Others covered the narrowing maintenance window (Trace-Kleeberg et al. 2023) and SLR impact on degradation with increasing maintenance from ageing, faced with shorter maintenance periods. These studies inform operational strategies, changes to maintenance plans, and collaborations with stakeholders on network performance and ecological impacts. However, interviewees note that their high workload hinders closer collaboration to enable integration with long-term preparations. Reconfiguration of capacity-task fit and collaborative capacity can consider short/long-term integrations and their utilisation to update maintenance plans and contracts. This supports preparations for SLR, which in turn enables re-alignment of asset restrictions-plans. The noted studies, for instance, provide signals (i.e. maintenance window reduction, unplanned maintenance ratio, restricted maintenance project share, maintenance plan-capacity coverage). These can be linked and monitored with maintenance coordination and its execution. It becomes an essential task to facilitate long-term preparations and adaptations, informing actors across levels. Furthermore, SLR impacts propagate to contracts and workloads, thus re-aligning social and technical elements of provider relationship-contract fit and capacity-task to enable flexibility in planning, execution, and re-prioritisation.

These empirical observations illustrate the STS adaptation mechanism in practice: actors sense external changes, learn how these disrupt existing alignments, and reconfigure practices or relationships to restore fit.

5 Discussion

The findings of this study contribute to theory and practice on various grounds. Our study moves beyond a hierarchical and isolated processes and activities view of AM performance (Attwater et al. 2014; Kaplan 2009; Wang et al. 2016). It embraced complexity with STS perspective to study AM performance. This enabled considering interactions between stakeholders, multiple disciplines, functions, and changing internal and external contexts. This study builds on recent theories on performance management accounting for complexity and social dynamics (Bourne et al. 2018; Mackenzie and Bititci 2023). But rather than adding another indicator catalogue, we specify where performance is generated, how drift propagates, how to restore fit, and how to support adaptation. We concluded alignments and performance in a model showing connections of feedback, propagation, and accumulation, aligning with recommendations to study performance as an emergent interactive process (Mackenzie and Bititci 2024; Pavlov and Micheli 2022).

This study contributes to ongoing work on AM resilience and adaptation (ISO, 2024a), the transition toward Industry 5.0 with greater attention to human factors (Chabane et al. 2023), and the application of the STS perspective to dynamic and complex contexts (Diop et al. 2022; Pasmore et al. 2019). Building on the proposed model, we operationalise resilience through a sense-learn-reconfigure cycle aligned with Hollnagel (2014), resilience framework, in which actors detect contextual change, identify vulnerable alignments, and reconfigure affected sociotechnical elements to restore fit. The findings confirm the central role of people in anticipating change and continuously adjusting practices in response to evolving conditions (Bellini et al. 2020; Hollnagel 2014; Mehvar et al. 2021). Furthermore, this study bridges the gap in prevailing research framing STS for resilience and adaptation, yet focused on infrastructure assets (Allen et al. 2025; Bollinger et al. 2014; Manny et al. 2022; Mehvar et al. 2021) and a high-level perspective to adaptation and resilience of AM for future-proofing (Masood et al. 2016). We explicitly linked resilience and adaptation to the monitoring and management of AM performance over time. This reframes adaptation from a strategic intent into an operational capability embedded in routine performance reviews, indicating signs for sociotechnical re-alignment and fit to the context (Baxter and Sommerville 2011; Clegg 2000).

Focusing on SSBs, the findings support SSB asset managers in monitoring and managing AM performance. The model informs decision-making on where and how to intervene while bringing attention to propagations of decision impacts. We contribute to the call for more studies to understand SSBs and their impacts with an interdisciplinary perspective (Orton et al. 2023). Also, our study enables complementing the technical-focused studies, such as SLR implications on maintenance (Trace-Kleeberg et al. 2023; Vader et al. 2023). The analysis emphasised the sociotechnical adaptation for future preparation, such as SLR compressing maintenance windows and hindering capacity-tasks fit. It noted the role of SSB teams and the need to consider their needs. STS advocates involving those who enact and experience change in design and management, and adopting a human-centred approach that empowers stakeholders to shape adaptation and resilience (Chabane et al. 2023; Mehvar et al. 2021).

Despite the case study research of AM of SSB in the Netherlands, the findings of the study are valuable for SSBs worldwide and other infrastructure assets. AM for SSBs, ProBO, provided a rich case since it vividly covers sociotechnical elements of AM (e.g. maintenance plans, AM decisions, knowledge, relationships). It sets a great example to work with for a STS perspective with interactions and connections with the asset and context. Thus, we provide case study research while having theory-grounded concepts, claiming analytic, not statistical generalisation, with theory refinement and transferable propositions (Yin 2018). We integrated sociotechnical systems and performance management concepts to examine how AM performance can be monitored, managed, and adapted over time. We provide in-depth empirical evidence of this perspective in practice and conclude with a model that yields transferable propositions (e.g., improved cross-level information fit reduces decision latency). These propositions are amenable to statistical testing through survey-based analysis.

Transferability nonetheless requires further work: (1) multiple case studies (e.g. other SSBs, locks) and (2) longitudinal studies that operationalise the proposed leading/lagging indicators and targeted interventions. The STS framing and the reported analysis steps ease such replication. The resulting model from the STS perspective should be translated for quantitative testing and expanded with further data collection to capture additional aspects of ProBO, covering its full scope. The alignments and indicators identified and defined provide a structured basis for collecting and analysing quantitative data to test the strength and sensitivity of the identified mechanisms. Even without the latter points, the current findings provide an analysis and communication tool bridging gaps between stages and actors and explaining AM performance and how it can help with improvements and adaptation. Finally, system dynamics modelling could probe the non-linearities and feedback implied by our model, strengthening causal claims and decision support (Feldman & Pentland, 2003; Pavlov and Micheli 2022).

6 Conclusion

AM performance is the natural lever to navigate the changing context of infrastructure assets operating in dynamic environments. We advance STS perspective for AM performance by investigating the emergence of performance from interdependencies between the social subsystem, the technical subsystem, asset specifics, and the context. We conducted case study research on the AM of SSBs in the Netherlands. The field evidence led to identifying interdependencies and distilling them into a manageable set of alignments whose joint fit between social and technical elements shapes performance.

With the STS perspective to AM performance, the study contributes to monitoring and managing performance over time and embedding resilience and adaptation. The results build on contemporary performance theories to consider the complexity and dynamic nature of AM. It emphasised the influence of the context on performance, connecting it to resilience and adaptation by routing contextual signals to impacted alignments to enable social and technical adjustments. This study operationalises the resilience cycle, yielding into targeted adaptations of alignments generating performance. We recast AM performance as a forward-looking, governable capability able to sustain SSB reliability now while adapting coherently as context shifts.

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Data availability The data is protected and not available as it includes secured governmental documents and confidential transcripts of interviews.

Declarations

Conflict of interest The authors declare no conflict of interests.

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References

Allen E, Costello SB, Henning TF, Chamorro A, Echaveguren T (2025) Integration of resilience and risk to natural hazards into transportation asset management of road networks: a systematic review. Struct Infrastruct Eng 21(5):755–773

Almeida N, Trindade M, Komljenovic D, Finger M (2022) A conceptual construct on value for infrastructure asset management. Utilities Policy 75:101354

Alquraidi A, Awad M (2024) Physical asset management for critical utilities-a systematic literature review. IEEE Access

Arthur D, Schoenmaker R, Hodkiewicz M, Muruvan S (2016) Asset planning performance measurement. Proceedings of the 10th World Congress on Engineering Asset Management (WCEAM 2015)

Attwater A, Wang J, Parlikad A, Russel P (2014) Measuring the performance of asset management systems. Asset Management Conference 2014

Aven T, Ylönen M (2018) A risk interpretation of sociotechnical safety perspectives. Reliab Eng Syst Saf 175:13–18

Baxter G, Sommerville I (2011) Socio-technical systems: From design methods to systems engineering. Interact Comput 23(1):4–17

Bellini E, Gaitanidou E, Bekiaris E, Ferreira P (2020) The RESOLUTE project's European resilience management guidelines for critical infrastructure: development, operationalisation and testing for the urban transport system. Environ Syst decisions 40(3):321–341

Bititci US (2015) Managing business performance: the science and the art. Wiley

Bollinger L, Bogmans C, Chappin E, Dijkema GP, Huibregtse J, Maas N, Schenk T, Snelder M, Van Thienen P, De Wit S (2014) Climate adaptation of interconnected infrastructures: a framework for supporting governance. Reg Envriron Chang 14(3):919–931

Bolton R, Foxon TJ (2015) Infrastructure transformation as a socio-technical process—implications for the governance of energy distribution networks in the UK. Technol Forecast Soc Chang 90:538–550

Bostrom RP, Heinen JS (1977) MIS problems and failures: A socio-technical perspective. Part I: The causes. MIS Q, 17–32

Bourne M, Franco-Santos M, Micheli P, Pavlov A (2018) Performance measurement and management: a system of systems perspective. Int J Prod Res 56(8):2788–2799

Bowen GA (2009) Document analysis as a qualitative research method. Qualitative Res J 9(2):27–40

Chabane B, Komljenovic D, Abdul-Nour G (2023) Converging on human-centred industry, resilient processes, and sustainable outcomes in asset management frameworks. Environ Syst Decisions 43(4):663–679

Chappin EJ, van der Lei T (2014) Adaptation of interconnected infrastructures to climate change: a socio-technical systems perspective. Utilities Policy 31:10–17

Clegg CW (2000) Sociotechnical principles for system design. Appl Ergon 31(5):463–477

da Silva RF, de Andrade Melani AH, de Carvalho Michalski MA, de Souza G, Nabeta SI, Hamaji FH (2020) Defining Maintenance Performance Indicators for asset management based on ISO 55000 and balanced scorecard: a hydropower plant case study. Proceedings of the 30th European Safety and Reliability Conference and the 15th Probabilistic Safety Assessment and Management Conference, Venice, Italy

Davis MC, Challenger R, Jayewardene DN, Clegg CW (2014) Advancing socio-technical systems thinking: a call for bravery. Appl Ergon 45(2):171–180

Deltares (2025) Oosterscheldekering tot het uiterste getest. https://www.deltares.nl/nieuws/oosterscheldekering-tot-het-uiterste-getest

Diop I, Abdul-Nour GG, Komljenovic D (2022) A high-level risk management framework as part of an overall asset management process for the assessment of industry 4.0 and its corollary industry 5.0 related new emerging technological risks in socio-technical systems. Am J Industrial Bus Manage 12(7):1286–1339

Duits M, Vuik V, Caspers J, Nicolai R, Pleijter G (2024) *Constructieve houdbaarheid en oprekbaarheid van de Oosterscheldekering*. https://open.rijkswaterstaat.nl/@286034/constructieve-houdbaarheid-oprekbaarheid/

Emery FE, Trist EL (1960) Socio-technical systems. Manage Sci models techniques 2:83–97

Fereday J, Muir-Cochrane E (2006) Demonstrating rigor using thematic analysis: a hybrid approach of inductive and deductive coding and theme development. Int J qualitative methods 5(1):80–92

Gavrikova E, Volkova I, Burda Y (2020) Strategic aspects of asset management: an overview of current research. Sustainability 12(15):5955

Haigh ID, Fuller M, Walraven M, Batchelor A, Trace-Kleeberg S, Huibregtse E, Nicholls R (2024) Understanding the challenges facing storm surge barriers in the past, present, and future

Hollnagel E (2014) Resilience engineering and the built environment. Building Res Inform 42(2):221–228

IAM (2015) Asset Management—an anatomy. In: Institute of Asset Management London, UK

ISO (2018) Asset management—Management systems—Guidelines for the application of ISO 55001. In

ISO (2024a) ISO 55000 Asset management—Vocabulary, overview and principles. In

ISO (2014b) ISO 55001 Asset management—management systems—requirements. In

ISO (2014a) ISO 55000 Asset management—overview, principles and terminology. In

ISO (2024b) ISO 55001 Asset management—Asset management system—requirements. In

Kamps M, van den Boomen M, van den Bogaard J, Hertogh M (2024) Intergenerational transfer of engineering expertise: knowledge continuity management in storm surge barrier engineering. Built Environ project asset Manage 14(6):874–891

Kaplan RS (2009) Conceptual foundations of the balanced scorecard. Handbooks Manage Acc Res 3:1253–1269

Kharoubi Y, van den Boomen M, van den Bogaard J, Hertogh M (2024) Asset management for storm surge barriers: How and why? Struct Infrastruct Eng, 1–15

Kleiner BM, Hettinger LJ, DeJoy DM, Huang Y-H, Love PE (2015) Sociotechnical attributes of safe and unsafe work systems. Ergonomics 58(4):635–649

Komljenovic D, Gaha M, Abdul-Nour G, Langheit C, Bourgeois M (2016) Risks of extreme and rare events in asset management. Saf Sci 88:129–145

Le Gat Y, Curt C, Werey C, Caillaud K, Rulleau B, Taillandier F (2025) Water infrastructure asset management: state of the art and emerging research themes. Struct Infrastruct Eng 21(4):539–562

Leveson N (2004) A new accident model for engineering safer systems. Saf Sci 42(4):237–270

Lima ES, Costa APCS (2019) Improving Asset Management under a regulatory view. Reliab Eng Syst Saf 190:106523

Lima ES, McMahon P, Costa APCS (2021) Establishing the relationship between asset management and business performance. Int J Prod Econ 232:107937

Mackenzie H, Bititci US (2023) Understanding performance measurement and management as a social system: towards a theoretical framework. Int J Oper Prod Manage 43(7):1098–1120

Mackenzie H, Bititci U (2024) Reconceptualising performance measurement and management: evaluating a social complexity framework. J Organizational Effectiveness: People Perform 12:675

Maletič D, Marques de Almeida N, Gomišček B, Maletič M (2022) Understanding motives for and barriers to implementing asset management system: an empirical study for engineered physical assets. Prod Plann Control, 1–16

Manny L, Angst M, Rieckermann J, Fischer M (2022) Socio-technical networks of infrastructure management: network concepts and motifs for studying digitalization, decentralization, and integrated management. J Environ Manage 318:115596

Masood T, McFarlane D, Parlikad AK, Dora J, Ellis A, Schooling J (2016) Towards the future-proofing of UK infrastructure. Infrastructure Asset Manage 3(1):28–41

Mehvar S, Wijnberg K, Borsje B, Kerle N, Schraagen JM, Vinke-de Kruijf J, Geurs K, Hartmann A, Hogeboom R, Hulscher S (2021) Towards resilient vital infrastructure systems–challenges, opportunities, and future research agenda. Nat Hazards Earth Syst Sci 21(5):1383–1407

Neely AD, Adams C, Kennerley M (2002) The performance prism: the scorecard for measuring and managing business success. Prentice Hall Financial Times London

Orton P, Ralston D, van Prooijen B, Secor D, Ganju N, Chen Z, Fernald S, Brooks B, Marcell K (2023) Increased utilization of storm surge barriers: a research agenda on estuary impacts. Earths Future 11(3):e2022EF002991

Osman H, Nikbakht M (2014) A game-theoretic model for roadway performance management: a socio-technical approach. Built Environ project asset Manage 4(1):40–54

Pasmore W, Winby S, Mohrman SA, Vanasse R (2019) Reflections: sociotechnical systems design and organization change. J Change Manage 19(2):67–85

Pavlov A, Micheli P (2022) Rethinking organizational performance management: a complexity theory perspective. Int J Oper Prod Manage 43(6):899–915

Roda I, Fochesato D, Polenghi A, Luciano M, Tordi I, Di Pasquale L, Cavaiuolo I (2022) A methodology for ensuring strategic alignment of railway infrastructure asset management processes. World Congress on Engineering Asset Management

Ruitenburg RR, Braaksma AJ (2017) Mitigating change in the goals and context of capital assets: design of the lifetime impact identification analysis. CIRP J Manufact Sci Technol 17:50–59

Salmon PM, Cornelissen M, Trotter MJ (2012) Systems-based accident analysis methods: a comparison of Accimap, HFACS, and STAMP. Saf Sci 50(4):1158–1170

Sandu G, Varganova O, Samii B (2023) Managing physical assets: a systematic review and a sustainable perspective. Int J Prod Res 61(19):6652–6674

Too EG (2012) Capability model to improve infrastructure asset performance. J Constr Eng Manag 138(7):885–896

Trace-Kleeberg S, Haigh ID, Walraven M, Gourvenec S (2023) How should storm surge barrier maintenance strategies be changed in light of sea-level rise? A case study. Coast Eng 184:104336

Trist EL (1981) The evolution of socio-technical systems, vol 2. Ontario Quality of Working Life Centre Toronto

Trist EL, Bamforth KW (1951) Some social and psychological consequences of the longwall method of coal-getting: An examination of the psychological situation and defences of a work group in relation to the social structure and technological content of the work system. Hum Relat 4(1):3–38

Vader H, Bakker AM, Jonkman SN, van den Boomen M, van Baaren E, Diermanse FL (2023) A framework for assessing the remaining life of storm surge barriers. Struct Infrastruct Eng, 1–13

van Alphen J, Haasnoot M, Diermanse F (2022) Uncertain accelerated sea-level rise, potential consequences, and adaptive strategies in The Netherlands. Water 14(10):1527

van den Bogaard J, van Akkeren K (2011) *Leidraad risicogestuurd beheer en onderhoud conform de ProBO werkwijze*. The Netherlands Retrieved from https://open.rijkswaterstaat.nl/@37986/leidraad-risicogestuurd-beheer-onderhoud/

Walraven M, Vrolijk K, Kothuis BB (2022) Design, maintain and operate movable storm surge barriers for flood risk reduction. Coastal Flood Risk Reduction. Elsevier, pp 271–286

Wang J, Chen Z, Parlikad A (2016) Designing performance measures for asset management systems in asset-intensive manufacturing companies: a case study. Proceedings of the 10th World Congress on Engineering Asset Management (WCEAM 2015)

Yin RK (2018) Case study research and applications (Vol. 6). Sage Thousand Oaks, CA