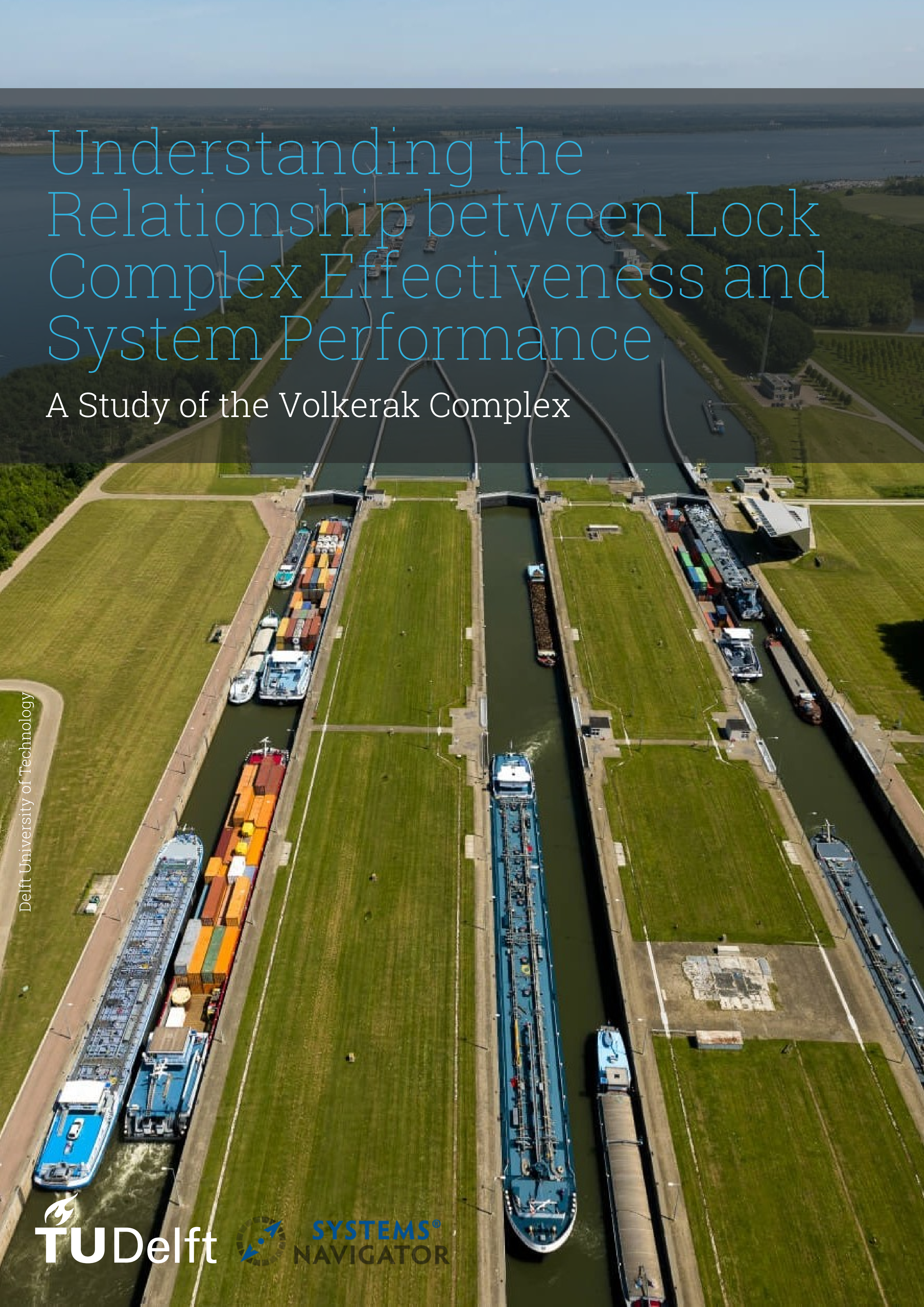
# Understanding the Relationship between Lock Complex Effectiveness and System Performance

## A Study of the Volkerak Complex



Delft University of Technology

# Understanding the Relationship between Lock Complex Effectiveness and System Performance

## A Study of the Volkerak Complex

by

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Cover: Volkerak Complex by Rijkswaterstaat (Modified)

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Çağla Yaren Aslan<br>
Delft, August 2023

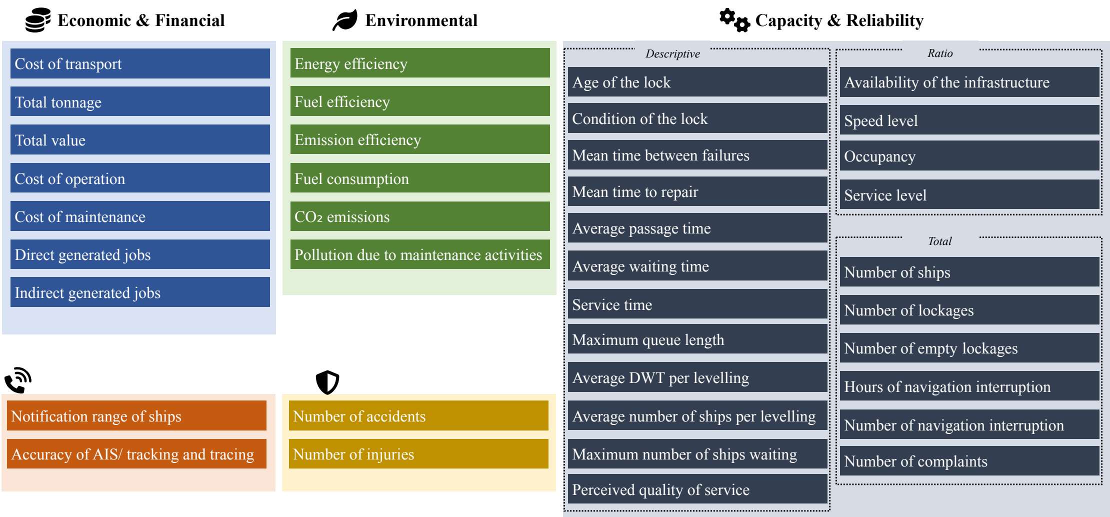
# Executive summary

## Laying the foundation

Inland Waterway Transport (IWT) is an untapped resource that can be mobilised to achieve a more sustainable transport system without compromising competitiveness. It outperforms rail and road alternatives in terms of low emissions, costs, high capacity, energy efficiency, freight safety, and security. Waterway locks are ageing assets in IWT systems and are infamous for creating bottlenecks. The effectiveness and performance of these locks can be measured and integrated into decision making to establish well-informed operational, maintenance, and renewal policies. This study addresses the following research question: *How can the effectiveness of waterway locks be assessed to support lock maintenance and operation?* Simulation modelling, which offers an efficient and low-risk evaluation of policy options while incorporating the intrinsic variability of the system, is selected as the core methodology. The simulation model incorporates operational aspects of the system, malfunctions, corrective maintenance activities, and the calculation of various performance indicators.

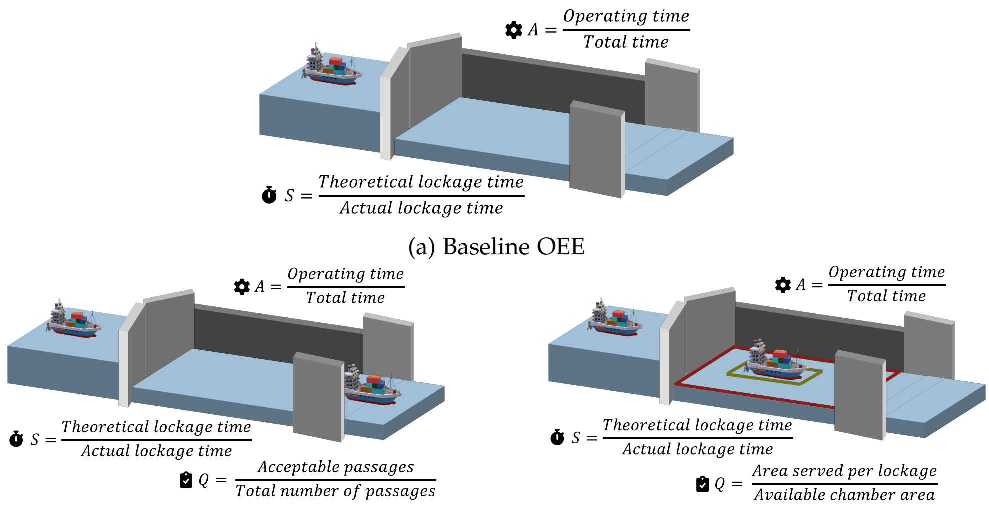
## Understanding the problem

An extensive list of performance indicators is complied through literature research. These indicators include infrastructure occupancy, vessel waiting times, costs, and emissions.




High level conceptual model

In addition to existing indicators, three formulations for Overall Equipment Effectiveness (OEE) are proposed in lock complexes.



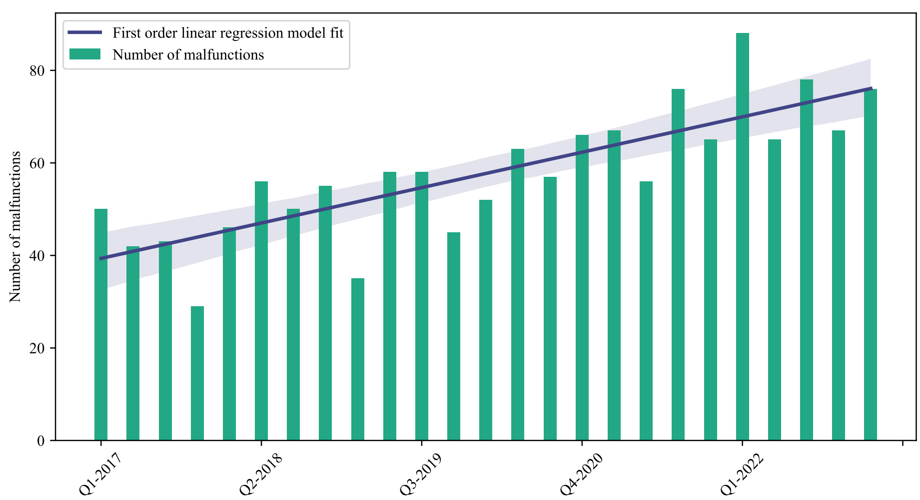

(a) Baseline OEE

(b) Service-based OEE

(c) Efficiency-based OEE

OEE formulations

The applicability of the selected methodology is demonstrated by employing a case study of the Volkerak complex, one of the largest and busiest lock complexes in Europe. Quantitative and qualitative data, collected through operational logs, maintenance reports, and interviews with experts, support that as the lock complex gets older, malfunctions become more frequent.




Number of malfunctions in the Volkerak complex over time

SIVAK, a software package utilised by the Ministry of Infrastructure and Water Management of the Netherlands (”Rijkswaterstaat”, RWS), is used as the basis of the simulation model. Extensions are made to calculate additional performance indicators and to simulate fluttering doors and slowdowns, two types of malfunctions that are diagnosed to be frequent and impactful based on maintenance reports and interviews. Experiments are designed to explore the performance of different maintenance policies, such as mean time to repair (MTTR) and inspection frequency, and different operational policies such as locking regimes under various fleet mix and lock condition scenarios. Stress tests and univariate analyses are also conducted.

## Synthesising the findings

The study findings highlight the following:

- With rising demand, the significance of lock condition in maintaining acceptable service levels and minimising $CO_2$ emissions becomes more evident. The findings indicate a trade-off between preventive and corrective maintenance efforts. In challenging lock conditions, faster repairs and more frequent inspections are needed to prevent capacity problems, leading to longer waiting times. Notable differences in handling capacity are observed in the three lock conditions studied.
- The concept of baseline OEE proves to be valuable as a maintenance-oriented metric. It emphasises that proficient maintenance strategies can counteract deficiencies in the lock system, resulting in improved capacity, reduced transit times, and reduced $CO_2$ emissions. A general rule of thumb suggests that improving baseline OEE by one point corresponds to about a 1.2%-1.5% improvement in waiting times and emissions.
- Changing MTTR and inspection policies influences baseline OEE scores, but these adjustments must be aligned with the lock condition. Frequent inspections might yield unnecessary availability losses when the lock is well maintained. Similarly, the extent of benefits of shorter MTTRs depends on the frequency of breakdowns.
- A prominent dilemma in lock systems involves balancing transit times and the number of levellings. Locking regimes capture this trade-off, where reducing waiting time thresholds increases levellings and operational costs. However, some strategies can achieve an improvement in both aspects. These include expanding traffic range and considering the current state of the system when assigning lock chambers to incoming vessels.
- Service-based OEE, integrating operational and maintenance policies, aligns better with waiting times and $CO_2$ emissions compared to the service level alone. This composite index can serve the purpose of monitoring waterway network lock systems, helping to identify losses due to unavailability and reduced speed.

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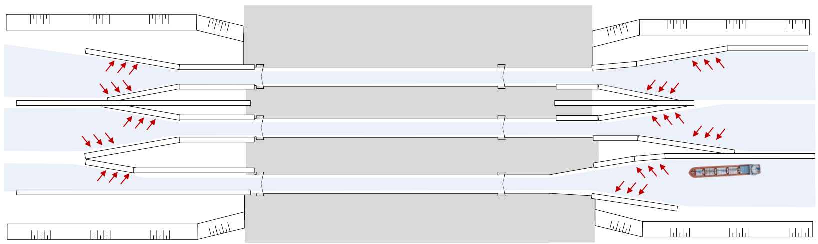
# Acronyms

**IWT** Inland Waterway Transport . . . 2
**LSP** Logistics Service Providers . . . 3
**RWS** Rijkswaterstaat . . . 2
**GHG** Greenhouse Gas . . . 2
**OEE** Overall Equipment Effectiveness . . . 6
**AIS** Automatic Identification System . . . 6
**KPI** Key Performance Indicator . . . 3
**TEU** Twenty-foot Equivalent Unit . . . 13
**PIANC** The World Association for Waterborne Transport Infrastructure (previously known as the Permanent International Association of Navigation Congresses) . . . 7
**CMTS** U.S. Committee on the Marine Transportation System . . . 7

# Glossary

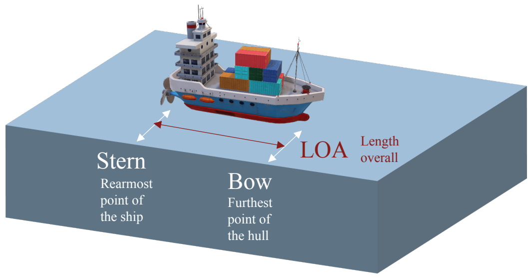
**DWT** is an abbreviation for Deadweight Tonnage. It is the total maximum weight that can be carried by a ship.

**guide jetty** (also known as leading jetty, guide fender or funnel) is a structure that physically and visually guides ships into the lock chamber. Below are schematic diagram and top view of the Volkerak complex (Photo credit: Marinas (2023)) with guide jetties highlighted.

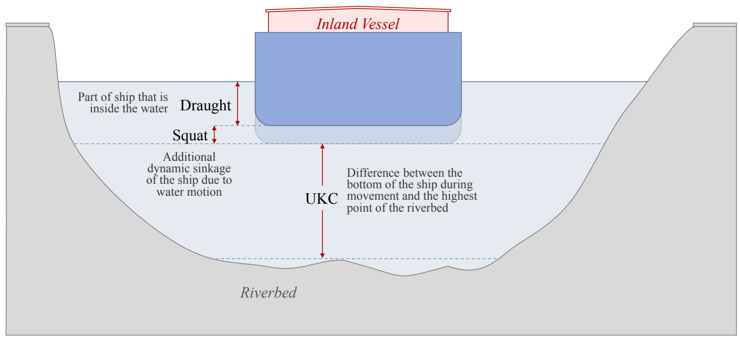


**hull** is the outer shell of the ship that is designed to be in contact with water.


**LOA** is an abbreviation for Length Overall. It is the maximum length of the ship from the stern to the bow. Stern is the rearmost point of the ship and the bow is the furthest point of the hull.




**UKC** is an abbreviation for Under Keel Clearance. Below is a visual representation of UKC reprinted from Meinel (2022).



# Part I.

# Laying the foundation

# 1. Introduction

With its large share in energy consumption and pollution, transport represents a serious challenge that must be addressed in order to ensure sustainable development (Mihic et al., 2011). In particular in Europe, Inland Waterway Transport (IWT) is an untapped resource that can be mobilised to achieve a more sustainable transport system without compromising competitiveness (European Commission, 2021a). The benefits that can be achieved through further development and increased integration of IWT are not limited to the reduction of Greenhouse Gas (GHG) emissions and improved energy efficiency, but also include economic gains (Buchem et al., 2022). This mode of transport has advantages over rail and road alternatives due to its low cost, high capacity, and cargo safety and security (Wiegmans & Konings, 2017). Given these advantages, IWT is recognised as a major source of transport capacity (Maraš, 2017, p. 188).

The untapped potential of IWT has been highlighted on numerous occasions by European policymakers. As early as 1992, with the White Paper *The Future Development of the Common Transport Policy*, European Commission noted that the volumes of inland navigation transport were considerably lower than the capacity. The report emphasised the importance of funding infrastructure maintenance and development, with a priority given to the elimination of bottlenecks to better exploit the potential of IWT. This potential is particularly valuable for tackling congestion on overcrowded road and rail networks and reducing air pollution. White papers and action programmes have followed since (European Commission, 2001, 2006, 2011, 2013). More recently, in 2021b, IWT has been re-discussed by European Commission, this time with a greater focus on sustainability.

However, infrastructure in Europe remains disproportionately underinvested (Wiegmans & Konings, 2017). Lack of investment becomes increasingly pressing as assets age towards the end of their technical life (Willems et al., 2018). Waterway locks are one of those assets and are notorious for creating bottlenecks as the main source of delays in IWT systems (Buchem et al., 2022; Oztanriseven et al., 2022). As the number of technical problems at the locks increases, the waiting times at these locations become longer and more uncertain. This not only leads to higher fuel consumption, hence resulting in higher greenhouse gas emissions and costs (Buchem et al., 2022), but also reduces the attractiveness of IWT. The problem creates a vicious circle since limited investment is made due to reduced attractiveness, which in turn exacerbates the problem (Nassar et al., 2023).

Rijkswaterstaat (RWS) is the governing body of the IWT infrastructure in the Netherlands (Wiegmans & Konings, 2017). With regard to the high costs of waterway infrastructure projects, it is a challenge to ensure that the budget is managed responsibly to design, construct and maintain the waterway network in an accountable way. Recently attracting attention as a source of improvement for the efficiency and reliability of inland navigation (DIWA, 2019; European Commission, 2021b), digitalisation can be exploited for this challenge. One field that can realise the advantages of the digitalisation initiative is the measurement of infrastructure effectiveness in lock complexes and the integration of this measurement into decision making. This can assist in identifying appropriate measures for addressing the necessary but overlooked maintenance and renewal of locks (Wiegmans & Konings, 2017), which is expected to gain urgency with the growing demand following the Covid-19 recovery (European Commission, 2022).

The implementation of continuous effectiveness assessment systems brings several benefits. First, such assessments can be used as benchmarks in longitudinal analyses to measure improvements or deterioration of performance in a lock system (Garza-Reyes et al., 2010). Regarding the potential of effectiveness measures to become catalysts for improvement in organisations (Bamber et al., 2003), evaluation systems can contribute to overcome the lack of innovation culture, which is recognised as one of the weak spots in IWT (Maraš, 2017). With enhanced transparency achieved through well-chosen indicators, the relevance of IWT can be improved (Posset et al., 2009). Second, these indicators can be useful to compare the performance between lock systems (Bamber et al., 2003). Lock complexes that operate in a less effective way can be identified as candidates for improvements and increased resource allocation (Nakajima, 1988).

The success of such measurement and integration is highly dependent on the level of acceptance and collaboration of stakeholders (Buchem et al., 2022). The IWT system in the Netherlands has a rich political arena with private actors on the demand side, such as freight owners and Logistics Service Providers (LSP), and public and private actors on the supply side, such as RWS, contractors and terminal operators (Wiegmans & Konings, 2017). Even within RWS, there are branches that manage interdependent resources with divergent interests.

These divergent interests, both within and outside RWS, create a system where there might not be definitive best strategies for operational and maintenance decisions. Usually, a solution that favours one Key Performance Indicator (KPI) results in suboptimal performance for another. A prominent trade-off frequently faced by lock operators is whether to begin levelling the lock when there is still room in the chamber. If the decision is to wait for new arrivals, this results in higher occupancy of the lock chamber and lower costs associated with pumping, electricity, and depreciation. However, this also means that ships that are already in the lock need to wait longer for the line-up call, resulting in longer travel times, increased costs, and increased emissions. Such dilemmas even exist across the KPIs of a single actor. For example, the travel time of a ship and emissions, two KPIs that are important to shippers, exhibit a trade-off that must be considered when scheduling locks (Passchyn, Briskorn, et al., 2016).

In this study, we address the challenge of measuring and deriving insight from the effectiveness and performance of lock complexes to support informed policy making in lock systems. To achieve this goal, we employ a methodology based on simulation modelling. Simulation enables the exploration of the system under controlled scenarios, without incurring high investment costs or disrupting real-life operations (Robinson, 2004). This exploration is not bounded by the conditions of today, but can be expanded to account for future projections. Secondly, simulation allows inclusion of stochasticity in the analysis, which is often overlooked in studies on locks (Buchem et al., 2022). Furthermore, simulation facilitates recognition and investigation of rippling effects.

To demonstrate applicability of effectiveness and performance measurements in lock complexes, to generate illustrative insights into alignments and conflicts between these measurements and to explore how different policies affect these measurements, a case study is adapted. The Volkerak complex, one of the largest and busiest lock complexes in Europe (Steenhuis, 2015), is selected as the focus of the case study. Operational logs collected on site and expert interviews are considered primary sources of information.

This report is organised as follows. Chapter 2 focusses on research design by describing the research gap and questions, the approach, the methods, and the flow. Chapter 3 concerns a finer description of the IWT system and waterway locks from several points of view. It discusses performance indicators, challenges, potential interventions, and introduces the lock complex. Motivated by this description, Chapter 4 targets the challenge of modelling IWT. Chapter 5 outlines the experimental design adopted in this study. The results of the simulation experiments are presented in Chapter 6 and are discussed in 7. The report is concluded with Chapter 8, where research questions are revisited and an agenda is drafted for the benefit of policy makers and future researchers.

# 2. Research design

## 2.1. Literature review

### 2.1.1. Inland waterway transport in literature

Given the growing global demand for more sustainable transport systems, it is not surprising that there is growing academic interest in improving the IWT system (Sugrue & Adriaens, 2021). Academics from different disciplines are focussing on different parts of the problem in various geographical settings.

For example, Gardels et al. (2016) and Kruse et al. (2014) discuss the tight budget constraints faced by the US Army Corps of Engineers, the government agency responsible for IWT infrastructure in the United States, and propose public-private collaboration to overcome the problem of underinvestment. The article by Hijdra et al. (2014) also has a financial focus, but the methodology used is more in line with accounting practises than with a stakeholder approach. Chimka et al. (2019) analyse the costs associated with deferred maintenance. Some studies examine lock systems by analysing their physical structure and interaction with water using physical tests (Perkins et al., 2017; Spörel, 2018, 2019), while others look at the challenges of managing IWT construction projects (Ge et al., 2020).

Despite these different focusses, a large proportion of studies analyse functioning of the system. On the one hand, there are those which take the perspective of the ship operators and focus on the way in which ships are navigated when passing through locks and canals. For example, studies by Liu et al. (2021) report field experiments with alternative ship formations in the lock. Carral et al. (2017) explain the statistical importance of the pilot's skill in operation and experience in the particular canal. On the other hand, an even greater number of scholars look at the system through the eyes of the lock operator.

A popular area of research among these scholars is the scheduling problem (Guan et al., 2021; Ji et al., 2022; Kanović et al., 2019; Passchyn, Coene, et al., 2016; Zhao et al., 2020). Most of these scholars use mathematical models of various kinds. Ji et al. (2022) formulate the problem as discrete optimisation, Guan et al. (2021) as mixed integer programming, Passchyn, Coene, et al. (2016) as dynamic programming. Kanović et al. (2019) introduce a novel approach by developing a decision support tool that distils expert opinion using artificial intelligence and evolutionary algorithms. These studies mostly use cost- or time-based minimisation. More recently, researchers have also incorporated fuel consumption (Golak et al., 2022) and emissions (Passchyn et al., 2014; Shi et al., 2016; Zhao et al., 2022) as additional optimisation objectives. Furthermore, supporting Buchem et al. (2022)'s remark about the neglect of stochasticity in lock research, most of these studies operate within deterministic settings.

Another group of researchers works on ship patterns, in particular understanding (Asborno et al., 2022; Kruse et al., 2018; Mitchell & Scully, 2014; Sugrue & Adriaens, 2021) and improving them (Zhao et al., 2022). This contributes to more accurate modelling of arrivals (and thus improvements in scheduling evaluation) and waiting patterns (and thus identification of bottlenecks in the IWT system). Recently, the use of Automatic Identification System (AIS) data for this purpose has attracted attention (Asborno et al., 2022; Kruse et al., 2018; Mitchell & Scully, 2014; Sugrue & Adriaens, 2021). The results of Asborno et al. (2022) provide evidence that earlier concerns about the coverage of AIS data may not be as relevant given recent improvements in the tracking capabilities of AIS. Their coverage analysis reports that ship movements through locks can be matched with over 83% accuracy. Work by Sugrue and Adriaens (2021), Kruse et al. (2018) and Mitchell and Scully (2014) supports the argument for the potential value of AIS in monitoring IWT infrastructure performance and thereby supporting informed investment decisions. However, they focus mainly on port performance.

Although the IWT infrastructure is examined in the literature, lock complexes receive limited attention compared to ports. A large number of studies focus on improving the system through better scheduling algorithms or alternative formations in the locks; however, they overlook or aggregate the impact of technical failures in the infrastructure, rather than exploring and incorporating their stochastic nature (Buchem et al., 2022). Regarding the fact that the quality of components is deteriorating (Willems et al., 2018) and that the IWT system is faced with increasing demand pressure (European Commission, 2022), this lack of knowledge becomes increasingly critical for decision makers and academics (Guan et al., 2021).

### 2.1.2. Performance measuring in IWT

Performance measurement is described as the process of quantifying operation efficiency and effectiveness (Neely et al., 1995). The first of these two similar but distinct concepts, efficiency, refers to ”doing things right”, which is achieved by optimal use of resources when providing a given level of customer satisfaction (Åhérn & Parida, 2009; Neely et al., 1995). Efficiency is measured as the ratio of input to output, where inputs are the allocated resources and outputs are the results, services or products (Carter et al., 1995; Joumard & Gudmundsson, 2010, p. 37). Effectiveness, on the other hand, is related to ”doing the right things” and achieving operational objectives (Carter et al., 1995; Neely et al., 1995).

The development of comprehensive indicators that measure resource efficiency and effectiveness has been a long-standing challenge in various industries. Such indicators serve multiple purposes, including providing a benchmark to track progress over time (Bamber et al., 2003), to monitor process improvement initiatives (Garza-Reyes et al., 2010), and to evaluate maintenance and operation strategies (Dal et al., 2000). Additionally, these indicators allow for benchmarking across production or service systems (Bamber et al., 2003), preventing sub-optimisation of individual machines or production lines, and identifying underperforming machines. They also foster a shared understanding and purpose within organisations (Bamber et al., 2003).

In response to this challenge, implementation of Overall Equipment Effectiveness (OEE) has emerged as a widely recognised approach in the manufacturing industry (Braglia et al., 2008; Garza-Reyes, 2015; Kvak, 2022; Nachiappan & Anantharaman, 2006; Nakajima, 1988; P., 1995; Perumal et al., 2016). Scholars have also investigated the potential of this widely used metric in different contexts, such as logistics processes (Ng Corrales et al., 2022), labour effectiveness (Braglia et al., 2020; Soragaon et al., 2012), bike sharing systems (Yahya, 2017), public transport vehicles (Kuboń et al., 2019) and railway infrastructure (Åhérn & Parida, 2009; Nikolić et al., 2016).

However, the performance measurement of IWT infrastructure components remains mainly underdeveloped (Sugrue & Adriaens, 2021). One of the few compilations of IWT performance indicators comes from the work by The World Association for Waterborne Transport Infrastructure (previously known as the Permanent International Association of Navigation Congresses) (PIANC). PIANC InCom, WG 32 (2010) identifies over 100 indicators from nine thematic areas such as infrastructure, ports, environment, fleet and vehicles, and economic development. This list of indicators includes those concerning locks, such as ”total availability for service of lock” or ”average utilisation of lock capacity per lockage”. U.S. Committee on the Marine Transportation System (CMTS) build up on this work and list 17 indicators classified into five as (1) economic benefits to the nation, (2) capacity and reliability, (3) safety and security, (4) environmental management and (5) resilience (2015). There are no previous studies investigating the potential of OEE in the context of lock complexes.

## 2.2. Research gaps

Following gaps are identified in the literature:

- The current literature shows limited regard for stochasticity in lock systems. Although optimisation studies seek improvements in operational and maintenance policies, they are tested in deterministic settings.
- There is a lack of research focussing on the development of performance measurement systems tailored to locks. While some studies attempt to define metrics for locks, they often remain in the theoretical space and do not provide a clear operationalisation of these metrics.
- There is limited exploration of the relationships between different metrics and operational and maintenance policies. Discussions around non-financial aspects of performance, such as environmental sustainability, remain underdeveloped.

This research aims to target these gaps by investigating the effectiveness and performance metrics for locks, incorporating stakeholder perspectives, and using simulation modelling to operationalise these metrics and investigate the relationships between them. Operational and maintenance policies are formulated and tested under different scenarios. Their implications on these different performance aspects, including non-financial indicators, are discussed.

## 2.3. Research questions

The main research question of this thesis project is formulated as follows:

**Main Research Question**

How can the effectiveness of waterway locks be assessed to support lock maintenance and operation?

The following sub-questions are generated to address the main research question:

**❓ 1st Sub-question**

How can we operationalise the performance measurement of lock complexes?

The questions of ”how effective a lock complex functions” or ”how well it performs” lack a definitive answer and are subject to variation based on different perspectives. Stakeholders' understanding of effectiveness and performance is influenced by their individual perceptions and values, which shape their desired outcomes for the system. This research question aims to explore potential approaches for operationalising effectiveness and performance by taking into account various perspectives.

**❓ 2nd Sub-question**

What are the main sources of data that can be used to monitor the effectiveness of lock systems?

The second sub-question concerns the data needed for the case study. It triggers an investigation of the operational logs and sensors that provide data, as well as the lock design specifications. Interviews with experts might reveal information about the accuracy and usefulness of these sources, as well as about other alternatives.

**❓ 3rd Sub-question**

What is the impact of deficiencies in effectiveness in lock systems on the performance of the IWT system?

As infrastructure components age towards the end of their technical lifespan, they are more susceptible to malfunctions in the form of slowdowns and unavailability. There are stochasticity and cascade effects that must be taken into account when assessing the impact of such malfunctions in locks. Simulation can be used to study what-if scenarios and alternative policies.

**❓ 4th Sub-question**

What are the right action points for RWS given budget considerations, inefficiencies in Volkerak locks and their impacts on the IWT performance?

Alternative policies that are available to RWS concern maintained condition of the lock, which can be improved by rehabilitation or renewal, corrective maintenance policies, chamber prioritisation and locking schemes. Given budget constraints and the results of the simulation model, what policy advice can be given to RWS in the context of the Volkerak complex?

## 2.4. Research approach

The IWT infrastructure constitutes an interrelated system, comprising both social and technical elements, and exhibiting dependencies among stakeholders and technological components. It is challenging, if not impossible, to understand the functioning of the system without establishing and testing the consistency of logical causal relations and their links with the data (Epstein, 2008). Adopting a modelling approach facilitates precise identification of assumptions and offers insight into the system's operation, without overly relying on subjective predictions (Banks, 1998; Epstein, 2008). This approach provides a cost-effective and low-risk evaluation of action alternatives, eliminating the costly investment and operational disruptions associated with real-world implementation (Robinson, 2004). Furthermore, experimenting with models reduces the potential consequences of erroneous decisions compared to real-world implementation, where reversing mistakes may prove costly, if not unfeasible.

The use of simulation modelling offers several advantages over alternative modelling methods. First, simulation enables the examination of a variety of future scenarios by providing a means to expand the temporal scope and explore possibilities (Banks, 1998). Once the model is validated, it can be used to evaluate changes in conditions, such as variations in ship composition or arrival frequencies. Second, simulation models can incorporate stochasticity (Robinson, 2004). When components exhibit variability, an accurate prediction of system performance can only be achieved by incorporating such stochastic elements. In IWT, both arrival patterns and technical failures are inherently random. Lastly, simulation models provide a clear and transparent way to understand the underlying causes of the observed phenomena (Banks, 1998; Robinson, 2004). The results are closely linked to the sequences of events that occur in the simulation model, allowing for an intuitive examination to understand the reasons behind the phenomenon. It is worth nothing that this methodology is data hungry (Robinson, 2004). Workings of the system should be derived from various and voluminous data that are collected, analysed, and validated.

In this study, our objective is to explore the improvement potential that can be realised by measuring and integrating performance indicators in waterway locks. To accomplish this goal, we adopt a case study approach as a means to demonstrate the applicability of the proposed methodology. Studies based on empirical evidence offer an opportunity to test and validate theories, as well as to prove their practical relevance (Eisenhardt, 1989). This approach also enables the identification of strengths and challenges associated with the methodology (Yin, 2011). However, the generalisability of the findings of case studies is often debated (Yin, 2011). While there are certainly aspects of a case study that are unique to the specific situation, they can still serve a valuable purpose in uncovering new relationships that may be relevant to similar systems.

## 2.5. Research methods

Figure 2.1 provides an overview of the research flow. The aim of the research activities can be considered to serve three purposes: understanding the physical system, creating the simulation model, and discussing the findings with relation to the policy space. Section 2.5.1 discusses the methods to be used to generate an understanding of the case to be studied, which leads to identification of the main data sources. Section 2.5.2 is motivated by the third sub-question and concerns the building of the simulation model to link inputs to calculation of KPIs. Lastly, 2.5.3 explain the process of targeting the fourth and fifth sub-questions. This section describes how preliminary analysis and simulation runs can assist informed policy making, both for the case and on a larger global scale.

### 2.5.1. Literature review and interviews

The initial phases of conducting a case study involve understanding the real-life system and defining it as a case (Yin, 2011). This requires the gathering of both quantitative and qualitative data. Quantitative data relate to specifics of waterway infrastructure, ship characteristics and arrival patterns, mean times to failure and repair, weather conditions, and more. Qualitative data are related to the perspectives and values of stakeholders.

Given the variety and volume of data required, data collection can prove to be a difficult task. However, the collaboration with RWS in this study provides critical access to the data. Interviews with experts, visits to the lock complex, and desk research can reveal the data sources needed for the project. It is worth nothing that, despite the advantage of direct collaboration with the problem owner, not all data may be readily accessible. Other data owners, in particular private entities, may not be open to collaboration. Furthermore, considering that RWS is a large organisation with many branches, acquiring these data might require connections across departments. In cases where data prove to be inaccessible, alternative sources, such as research in the literature and informed assumptions, are utilised.

### 2.5.2. Simulation

Simulations are widely considered as being useful for modelling transportation and service systems due to their ability to incorporate interconnections and model variability. RWS has also used simulation modelling, particularly for long-term capacity planning and scenario analyses (Bijlsma & van der Schelde, 2019). SIVAK, which stands for **SI**mulatiepakket voor de **V**erkeers**A**fwikkeling bij **K**unstwerken in Dutch (or ”Simulation Package for Traffic Flow at Engineering Structures”), is a software package that has been deployed since 1990 (Rijkswaterstaat, 1991). Given its object-oriented design, SIVAK offers the advantage of facilitating reuse and extension of model components (Banks, 1998). In this project, we use the SIVAK package to benefit from this advantage, thus saving time and mitigating the drawback of simulation modelling being a time-consuming process (Banks, 1998).

### 2.5.3. Experimental design and output analysis

The last phase of the study involves exploration of the policy and uncertainty space in light of the findings of the simulation model. This requires a systematic experimentation with the input variables to reach statistically sound conclusions. Factorial design serves a basis for covering the alternative simulation states. In the end, data analytics and visualisation techniques are utilised to derive meaningful insights from the experimentation.

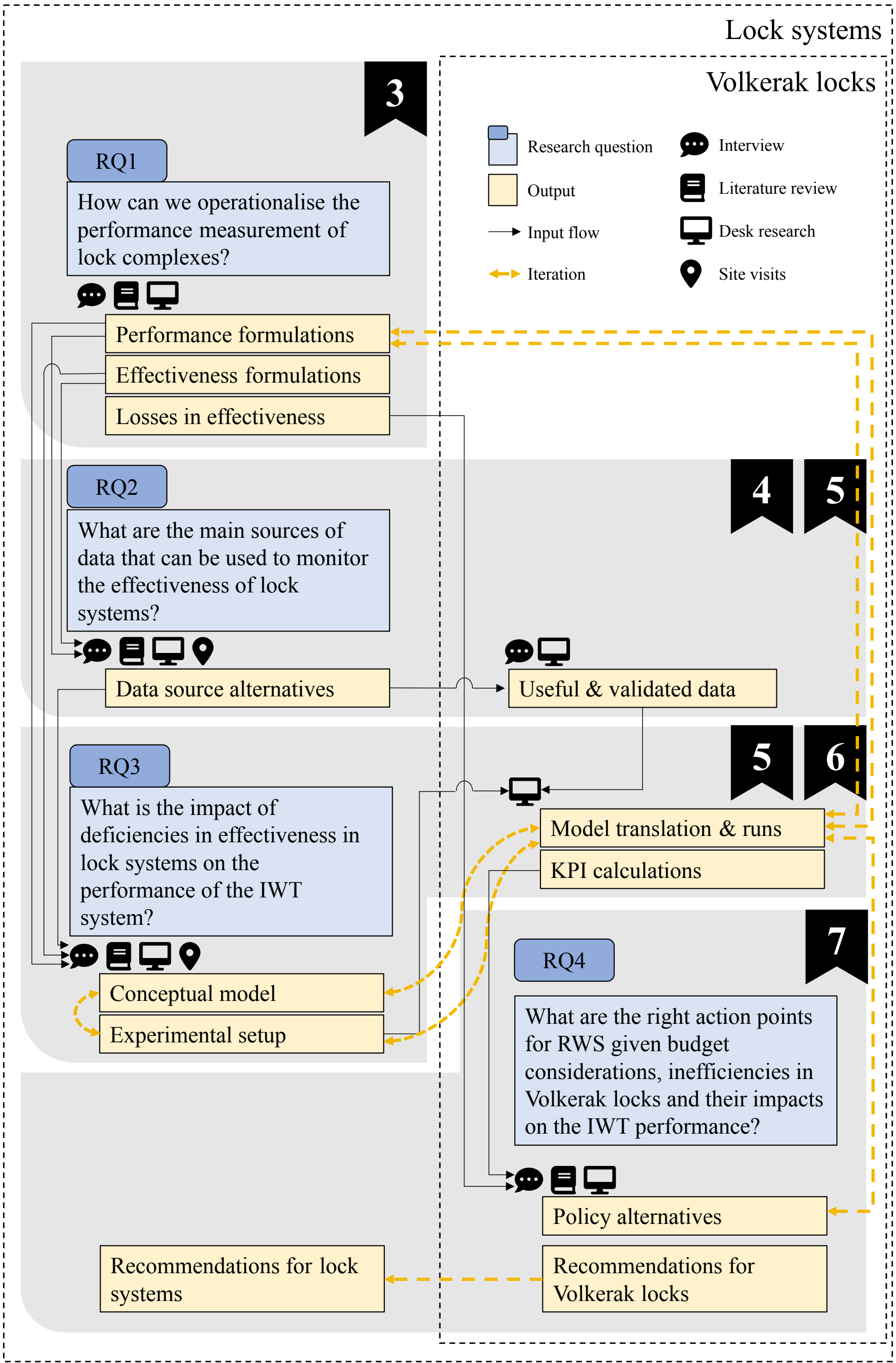



Figure 2.1.: Research flow

# Part II.

# Understanding the problem

# 3. Operationalizing effectiveness and performance in waterway locks

## 3.1. Development of IWT

Waterways, providing a connection to the outer world, have historically been important for the economic development of hinterlands across the world with varying degrees depending on the topology (McCartney et al., 1998). In the Netherlands prior to the 19th century, the waterway was the usual mode of transportation, as a large portion of the land was accessible by water and other modes were yet to develop (Vrijburcht, 2000b). Natural limitations were in effect not only to establish the waterway network but also to impose when this network can be used. Changes in currents and water depths predominantly determined navigability (McCartney et al., 1998). With inventions and innovations, the waterways became increasingly more controlled (Irvine, 2015). The construction of locks offered safe passage from one section of the waterway to another despite different levels of elevation; dams provided means to maintain favourable and predictable water levels (McCartney et al., 1998). The waterway network expanded beyond natural rivers to include artificially created canals and basins (Vrijburcht, 2000b).

With the modernisation of rivers, particularly the Rhine in Europe, IWT gained popularity. The late 1970s marked a milestone for the region with the gradual acceptance of containerisation (PIANC InCom, WG 5, 1992). The volume of containers transported in the river grew more than tenfold in less than 15 years between 1977 and 1991, jumping from around 43 thousand Twenty-foot Equivalent Unit (TEU) to over 450 thousand. Currently, container volume handled only in Rotterdam exceeds 15 million TEU per year (Port of Rotterdam, 2021).

Nonetheless, even with steady growth, only a small part of the IWT capacity is in use today. Lack of infrastructure and low density are considered to be among the key stopping forces against the increased modal share of IWT (PIANC InCom, WG 21, 2005). These forces bring the challenge of integration with other modes of transport in most origin and destination combinations. In addition, transport speed attained by IWT is significantly slower than the rail and road alternatives (Macharis et al., 2011). Lastly, natural factors still exert a certain level of influence on the accessibility of the network. This level of influence is gaining importance with extreme weather and low water events in relation to climate change (CCNR, 2021).

These obstacles stand on the way to seize the advantages offered by IWT to a greater extent. Such advantages include low cost, high traffic volume capacity, and freight safety and security (PIANC InCom, WG 21, 2005). Recently, superior environmental performance of IWT has received increasing attention. It requires less energy use and results in limited air pollution and $CO_2$ emissions, negligible noise (PIANC InCom, WG 21, 2005).

The competitiveness of IWT in the current market is directly related to these obstacles and advantages (Wiegmans & Konings, 2016a). Bulk commodities account for a substantial portion of IWT volume. These are products such as coal, iron ores, petroleum and chemicals. They are relatively time-insensitive, making them more resistant to slow speeds. They are usually shipped in high volumes and have low values per tonnage. As a result, the cost of transport accounts for a significant proportion of their price.

To make IWT a favourable alternative to the logistic challenges of containers and other product groups, policy makers continue to discuss and implement possible interventions that minimise weaknesses and emphasise the strengths of inland navigation (Maraš, 2017). The Trans-European Transport Network (TEN-T) policy plays a central role in this initiative in Europe. The main intervention examined under this policy concerns the maintenance and improvement of the waterway network. Given the considerable costs and time required for these investments, particular attention is paid to identifying bottlenecks and critical points within the network on the basis of their economic importance (Maraš, 2017; Siedl & Schweighofer, 2014; Wiegmans & Konings, 2016b). As traffic growth is increasingly important, also in light of the Covid-19 recovery, the capacity of the waterways is expected to gain importance, placing additional emphasis on infrastructure reliability (European Commission, 2022; PIANC InCom, WG 21, 2005).

The main focus of the second intervention is to promote an innovation culture for both shippers and infrastructure, which is argued to be lacking in IWT (Maraš, 2017). Wiegmans and Konings (2016a) suggest that benchmarking practises would create value in IWT, as they would enable comparisons between entities and provide learning opportunities.

## 3.2. Waterway locks

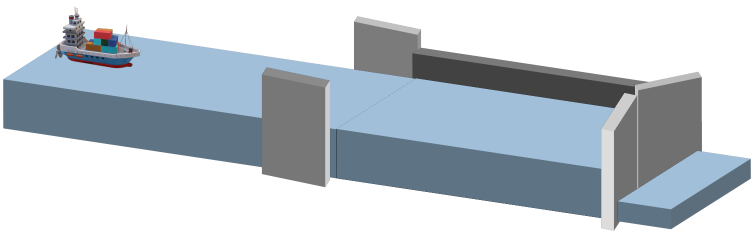
Waterway locks are infrastructures that grant ships entry into rivers and canals with different water levels (Vrijburcht, 2000b). The lockage process primarily concerns four functions (1) ship or ships sailing in and tying up, (2) ship or ships untying and sailing out, (3) closing and opening of gates and (4) the levelling of the water in the chamber (Glerum et al., 2000). Figure 3.1 illustrates these functions.

The locks in the Netherlands and other IWT infrastructure such as bridges, canals, and dams, are operated by RWS. Labour cost is the main expense associated with lock operation, followed by the cost of pumping water into and out of the lock chamber (PIANC InCom, WG 21, 2005). This pumping process consumes both energy and water resources (Bugarski et al., 2013). Therefore, reducing the number of lockages proves advantageous for the lock operator in terms of cost management.

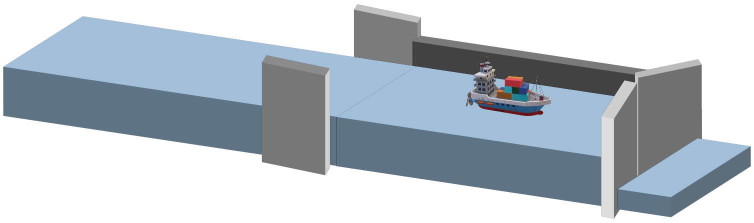
For ship operators, the most significant concern is the transit time, which represents an opportunity cost. Furthermore, the transit time is strongly correlated with other cost items such as equipment, labour, and fuel expenses, and cargo depreciation costs (De Salvo & Lave, 1968; Ting & Schonfeld, 2001).

### 3.2.1. Maintenance in waterway locks

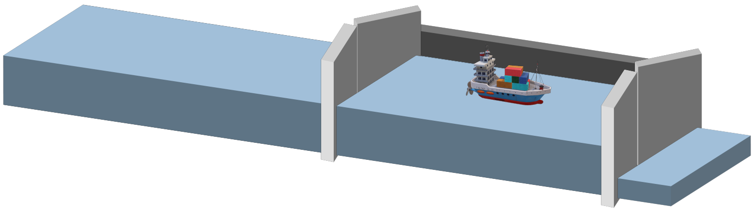
Preserving and improving waterway networks is time-consuming and expensive (PIANC InCom, WG 21, 2005; Wiegmans & Konings, 2016b). As locks age, there is a greater need for cost-effective maintenance policies that ensure acceptable service, safety, and accessibility. cost of maintenance for locks is determined by several important factors including the age and



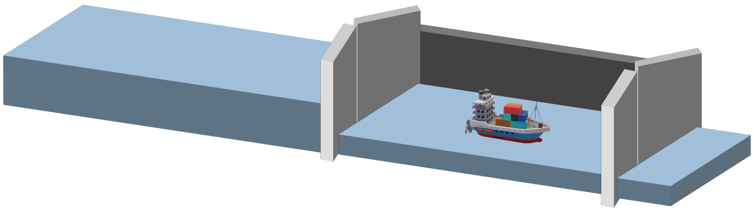
(a) Before sail-in



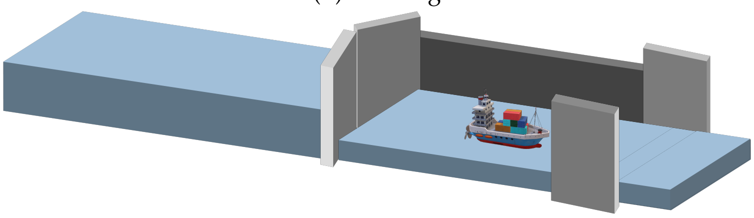
(b) After sail-in



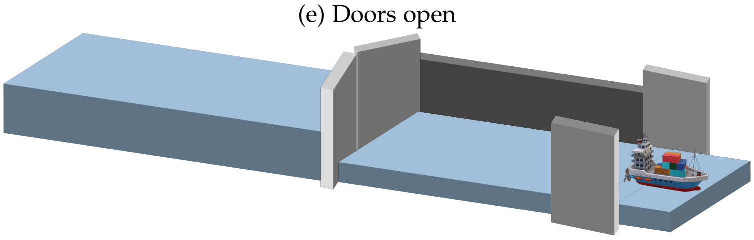
(c) Doors close



(d) Leveling



(e) Doors open

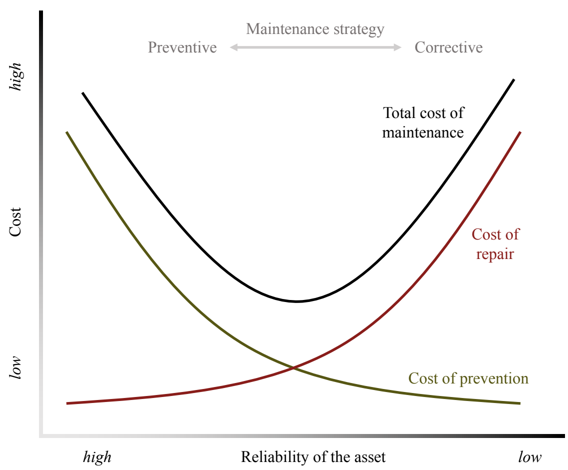


(f) Sail-out

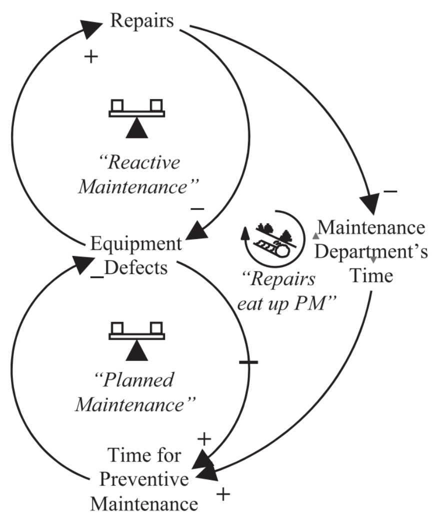
Figure 3.1.: Lockage process

condition of the lock, the acceptable level of availability of the infrastructure, the intensity and the characteristic of traffic flow (PIANC InCom, WG 21, 2005). If a lock is a critical part of the waterway network with a large number of ships passing through, maintenance costs are expected to be higher.

One thing to consider when designing maintenance policies is the need to balance predictive and corrective maintenance activities. Repair cost can be reduced to low levels with a highly preventive maintenance strategy, as seen in Figure 3.2a. However, this would require a high frequency of preventive maintenance, and thus high costs associated with inspection and prevention. On the other edge, if the budget allocated for preventive maintenance activities is too limited, equipment defects become more frequent, and thus the repair cost increase. It is important to find a strategy that corresponds well with the condition of the lock and costs associated with the maintenance activities,




(a) Maintenance strategies and associated costs, reprinted from PIANC InCom, WG 25 (2006)




(b) Causal loop diagram of maintenance activities, reprinted from Thun (2006)

Figure 3.2.: Balance between predictive vs. corrective maintenance

## 3.3. Indicators in IWT

Tables 3.1 to 3.7 present a comprehensive list of indicators obtained from the literature, following the literature review strategy outlined in Appendix A.1. These indicators are categorised according to the framework proposed by PIANC InCom, WG 32 (2010). Taking into account the research objectives, particular emphasis was placed on the capacity and reliability indicators. These indicators are further subcategorised based on the terminology suggested by Joumard and Gudmundsson (2010). Descriptive indicators provide insights into observed phenomena, such as average passage time. Ratio indicators, also known as efficiency indicators, offer measures relative to specific factors, such as infrastructure availability or occupancy. Total indicators provide aggregate information, such as the DWT served by the lock over a specific period.

Table 3.1.: Economic and financial indicators

| Indicator | Description | Unit | Applications & Relevant literature |
|---|---|---|---|
| **Cost of transport** | Expenditure incurred in moving goods per tonne per kilometer | EUR/ tonne/ km | - Waterway locks (Shi et al., 2016; Ting & Schonfeld, 2001; Zhao et al., 2020)<br>- Waterway transport system (Kress et al., 2015; PIANC InCom, WG 32, 2010; Van Koningsveld & Pauli, 2023) |
| **Total tonnage** (i.e., total tonnage worked, total tonnage moved, total DWT of ships passing through) | Sum of tonnage carried by all ships passing through the facility | ton | - Waterway locks (Carroll & Bronzini, 1973; Tang et al., 2023)<br>- Terminals and ports (Cullinane et al., 2005; UNCTAD, 1976)<br>- Waterway transport system (Kress et al., 2015; PIANC InCom, WG 32, 2010)<br>- Logistics and supply chain management (Gunasekaran & Kobu, 2007) |
| **Total value** (i.e., total value moved) | Sum of the value carried by all ships passing through the facility | euro or dollar | - Waterway transport system (Kress et al., 2015) |
| **Cost of operation** | Expenses associated with running the infrastructure. It includes costs such as energy, water, labour, and administrative expenses. | EUR | - Waterway locks (Kanović et al., 2019; Shi et al., 2016) |
| **Cost of maintenance** | Costs for the upkeep, repair, and preservation of the infrastructure. It includes costs associated with regular inspections, necessary repairs. | EUR | - Waterway transport system (PIANC InCom, WG 32, 2010) |
| **Direct generated jobs** | Employment directly created for waterway transport activities such as vessel operations, terminal operations, maintenance and repair. | jobs | - Waterway transport system (Kress et al., 2015; PIANC InCom, WG 32, 2010; Posset et al., 2009) |
| **Indirect generated jobs** | Employment created in related industries as a result of the activities and demand generated by inland waterway transport | jobs | - Waterway transport system (Kress et al., 2015; PIANC InCom, WG 32, 2010; Posset et al., 2009) |

Table 3.2.: Environmental indicators

| Indicator | Description | Unit | Applications & Relevant literature |
|---|---|---|---|
| **Energy efficiency** | How efficiently energy is utilised in the transportation process. It includes all energy consumption items | kWh/ tkm | - Waterway transport system (European Commission, 2021b; Van Koningsveld & Pauli, 2023) |
| **Fuel efficiency** | How efficiently the fuel is utilised for transport | g fuel/ tkm | - Waterway transport system (Van Koningsveld & Pauli, 2023) |
| **Emission efficiency** | Amount of pollutants released per good per transported distance | kg/ tkm | - Waterway transport system (PIANC InCom, WG 32, 2010; Van Koningsveld & Pauli, 2023) |
| **Fuel consumption** (i.e. vessel fuel consumption, fleet fuel consumption, fuel sales to the industry) | Total amount of fuel consumed during the period of observation | kg fuel | - Waterway locks (Golak et al., 2022; Passchyn et al., 2014; Systems Navigator, 2023a)<br>- Waterway transport system (PIANC InCom, WG 32, 2010; Van Koningsveld & Pauli, 2023) |
| $CO_2$ **emission** | Total amount of $CO_2$ released during the period of observation | kg | - Waterway locks (Passchyn et al., 2014; Shi et al., 2016; Systems Navigator, 2023a; Zhao et al., 2022)<br>- Waterway transport system (European Commission, 2021b; PIANC InCom, WG 32, 2010; Posset et al., 2009) |
| **Pollution due to maintenance activities** | Total amount of pollutants released as a result of maintenance and repair operations conducted on vessels or the infrastructure | g/m3 | - Waterway transport system (Han et al., 2023) |

Table 3.3.: Information and communication indicators

| Indicator | Description | Unit | Applications & Relevant literature |
|---|---|---|---|
| **Notification range of ships** | Distance within which vessels are required to provide notifications to the authorities or other vessels. | km | - Waterway transport system (PIANC InCom, WG 32, 2010) |
| **Accuracy of AIS/ tracking and tracing** | Degree of precision in capturing and reporting vessel positions, movements, and other related information. | % | - Waterway transport system (PIANC InCom, WG 32, 2010) |

Table 3.4.: Safety and security indicators

| Indicator | Description | Unit | Applications & Relevant literature |
|---|---|---|---|
| **Number of accidents** | Count of undesirable incidents or collisions | accidents | - Waterway transport system (Kress et al., 2015; PIANC InCom, WG 32, 2010) |
| **Number of injuries** | Count of individuals who sustained physical harm or injuries while involved in an inland waterway transport activity | injuries | - Waterway transport system (Kress et al., 2015; PIANC InCom, WG 32, 2010; Posset et al., 2009) |

### 3.3.1. Overall Equipment Effectiveness

OEE aims at capturing losses in a manufacturing systems. Nakajima (1988) argues that these losses are connected to three aspects of the production line: availability, speed (commonly referred to as performance), and quality. OEE is often calculated as the multiplication of these three components. These losses can be further classified into six categories in relation with these three components: (two types of losses that affect availability) (i) equipment failure or breakdown and (ii) setup and adjustment, (two types of losses that affect speed) (iii) idling and minor stoppage and (iv) reduced speed, and (two types of losses that affect quality) (v) reduced yield occurring from the start-up to stabilisation and (vi) quality defects and reworks.

Losses in efficiency and performance vary across industries and service systems (Jeong & Phillips, 2001). Building on the work of Maternová et al. (2022) and incorporating insights from interviews (see Chapter B), an Ishikawa diagram is developed for waterway locks, as illustrated in Figure 3.4. It is essential to ensure that the measures designed for the system (1) cover possible improvements, (2) reflect and incentivise improvement efforts, and (3) provide continuous information for long-term improvement programmes (Bamber et al., 2003; Ishikawa, 1986), considering the unique characteristics of the system under focus.

Various industries, drawing inspiration from the manufacturing sector, have sought to develop comprehensive metrics inspired by OEE. For example, Braglia et al. (2020) propose the application of overall labour effectiveness (OLE) to monitor labour productivity losses, while Yahya (2017) derive overall bicycle effectiveness (OBE) to measure the performance of bike-sharing systems.

Table 3.5.: Capacity and reliability indicators: Descriptive

| Indicator | Description | Unit | Applications & Relevant literature |
|---|---|---|---|
| **Age of the lock** | Years passed since the construction/ renovation of the lock. | years | - Waterway locks (Kress et al., 2015) |
| **Condition of the lock** | Physical condition of the lock. It is dependent on factors such as the age of the lock, design of the lock, renovation projects conducted, previous failures and weather conditions. | score | - Waterway locks (Kress et al., 2015) |
| **Mean time between failures** | Average of time elapsed between consecutive failures of the system. | hour | - Logistics and supply chain management (Szwedzka, 2016) |
| **Mean time to repair** | Average time to repair the system after a failure. | hour | - Logistics and supply chain management (Szwedzka, 2016) |
| **Average passage time** (i.e. turnaround time, travel time, transit time) | Time between the arrival of the ship at the facility and the start of its departure. Figure 3.3 illustrates the key times and periods during passage through a lock. | hour | - Waterway locks (Bakker et al., 2010; Carroll & Bronzini, 1973; De Salvo & Lave, 1968; Guan et al., 2021; Ji et al., 2022; Kim & Schonfeld, 1995; Passchyn, Coene, et al., 2016; Passchyn et al., 2014; Systems Navigator, 2023a; Ting & Schonfeld, 1998, 2001)<br>- Terminals and ports (Caris et al., 2011; Cullinane et al., 2005; UNCTAD, 1976)<br>- Waterway segments (Kress et al., 2015)<br>- Logistics and supply chain management (Gunasekaran & Kobu, 2007) |
| **Waiting time** | Time between the arrival of the ship at the facility and the start of the service | hour | - Waterway locks (Bugarski et al., 2013; Carroll & Bronzini, 1973; Kanović et al., 2019; Rijkswaterstaat, Centre for Water, Transport and Environment, 2020; Systems Navigator, 2023a; Zhao et al., 2020)<br>- Terminals and ports (Caris et al., 2011; Cullinane et al., 2005; PIANC InCom, WG 32, 2010; UNCTAD, 1976) |
| **Service time** (i.e., leveling time, lockage time, speed of locks) | Time between | hour | - Waterway locks (Bakker et al., 2010; Systems Navigator, 2023a; Tang et al., 2023)<br>- Terminals and ports (UNCTAD, 1976) |
| **Maximum queue length** | Maximum number of ships waiting for levelling during the simulation period. | ships | - Waterway locks (Smith et al., 2009; Systems Navigator, 2023a) |
| **Average DWT per leveling** | Mean dead-weight tonnage pass through per leveling of lock | tonne | - Waterway locks (Tang et al., 2023) |
| **Average number of ships per leveling** | Mean number of ships that pass through in one cycle of levelling operation | ships | - Waterway locks (Systems Navigator, 2023a) |
| **Average number of ships per filled leveling** | Mean number of ships that pass through in one cycle of levelling operation during an filled (non-empty) lockage | ships | - Waterway locks (Systems Navigator, 2023a; Tang et al., 2023) |
| **Perceived quality of service** | Subjective assessment of overall satisfaction and service level experienced by users | score | - Waterway transport system (PIANC InCom, WG 32, 2010)<br>- Logistics and supply chain management (Gunasekaran & Kobu, 2007) |

Table 3.6.: Capacity and reliability indicators: Ratio

| Indicator | Description | Unit | Applications & Relevant literature |
|---|---|---|---|
| **Availability of the infrastructure** | Percent of time the lock is available for passage | % | - Waterway locks (Bakker et al., 2010; PIANC InCom, WG 32, 2010; Posset et al., 2009; Systems Navigator, 2023a)<br>- Logistics and supply chain management (Ahmad & Dhafr, 2002; Gunasekaran & Kobu, 2007) |
| **Speed level** (i.e., operational rate, performance) | Ratio of ideal cycle time to actual cycle time | % | - Logistics and supply chain management (Kuboń et al., 2019; Ng Corrales et al., 2022) |
| **Occupancy** (i.e., capacity utilization, occupy rate of chamber) | m2 utilization | % | - Waterway locks (Guan et al., 2021; PIANC InCom, WG 32, 2010; Systems Navigator, 2023a; Tang et al., 2023; Zhao et al., 2020)<br>- Terminals and ports (Caris et al., 2011; Posset et al., 2009)<br>- Logistics and supply chain management (Gunasekaran & Kobu, 2007) |
| **Service level** (i.e., conformance to specifications, quality rate) | Percent of passages at agreed passage time | % | - Waterway locks (Systems Navigator, 2023a)<br>- Logistics and supply chain management (Ahmad & Dhafr, 2002; Gunasekaran & Kobu, 2007) |

Table 3.7.: Capacity and reliability indicators: Total

| Indicator | Description | Unit | Applications & Relevant literature |
|---|---|---|---|
| **Number of ships** (i.e., arrival rate) | Total number of ships passing through the facility | ships | - Waterway locks (Carroll & Bronzini, 1973; Systems Navigator, 2023a; Tang et al., 2023)<br>- Terminals and ports (UNCTAD, 1976) |
| **Number of lockages** (i.e., number of levelings, number of lock activations) | Total number of lockages performed in the lock | lock-ages | - Waterway locks (Systems Navigator, 2023a; Tang et al., 2023) |
| **Number of empty lockages** | Total number of lockages with no ships in the lock chamber | lock-ages | - Waterway locks (Bugarski et al., 2013; Kanović et al., 2019; Systems Navigator, 2023a) |
| **Hours of navigation interruption** (i.e., hours of lock closures, unavailable time, non-operating time, losses in work time) | Total hours that the lock was not available for passage. This indicator can be further detailed as planned and unplanned. | hours | - Waterway locks (Kress et al., 2015) |
| **Number of navigation interruption** (i.e., number of lock closures) | Total number of times that the lock was closed. This. | lock clo-sures | - Waterway locks (Kress et al., 2015; PIANC InCom, WG 32, 2010; Posset et al., 2009)<br>- Terminals and ports (UNCTAD, 1976)<br>- Logistics and supply chain management (Kuboń et al., 2019; Ng Corrales et al., 2022) |
| **Number of complaints** | Total number of documented complaints | com-plaints | - Waterway transport system (Posset et al., 2009)<br>- Logistics and supply chain management (Ahmad & Dhafr, 2002) |

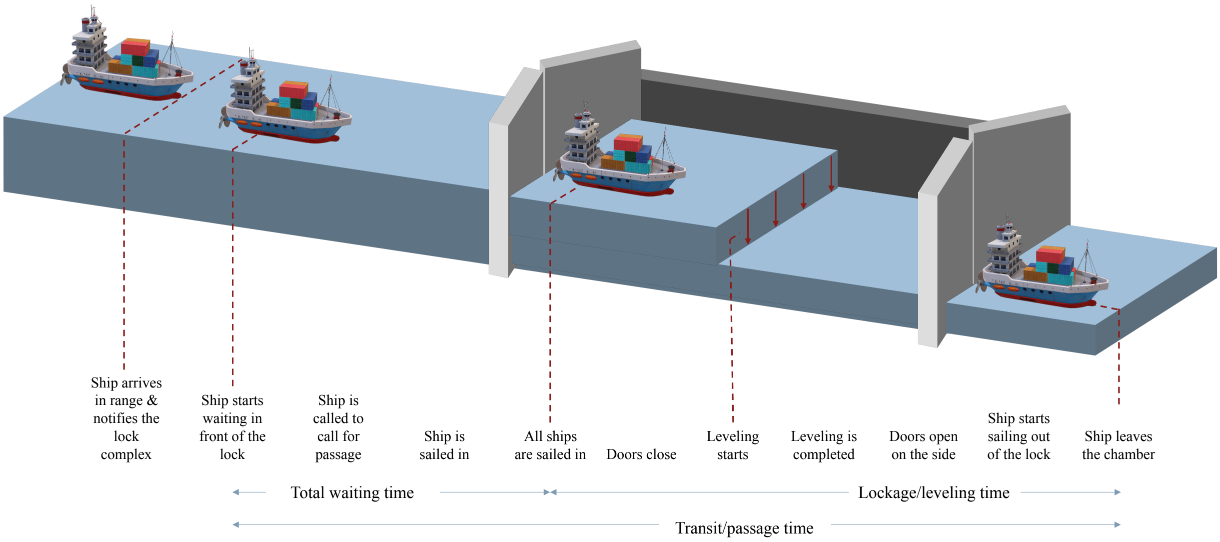



Figure 3.3.: Times and durations

The concept of OEE has also found application in the transport sector. Inbound logistics processes have been addressed through an OEE-inspired metric defined by Ng Corrales et al. (2022). Kuboń et al. (2019) propose a formulation to evaluate the efficiency of public transport vehicles. In the context of railway infrastructure, Åhérn and Parida (2009) introduce the concept of overall railway infrastructure effectiveness (ORIE) and applies it to Swedish railways, while Nikolić et al. (2016) implement the same framework for Serbian railways. A summary of the formulations presented by Ng Corrales et al. (2022), Kuboń et al. (2019), and Åhérn and Parida (2009) can be found in Table 3.8.

Table 3.8.: Applications of OEE in transportation systems

| Authors | Availability | Performance (Speed) | Quality |
|---|---|---|---|
| Ng Corrales et al. (2022) | Ratio of available time to allocated uptime. | Ratio of ideal time to actual time. | Ratio of number of trucks requested to the total number of truck arrivals. **Punctuality**, defined as the rate of timely arrivals, is also used as an additional component. |
| Kuboń et al. (2019) | Ratio of available time to allocated uptime. | Occupancy of available seats. | Rate of timely arrivals. |
| Åhérn and Parida (2009)<br>Nikolić et al. (2016) | Ratio of available time to allocated uptime. | Train delays due to speed reductions or other non-maintenance activities. | Vertical and horizontal alignment of the train and the track. Alternatively, ride comfort. |

In this study, we investigate three alternative formulations of OEE for waterway locks. The

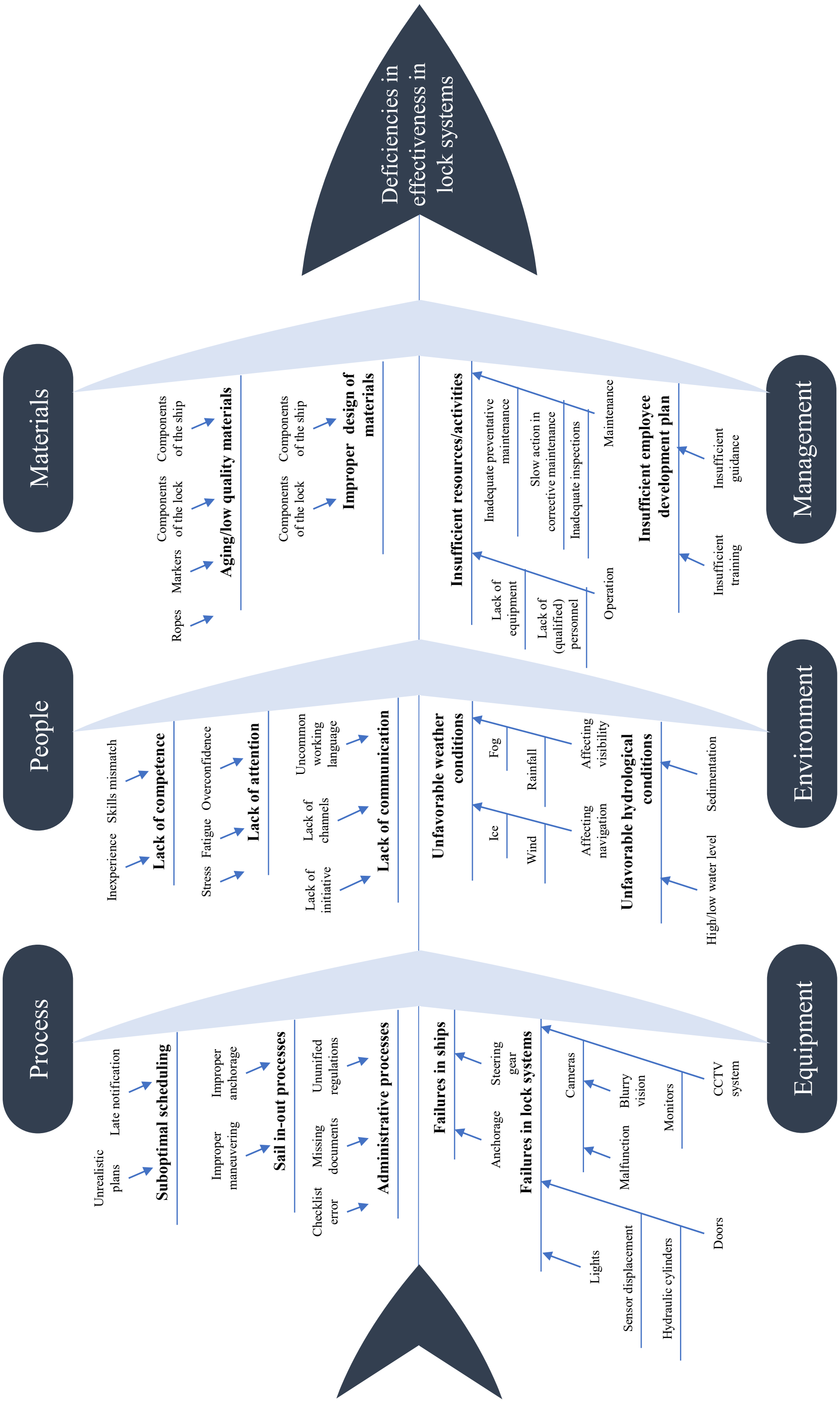



Figure 3.4.: Ishikawa diagram for loss of effectiveness in waterway locks

first formulation, labelled the baseline OEE, focusses on two key components: availability and speed. These components directly account for malfunctions and slowdowns that impact the lock's performance. The second formulation, called efficiency-based OEE, incorporates the occupancy rate of the waterway lock as a quality measure. This indicator captures the efficient utilisation of the lock's capacity. The third formulation, termed service-based OEE, uses the concept of service level as the quality component. It evaluates the percentage of lock passages completed according to predefined standards. According to the guidelines outlined by Rijkswaterstaat, Centre for Water, Transport and Environment (2020), a successful passage through the lock is determined by the total waiting time being less than 30 minutes. By exploring these alternative OEE formulations, our aim is to gain insight into their applicability and their effectiveness in reflecting improvements in critical performance indicators, such as emissions and waiting times.

# 4. Modelling waterway locks

## 4.1. Literature review

Researchers have explored various modelling approaches to analyse waterway locks. Early studies, such as De Salvo and Lave (1968), focused on estimating passage times by employing queuing theory models, initially assuming an exponential distribution for arrival and service times. However, it was argued that this assumption did not align well with empirical evidence, leading to the expansion of models to M/G/1 queues (Wilson, 1978). Soon, this model was also critisized. Martinelli et al. (1993) highlighted that waterway locks, depending on the number of chambers, can be modelled as either G/G/1 or G/G/M queues. They emphasised that the traditional queueing theory approaches are limited in providing adequate techniques to handle these types of queues effectively. Recognising this complexity, Martinelli et al. (1993), Dai and Schonfeld (1991) and Ramanathan and Schonfeld (1994) utilised simulation models. Non-simulation approaches, such as linear regression by Ting and Schonfeld (1998) and artificial neural networks by Kim and Schonfeld (1995), were also applied to predict delays.

In recent years, simulation-based approaches have gained prominence in lock modelling. Smith et al. (2009) developed a discrete event simulation model to assess the impact of alternative operating policies and lock renovation. Rogers and Hofseth (2012) introduced the Navigation System Simulation (NaSS) toolbox, which combined Monte Carlo simulation and data analysis to evaluate the effects of different operational policies and reliability scenarios. Nelson et al. (2017) used agent-based simulation to model decision-making processes of the tow operator and the lock manager under extreme water conditions. More integrated modelling approaches have also emerged, such as the Maritime Transportation Simulator (MarTranS) by Oztanriseven et al. (2022). MarTranS combined different modelling techniques such as system dynamics, agent-based modelling, discrete event simulation, and input-output models. This comprehensive approach allowed for a holistic examination of economic impacts.

## 4.2. SIVAK

SIVAK, a software package utilised by RWS since 1990 (Rijkswaterstaat, 1991), is primarily designed to perform long-term capacity analyses of waterway objects and identify the need for expansion. The model serves as a valuable tool in assessing the capacity of waterway infrastructure and understanding its limitations in accommodating current and future demands. By analysing various factors, such as traffic patterns, ship characteristics, and operational parameters, SIVAK helps identify potential bottlenecks and evaluate the effectiveness of different expansion strategies.

The simulation package underwent a recent renovation in 2019 and was migrated to Simio (Bijlsma & van der Schelde, 2019). With the new object-oriented design, SIVAK now has the advantage of facilitated reuse and extension of model components. Appendix F.1 presents the UML class diagram of the SIVAK model.

Some notable strengths of SIVAK include its ability to generate realistic fleets considering correlations between variables such as LOA, DWT, and other attributes of ships. The model takes into account seasonality, arrival patterns, and sail-in/sail-out times based on ship and lock chamber specifications, enabling a comprehensive representation of fleet operations. Capabilities of the model include detailed emission calculations and incorporation of various traffic-related considerations, such as overtaking of ships, speed limits based on ship classes, and tidal conditions. Additionally, SIVAK uses an optimisation algorithm for chamber filling, ensuring that the chambers are packed with the maximum number of ships while adhering to their safety allowance rules. It also allows for customisable chamber priority and locking regime selections.

Taking into account the research timeline, the use of SIVAK in this study offers additional practical benefits. The extensive usage of the software by RWS ensures its verification and validation by industry experts. This improves the reliability and credibility of the results obtained using SIVAK. Furthermore, familiarity with the SIVAK data structure increases the likelihood of having relevant data readily available in the appropriate format.

## 4.3. Conceptual model

To establish the scope of the model and promote transparency with respect to the underlying assumptions, the conceptual model in this study is developed by applying the OCIR framework introduced by Chwif et al. (2013) and is summarised in Table 4.1. OCIR represents four key considerations: (1) objectives, (2) complexity, (3) input/output, and (4) runs, which are crucial in the development of a conceptual model. Figure 4.1 illustrates the conceptual model at the high level with the main processes. Experimental and fixed data and their relationships with processes are also depicted. The selection of experimental and fixed data, along with their sources and considered levels, is discussed in detail in Chapter 5. Tables 4.2 and 4.3 outline the existing components of SIVAK and the extensions made.

## 4.4. Performance indicators

The selection of the output data is based on the performance indicators identified by the analysis performed in Section 3.3. Table 4.4 outlines the rationale for including or excluding each performance indicator within the research scope.

To ensure the precision of the reporting, the number of performance indicators reported in the main body is restricted to only those that are recognised as KPIs. This selection of KPIs is made based on three criteria: (i) whether the performance indicator targets an output that concern a direct objective of at least one of the stakeholders, exluding those focussing on inputs and processes, (ii) actionability, and (iii) incremental information that it offers. Appendix H.1 explains how this selection is made. In the end, five indicators are reported in the main body of this report: (1) $CO_2$ emission, (2) average lockage time and (3) average waiting time, (4) number of lockages and (5) hours of navigation interruption both in terms of planned and unplanned maintenance. However, additional remarks are also provided for the remaining indicators. The formulations of OEE, as defined in 3.3.1, are discussed, highlighting their strengths in terms of the insights they provide into the KPIs and the improvement potential they highlight.

Table 4.1.: OCIR definition

| OCIR Definition | Description |
|---|---|
| *(a) Objectives part* | *Objectives of the study are defined in this paragraph.* |
| Objectives | Identify relationships between different maintenance and operational policies, effectiveness and performance criteria. |
| *(b) Complexity part* | *Scope of the model and its level of detail are defined in this part.* |
| Complexity | The scope of the model is the generation and movement of ships, the scheduling and operation of the lock complex with three commercial chambers, the fluttering of doors and the slowdown of levelling as well as the correction of these malfunctions with repair and inspection. Operation of the lock concerns opening of the doors and thereby letting the ships sail-in, passage of the ships into the chamber, closing of the doors, levelling of the water in the chamber, opening of the doors from the other side, and thereby letting the ships sail-out. The sequence of lockage in the model is given in Appendix F.2.<br>Two types of malfunctions are included in the model scope to simulate deviation from intended performance:<br>• **Fluttering**: Fluttering refers to the phenomenon where the doors of the lock experience instability during the opening or closing operation. The probability of fluttering determines the success or failure of the operation, as it influences whether the door sensors detect the doors as fully opened or closed. If fluttering occurs, the lock operator will attempt the operation again. These consecutive attempts take the same time as the first. However, if the fluttering takes place twice consecutively, the lock chamber becomes non-operational until the doors are repaired. The repair time is modelled as an exponential distribution with a mean value equal to the MTTR.<br>• **Slowdown**: When a certain number of operations is reached, processes in operation may start to experience a slowdown. In the context of the model, a slowdown is incorporated as an effect on the duration of the levelling process. It is modelled using an exponential distribution with a mean value equal to the inputted mean slowdown threshold. The extent of the slowdown is determined by the slowdown effect, which quantifies the degree to which the levelling process slows after reaching the specified threshold. Periodic inspections cause slowdowns to disappear and reset the slowdown counter. Inspections take deterministically 2 hours and start early in the morning, at 8:00. Inspections of the chambers are therefore scheduled for 8:00, 10:00 and 12:00. The inspectors wait for the lockage to be completed. |
| *(c) I/O part* | *Inputs and outputs of the model are described in this paragraph.* |
| Input | Waterway, lock, lock chamber and fleet data. See Figure 5.1. |
| Output | Economic and financial, environmental and capacity and reliability indicators. See Table 4.4. |
| *(d) Runs definition part* | *This part concerns definition of scenarios and experiments.*<br>Discussed in Chapter 5, Table 5.3 |

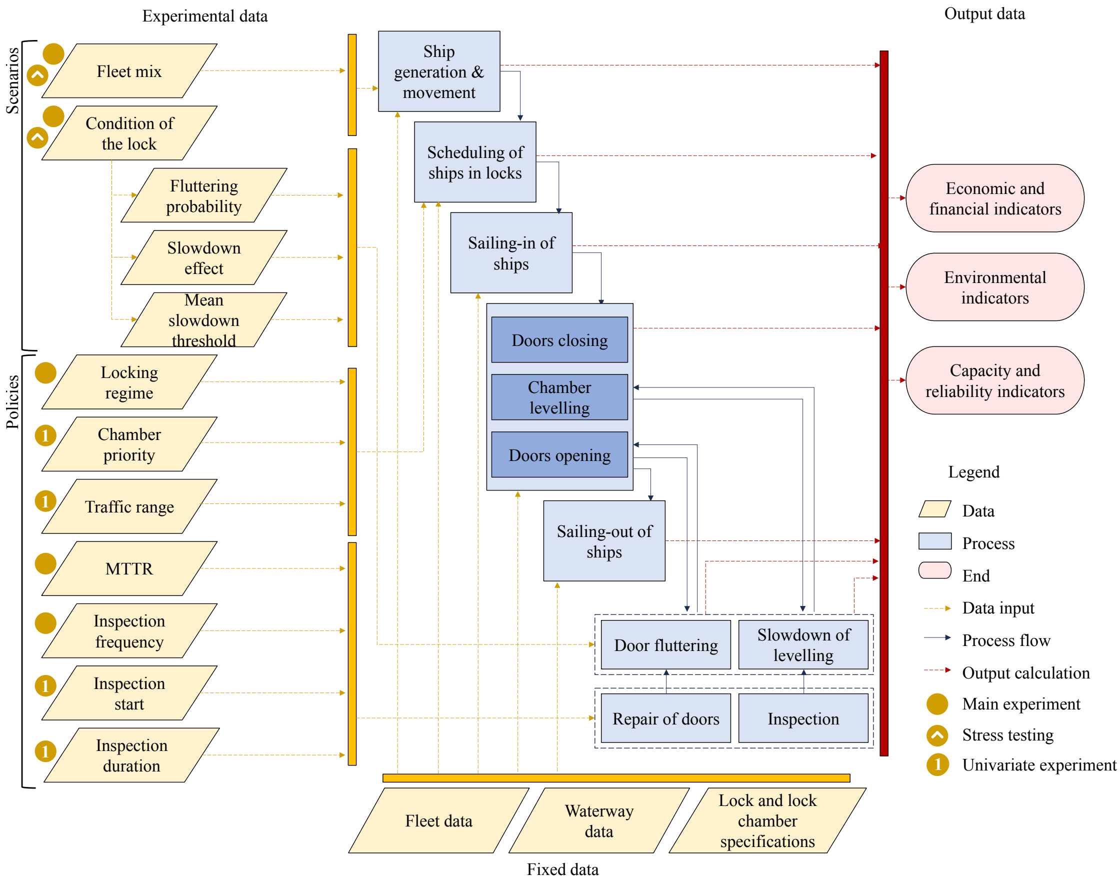



Figure 4.1.: High level conceptual model

Table 4.2.: Existing SIVAK components

| Component | Scp. | Modelling assumption if included/ Justification if excluded |
|---|---|---|
| Ship generation & movement | ✔ | For every ship class, a stochastic number of ships is generated weekly in the model based on fleet mix and seasonality. The exact arrival of the ship within that week is determined by the arrival pattern over the week. Each of the parameters defining the general characteristics of every ship, such as DWT and LOA, is drawn using the mean and standard deviation for the ship class. Then, these parameters are tested for their correlations and adjustments are made if needed. |
| Scheduling of ships in locks | ✔ | Appendix F.2 summarises lockage processes. Ships report to the lock complex when they are within the traffic range. For every chamber that is open on the side of the ship, following the order of chamber priority, the ship is tested for its fit in the current levelling plan. It is added to the plan if it does, and the search for alternatives continues if it does not. Lock chambers with the side closed are also considered if there is no chamber suitable with the side open. |
| Sailing-in and -out of ships | ✔ | Appendix F.2.2 discusses how sail-in and sail-out times are calculated for given ship and chamber characteristics. |
| Door closing, chamber levelling and doors opening | ✔ | Door closing, chamber levelling and doors opening take a deterministic duration, defined for the lock chamber. |
| Middle door | ✘ | Although it is possible to operate middle doors of the lock, these doors are used only on special occasions and not in daily operations (Interview B.1). |
| Water loss and saltwater incursion | ✘ | Instances of seepage occur during levelling. However,it is left out of the model scope considering research focus. |
| Dynamic water level | ✘ | It is possible to define tides in the model, to have dynamic water levels on the two sides of the lock. Nonetheless, it is considered out-of-scope considering the challenges of tide estimation as well as the additional computational load that is brought by the dynamic water level, |
| Squeezing | ✘ | When the lock chamber approaches its volume capacity, maneuvering needed for a new vessel to sail in the chamber becomes increasingly more difficult and time consuming. However, data available did not include the behaviour of this additional time consumption. |
| Emission calculations | ✔ | Appendix F.3 illustrates how emissions are calculated, |
| Average passage, waiting and levelling time calculations | ✔ | Figure 3.3 depicts the calculation of passage, waiting and levelling times for every transit. Averages of these transit are taken. |
| Calculations of average number of ships per levelling, average number of ships per filled levelling, number of lockages and number of empty lockages | ✔ | Number of lockages, number of empty lockages and number of ships served are accummulated throughout the simulation horizon. The statistics are calculated accordingly. |
| Notification range of ships | ✔ | Before their arrival at the lock complex, ships report to the lock complex to be considered in scheduling. |

Scp. refers to whether the component is included in the scope of this research. ✔: included, ✘: excluded.

Table 4.3.: Extensions in SIVAK

| Component | Frq. | Imp. | Data | Fsb. | **Modelling assumption if included/ Justification if excluded** |
|---|---|---|---|---|---|
| Door fluttering | ✓ | ✓ | i | ✓ | Arround 60% of the reported failures in the second half of the year 2022 is due to fluttering doors. It is by far the most frequent malfunction. It is assumed that every door opening and closing has a probability of success. This probability is estimated using counters on the lock doors. If the door opening takes place successfully, operations in the lock chamber continue. If the door does not open/close successfully, lock operators try opening/closing the door one more time. It is assumed that the probability of success is the same as the first round, and that it takes the same time to try the second time. If the door opening/closing is unsuccesful in the second round as well, operations can not continue until the repair of doors. |
| Repair of doors | ✓ | ✓ | ✓ | ✓ | Time it takes for the repair of doors are assumed to be exponentially distributed, with the mean value of MTTR. |
| Slowdown | ✓ | ✓ | i | ✓ | Slowdowns occur based on a threshold. This threshold is exponentially distributed with the mean value as an input. After every inspection, a value is drawn from this distribution and the counter resets for the number of levellings. When the counter reaches this predetermined threshold, the levelling starts taking longer, This effect of the slowdown is modelled as a deterministic variable read as an input parameter. |
| Inspections | ✓ | ✓ | ✓ | ✓ | Inspections cause slowdowns to disappear and slowdown counter to reset. They have no effect on fluttering. Inspections are intended to start at a given time; however, if the lock chamber is busy at the time of the inspection start, inspectors wait for the completion of the lockage. The time it takes for the inspection is deterministic. |
| Other malfunctions in the system | i | ✓ | ✓ | ✗ | Other malfunctions in the system are not modelled as they are not prioritised given their frequency. Leaving other malfunctions out of scope helps correlate the results directly with the fluttering doors and slowdowns. |
| Backing-out of ships | ✗ | ✓ | ✓ | ✗ | In relation with the other malfunctions in the system, ships can be ordered to back out from the chamber and be assigned in another one, if there is need for corrective maintenance in their current chamber. It is stated in Interview B.1 that this does not happen frequently in the real system, and it does not happen when repair is needed for fluttering, because it becomes impossible to re-open the door once it is not functioning. |
| Operator behaviour for unallowed passages & sedimentation | ✓ | i | i | ✗ | Lock operators may choose to approve unallowed passages, which are the commercial passages though recreational chamber and vice versa. Appendix G.2.2 analysis this behaviour. However, this practice is discouraged as the design of the lock chamber may not match the design of the vessel, resulting in difficulties in complying with safety regulations and sedimentation in the chamber, resulting in the chamber being unoperational (Interview B.1). In this analysis, we chose to leave this behaviour out of the scope as it is not encouraged. |
| Preventive maintenance | ✓ | ✓ | ✗ | ✗ | Preventive maintenance activities result in improved lock conditions, with less frequent malfunctions. However, no dsata was available to establish these relationships. Therefore, preventive maintenance activities are not explicitly modelled. Instead, multiple lock condition scenarios are formulated. |

Frq.: Frequency of the event in the real system. ✓: frequent (either interviews or maintenance reports suggest that the event takes place more than once every week) ✗: not frequent.

Imp.: Impact of the event in ✓: event is expected to have a direct impact in performance indicators, i: indirect impact.

Data: Availability of data to model the event. ✓: available, i: can be estimated, ✗: not available.

Fsb.: Feasibility of implementation based on the timeline. ✓: feasible implementation based on its priority, ✗: unfeasible.

Table 4.4.: Performance indicators

| Indicator | Scp. | Justification |
|---|---|---|
| Cost of transport | ✗ | Cost of transport correlates with transit time, however, the hourly cost of transit is different per ship class. Since the hourly cost data per ship class are not available, this indicator is left out of scope. |
| Total tonnage | 👤+ | Total DWT is calculated as an important indicator of economic value. |
| Total value | ✗ | Cost of transport correlates with total tonnage, however, value per tonnage is likely to differ per ship class. |
| Cost of operation | ✗ | As the main item of operational cost is primarily driven by the expense of pumping water into and out of the chamber (PIANC InCom, WG 21, 2005), cost of operation is strongly associated with the number of levelings. |
| Cost of maintenance | ✗ | No data available. |
| Direct generated jobs | ✗ | Outside the boundaries of the research objectives. |
| Indirect generated jobs | ✗ | Outside the boundaries of the research objectives. |
| Energy efficiency | ✗ | The energy, fuel, and emission efficiency indicators concern the entire journey of the ship and provide a basis for comparison across various modes of transportation. However, since including only a segment of the journey can lead to potential misinterpretation, these indicators are excluded from the scope of this study. |
| Fuel efficiency | ✗ | See the cell above. |
| Emission efficiency | ✗ | See the cell above. |
| Fuel consumption | ✗ | Time limitations. |
| **$CO_2$ emission** | ✓ | $CO_2$ emission calculation is available in SIVAK. It is used as an indicator of environmental performance. |
| Pollution due to maintenance activities | ✗ | No data available. |
| Age of the lock | ✗ | Age of the lock is an important indicator to monitor. It affects the condition and, thereby, the frequency of malfunctions. Additionally, as the lock ages, preventive maintenance activities may become less effective. However, there are not sufficient data to model these impacts. Therefore, the age of the lock is not internalised. |
| Condition of the lock | ℹ | Condition of the lock is not modelled explicitly; however, different lock condition scenarios are studied by varying the extent of fluttering and slowdowns. |
| Mean time between failures | 👤+ | There are two types of malfunction in the model: fluttering and slowdown of levelling. Fluttering is modelled using probability of flutter during every door closing/opening. The levelling slowdown is modelled using a threshold of number of operations, after which the levelling starts taking longer by a certain degree. |
| Mean time to repair | 👤+ | When a door flutters twice, maintenance is called for repair. MTTR is used to model the time it takes for the repair to be completed after the maintenance is called. |
| Average passage time | ✓ | The average passage time, along with its two components, waiting time and levelling time, are calculated. |
| **Average waiting time** | ✓ | See the cell above. |
| **Average lockage time** | ✓ | See the cell above. |
| Maximum queue length | ✓ | It gives an indication about queue characteristic. |
| Average DWT per levelling | 👤+ | DWT per levelling is an important indicator to reflect both the capacity and economic value. |
| Average number of ships per levelling | ✓ | Average number of ships per levelling expresses efficiency of the levelling plan as well as traffic intensity. |
| Average number of ships per filled levelling | ✓ | This statistic is similar to the previous one but excludes empty fillings, providing additional insight particularly in cases of directional traffic imbalances. |
| Perceived quality of service | ✗ | It is expected to be correlated with the average passage time. |
| Availability of the infrastructure | 👤+ | Considering research objectives, it is important to quantify the impact of losses in efficiency, both in the form of unavailability and slowdowns. |
| Speed level | 👤+ | See the cell above. |
| Baseline OEE | 👤+ | Availability and speed are used to calculate the baseline OEE. |
| Occupancy | ✓ | Occupancy represents the lock operator's aim to maximise the utilisation of the chamber area in an efficient manner. |
| Efficiency-based OEE | 👤+ | Efficiency-based OEE combines the occupancy indicator with the baseline OEE. |
| Service level | ✓ | Service level represents the quality of service. Service-based OEE combines the service level indicator with the baseline OEE. |
| Service-based OEE | 👤+ | Efficiency-based OEE combines the occupancy indicator with the baseline OEE. |
| Number of ships | ✓ | Number of ships reflects both the capacity and the economic value. |
| **Number of lockages** | ✓ | Number of lockages is an important indicator that provides insight into the cost of operation. |
| Number of empty lockages | ✓ | Lock owners consider the number of empty lockages as a waste of energy and water, leading them to prioritise minimising such incidents (Bugarski et al., 2013). |
| **Hours of navigation interruption** | 👤+ | To explore the balance between preventive and corrective maintenance, the duration of navigation interruptions is recorded, including a breakdown of planned and unplanned interruptions. |
| Number of navigation interruption | ✗ | The notion of unavailability is expected to be adequately represented by hours of navigation interruption. |
| Number of complaints | ✗ | Number of complaints is expected to be correlated with passage time and events that impact the passage time, such as inefficiencies, planned or unplanned maintenance activities that result in waiting or longer service time. |
| Notification range of ships | ✓ | Ships notify the lock prior to their arrival and are included in the levelling plan accordingly. Currently, the notification range at the Volkerak complex is around 3.5 km, but this can be improved with AIS technologies. The notification range is included in the experimental scope as an input variable. |
| Accuracy of AIS/ tracking and tracing | ✗ | Not included in SIVAK, the model is not expanded considering time limitations. |
| Number of accidents | ✗ | Outside the boundaries of the research objectives. |
| Number of injuries | ✗ | Outside the boundaries of the research objectives. |

Scp. refers to whether the calculation of the indicator is included in the scope of this research. Those that are colored are reported as KPIs.

✓ : included, was available in SIVAK, 👤+: included, SIVAK was extended for the calculation, ✗: excluded, ℹ: see detail.

## 4.5. Case Study: The Volkerak Complex

There are four main waterway corridors in the Netherlands, illustrated in Figure 4.2 (Rijkswaterstaat, 2021b). These corridors account for approximately a quarter of transported goods and one third of total transport in the country (Rijkswaterstaat, 2021a). The South corridor is the most critical among the four corridors in terms of transported tonnage. This corridor is characterised by heavy transport of chemical and petroleum products, a product group that represents more than one third of the total trade value shared between Belgium and the Netherlands (OEC, 2021).


Figure 4.2.: Waterway corridors in the Netherlands

Integral Mobility Analysis (IMA), is a detailed report published by RWS, where different growth scenarios are outlined in order to identify bottlenecks in the waterway network (Rijkswaterstaat, 2021b). Using socio-demographic outlooks as well as the policy agendas, such as dedication to energy transition, demand for product groups is discussed and the corresponding traffic volume scenarios are generated for the corridors. Projections until 2040 point to an expected increase on all corridors except the North corridor in low growth scenario. The South, in particular, is predicted to be faced with the most substantial growth in both low- and high-growth scenarios, with a significant portion of transport taking place via inland shipping.

It should be noted that although an increase is projected, IWT has not experienced significant growth in recent years. Figure 4.3 displays the recent observations of some indicators over the last five years. The low performance rate of IWT in the region over the past four years is often attributed to various factors including the Covid-19 crisis, periods of low water in 2021 and 2022, and the conflict in Ukraine (CCNR, 2023).

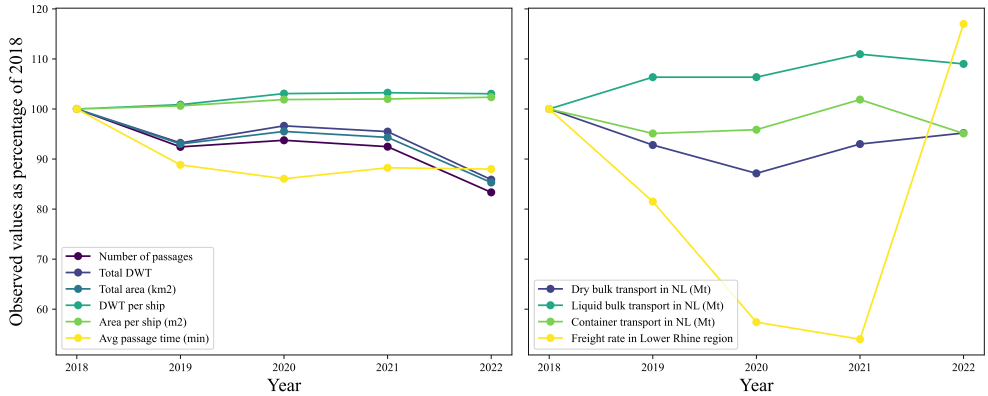



Figure 4.3.: Trends in IWT in the region. Left figure is created using own analysis from operational logs of the Volkerak complex. Right figure is plotted using data available in the Market Insights report by CCNR (2023).

### 4.5.1. About the facility

The Volkerak lock complex, located on the important shipping route between Antwerp and the Rhine, serves as a crucial "junction on the water" (Steenhuis, 2015). Construction of the complex began in 1957 (Steenhuis, 2015) and was completed in 1967 (Vialis B.V., 2023b). It initially consisted of two commercial chambers, an additional commercial chamber and a recreational chamber was added in 1977 to accommodate the increasing demand for transport capacity (Steenhuis, 2015).

Today, the Volkerak lock complex is recognised as one of the busiest and largest inland navigation lock complexes in Europe (Steenhuis, 2015). According to the flow analysis conducted by Systems Navigator (2023b), commercial traffic in the south of the Volkerak complex mainly consists of routes through Krammer and Kreekrak locks, with 46% and 54% respectively.

As shipping continues to expand, there have been plans to further expand the complex by constructing a fourth lock in the future (Steenhuis, 2015). The ageing infrastructure of the complex is evidently affecting availability, as the number of malfunctions grows steadily as shown in Figure 4.4.

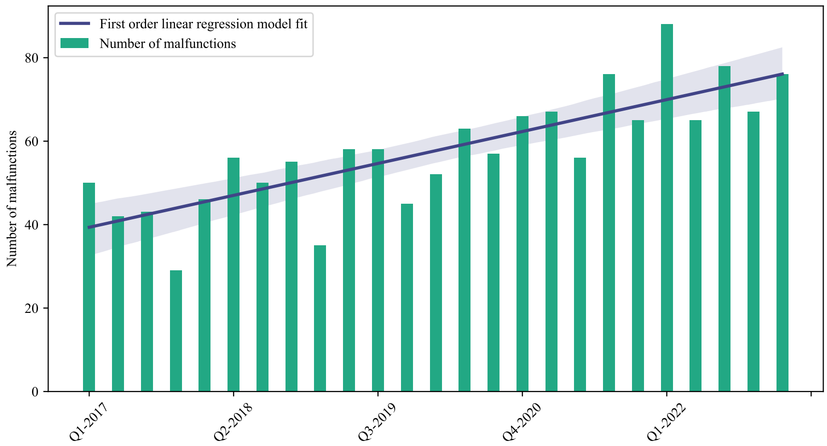



Figure 4.4.: Number of malfunctions in the Volkerak complex over time

In terms of technical design, the chambers of the Volkerak lock complex feature double-set two-sided turning mitre gates (see Appendix D for different types of lock designs) (Kranenburg & Vrijburcht, 2000). East and middle chambers also have middle gates; however, those are almost never used (Interview B). The filling of the chambers is done by sliding gate openings, which are operated using hydraulic cylinders (Kranenburg & Vrijburcht, 2000; Vrijburcht, 2000a). Stronger hydraulic cylinders are used to open and close gates (Kranenburg & Vrijburcht, 2000).

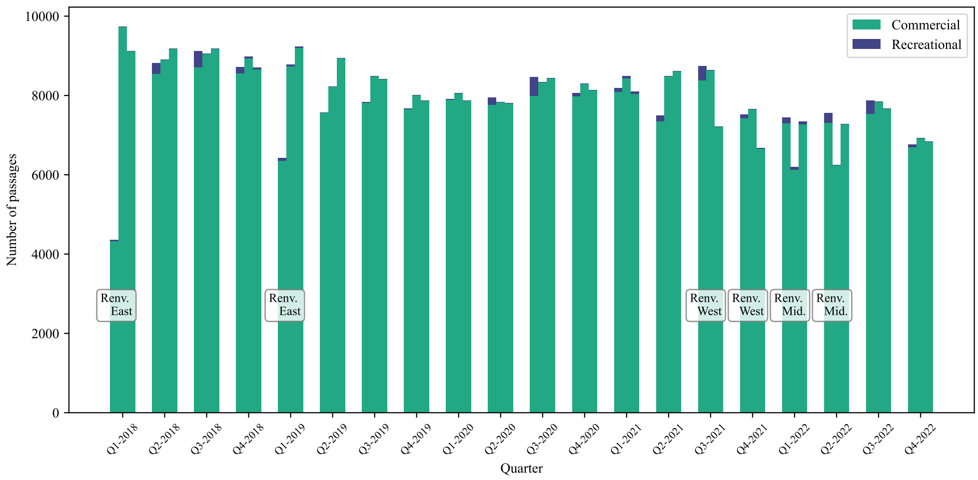



Figure 4.5.: Number of passages per chamber. Renovations in chambers are annotated. Recreational passages on commercial chambers (and vice versa) are discussed further in Appendix G.2.2.


Figure 4.6.: Volkerak complex

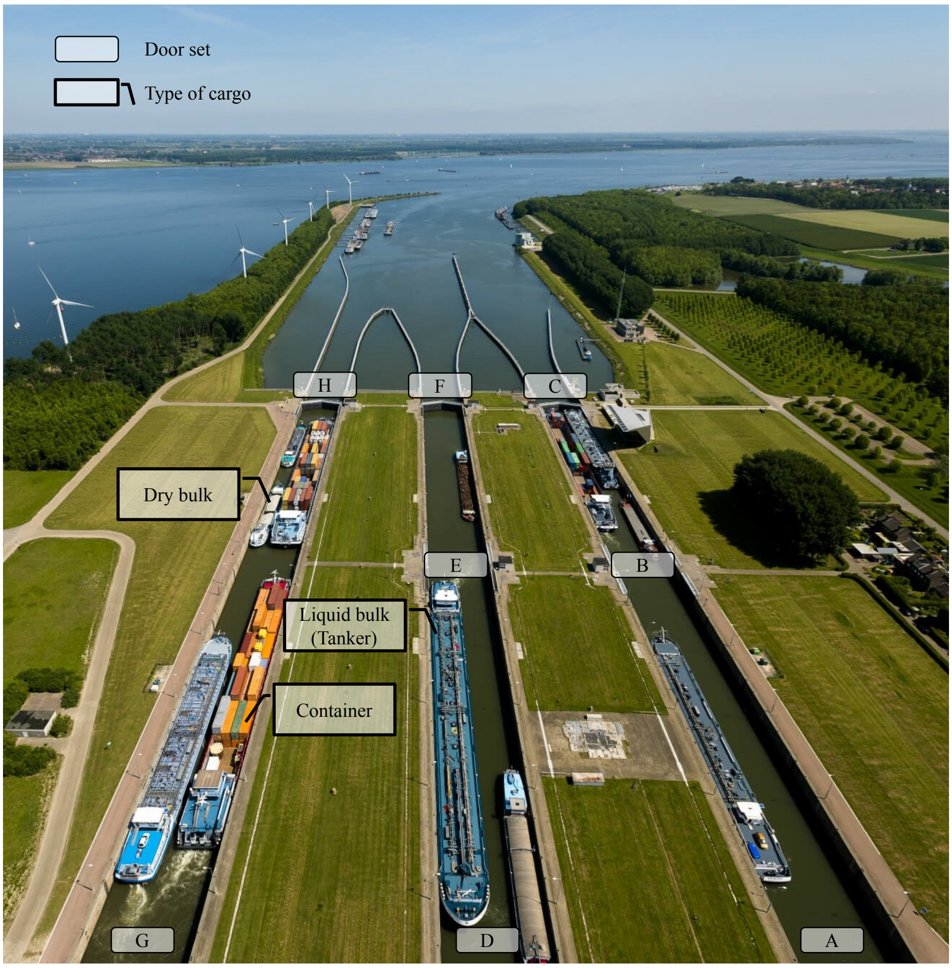



Figure 4.7.: Volkerak complex

## 4.6. Verification and validation

Verification involves testing the accuracy of the translation from the conceptual model to the software implementation. During the verification phase, the code and logic are thoroughly inspected, the model execution is closely monitored, and the model function is evaluated by verifying the results against the input provided (Whitner & Balci, 1989). A verified model means that the conceptual model is accurately translated into the software and that the software implementation is an equivalent. Validation refers to the process of determining the accuracy of the conceptual model, which is represented by the software implementation after model verification, compared to the actual physical system (Banks, 1998). Using the validated model and the settings for the experiments established in the experimental design, runs can be taken. Appendix E reports some of the verification and validation tests performed for this study.

# 5. Experimental design

## 5.1. Model inputs

Figure 5.1 illustrates the quantitative data requirements. Some terms used in this figure (such as guide jetty, UKC, DWT, LOA) are explained in the glossary. Qualitative data, on the other hand, include verbal explanation of the workings of the system and decision-making procedures of actors.

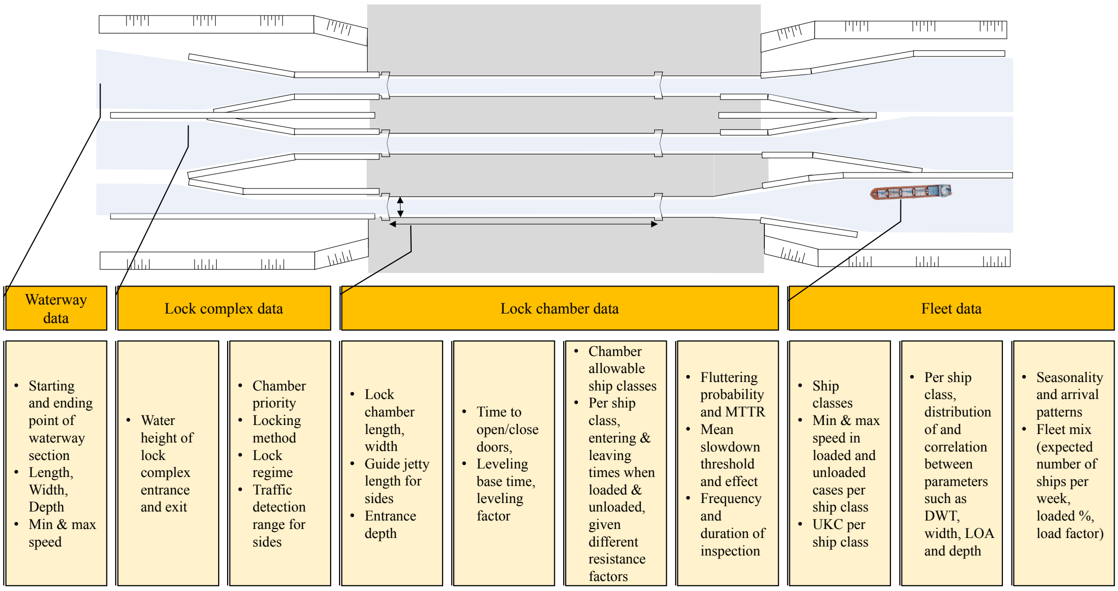



Figure 5.1.: Mapping of data requirements

In this section, we discuss these data requirements grouped by the subject they concern: waterway, lock complex, lock chamber and fleet. Some of these input data are treated as constant, and thus changing levels of these parameters are not considered in experiments. Fixed parameters include lock chamber dimensions, allowable ship classes for chambers and characteristics of these ship classes. Table 5.1 lists such data, along with their description and source. Some input data, however, are more dynamic in nature and correspond with scenarios and policies. Table 5.2 gives an overview of these parameters. Along with their description and data source, their inclusion in the three types of experiments formulated in this study is also shown.

Table 5.1.: Fixed data

**Waterway data**

| Data | Description | Source |
|---|---|---|
| - Starting and ending point<br>- Length, width, depth<br>- Min & max speed | Waterway links are defined on the two sides of the lock object to allow the generation and movement of ships along their designated routes. Additionally, these links allow ships to report within the traffic range prior to reaching the lock complex. Given that the study's focus is exclusively on the performance of the lock complex, without addressing movement within the waterway, the waterway links are modelled as dummy objects. | RWS scenario |

**Lock complex data**

| Data | Description | Source |
|---|---|---|
| Water height of lock entrance and exit | Water height is used to calculate the resistance factor, determining sail-in and -out times for ships (Appendix F.2.2). | RWS scenario |

**Lock chamber data**

| Data | Description | Source |
|---|---|---|
| - Lock chamber length, width | Lock chamber characteristics are important in not only determination of the capacity of the lock with respect to incoming ships, but also in calculation of the resistance factor for sail-in/out time adjustments. | RWS scenario & Rijkswater-staat (2023b) |
| - guide jetty length | Ships that are waiting on the lock complex require a correction time when they are called for entrance. This correction time is calculated using the guide jetty length. | RWS scenario |
| - Entrance depth | Entrance depth of the chamber determines whether the ship can enter the chamber given its minimum UKC requirement. | RWS scenario |
| - Time to open/close doors | Door opening and closing are modelled as delays with deterministic durations. | RWS scenario & Interview B.1 |
| - Levelling base time & levelling factor | Leveling is modelled as a delay with duration of levelling base time adjusted by the levelling factor and the water level difference between sides. As water levels are static in this study, levelling takes the same time as the leveling base time, except in cases of slowdown. | RWS scenario |
| - Chamber allowable ship classes | By principle, recreational vessels are not allowed in commercial chambers and vice versa. These relationships can be defined as an input data table. | RWS scenario |
| - Per ship class, entering and leaving times in loaded and unloaded cases with different resistance factors | Entrance and exit of ships are modelled as deterministic delays, duration of which depends on the ship class, whether it is loaded, and its resistance factor. See Appendix F.2.2 for more detail, | RWS scenario |

**Fleet data**

| Data | Description | Source |
|---|---|---|
| - Ship classes | There are in total 58 ship classes from ship groups motor vessel, vessel convoy, barges, passanger ships, tugs, recreational and seagoing vessels.Appendix G.1 provides some detail into these classifications. Different ship classes are characterised by changing speed levels, dimensions, fuel and emission related attributes. | SIVAK |
| - Min & max speed in loaded and unloaded cases per ship class | Ship speed is used to calculate delays in waterway sections. For instance, to determine delay until arrival after the reporting at the traffic range. | SIVAK |
| - Per ship class, distribution of and correlation between parameters ship characteristics | Ship generation process considers mean and standard deviation of attributes such as UKC, DWT, width, LOA and depth for the given ship class. Furthermore, these attributes are adjusted to ensure the correlation between these attributes. For instance, longer ships of the same ship class are more likely to be wider than the short ones, | SIVAK |
| - Loaded % and load factor of ship classes | Loaded % corresponds to the probability of the ship being loaded, whereas the load factor defines the degree of load. Speed, sail-in and -out times, emissions among others are all impacted by these two factors. | RWS scenario |
| Seasonality and arrival patterns | Seasonality refers to changes in fleet intensity over the year, whereas the arrival patterns define the likelihood of arrival during specific times of the week. | Own analysis from oper-ational logs (Section 5.2 & Appendix G.2.1) |

Table 5.2.: Experimental data

**Lock complex data**

| Data | Description | Source | Main | St.T. | Unv. |
|---|---|---|---|---|---|
| Chamber priority | When the lock master searches for a chamber to assign a vessel, chamber priority is followed. SIVAK allows for 4 types of chamber priority: chamber area, available area, occupancy or custom. Refer to Appendix F.2 for more detail on chamber assignment. | *SIVAK* | | | ● |
| Locking regime | Locking regime is used to determine whether locking will be initiated given the levelling plan. A locking regime is defined using three parameters: % occupancy requirement on the (1) open and (2) closed side of the lock chamber, and (3) the waiting time threshold for the ships assigned to the levelling plan. Based on validation with different options (Appendix E.2), the baseline locking regime was selected as defined by occupancy requirements of %40 and %80, and waiting threshold of 10 minutes. List of regimes was expanded for the main experiments to include two more levels: (1) regime with the same occupancy requirements and 20 minute wait threshold, and (2) regime with no wait (called ”No Regime”). | *Assumption* | ● | | |
| Traffic detection range | Before arriving at the lock complex, the vessels report to the lock so that they can be included in the levelling plan and receive an order to follow upon their arrival (Appendix C.1). A univariate analysis is conducted to investigate the potential for improvement through tracking technologies with more coverage. | RWS scenario | | | ● |

**Failure and maintenance data**

| Data | Description | Source | Main | St.T. | Unv. |
|---|---|---|---|---|---|
| Lock condition<br>- Fluttering probability<br>- Slowdown effect<br>- Slowdown threshold | Plausible intervals for the fluttering probability, mean slowdown threshold and slowdown effect were estimated through interviews conducted with the maintenance contractor. The concept of slowdowns is inspired by situations where one or more sliding gates experience malfunctions, while the operation can proceed with the gate openings that are still operational. In the Volkerak complex, each door consists of three openings, resulting in a total of six openings per door set. The upper range of the slowdown effect was estimated to reflect the case where two sliding gates become unavailable, leading to a 33.3% decrease in the speed of the process. | *Vialis B.V. (2023d)* & *Interview B.1* & *Assumption* | ● | ● | |
| MTTR | When fluttering takes place more than once, maintenance contractor is called for repair. MTTR defines the duration between the call for maintenance and the complete repair of the lock chamber. It is estimated as 2 hours based on interviews and maintenance reports. Different MTTR were investigated in the main experiments, by increasing and decreasing the responsiveness by 1.5 hours. | *Interview B.1 & Vialis B.V. (2023a)* | ● | | |
| Inspection frequency | Inspections on the doors are done once in every month. Impact of changing this frequency is explored in the main experiments. Next to the as-is case of monthly inspections, two additional levels are defined as ”once in 14 days” and ”once in 7 days”. | *Interview B.1 & Vialis B.V. (2023c)* | ● | | |
| Inspection starting time | Inspections are always conducted early in the morning, when the lock is still less busier. Nonetheless, Monday mornings are still not the least busy periods as they still accommodate more arrivals compared to the night, as can be observed in Figure 5.2. Although moving these inspections to the night might be considered desirable considering the experience of the ships, it comes with certain operational difficulties such as an increase in labour cost due to working hours outside the shift, requirement to ensure better illumination and to work in pairs in night for safety regulations. A univariate experiment is designed to evaluate the extent of benefits that can be gained through coping with these difficulties. | Interview B.1 | | | ● |
| Inspection duration | Inspection duration is the deterministic time duration between the start and end of the inspection. Depending on the inspection type, they take between 1-4 hours. Univariate experiment is conducted for exploring the sensitivity of the parameter. | *Interview B.1* | | | ● |

**Fleet data**

| Data | Description | Source | Main | St.T. | Unv. |
|---|---|---|---|---|---|
| Fleet mix<br>- Fleet composition<br>- Number of arrivals | Fleet mix data concerns the expected number of weekly arrivals from each ship class. It is estimated using forecasting on the operational logs. This baseline fleet mix is then adjusted to account for the expected shifts in IWT, underlined by the IMA. These two fleet mixes, named ”baseline” and ”IMA-driven” constitute the basis of the scenarios in the main experiments. Additionally, different fleet intensity scenarios, where the composition of the fleet remains the same with all ship classes scaling up by the same degree, are studied for the stress testing experiments. | Own analysis from operational logs (Section 5.2 and Appendix G.2.1) | ● | ● | |

The source is written in italics if the value can be derived as a range or a list of possible levels, rather than the exact value.
Exp. represents whether the variable is included in the main experiments with changing factor levels.
Sns. refers to whether a sensitivity analysis is performed on the variable.
Univariate experiments are taken in IMA-driven scenario

## 5.2. Formulating fleet mix scenarios

### 5.2.1. Operational logs

Upon request, RWS shared the operational logs of passages through the Volkerak complex. These data included information on the start of the event, duration of the event, direction, chamber used, and lastly, classification of the ship based on RWS's typology and international standards. These are detailed in Appendix G.1. It is worth mentioning that there was no direct one-to-one correspondence between the ship classes recorded in the operational logs and the ship classes available in the SIVAK. In such cases, assignments were performed on the basis of estimated likelihood with available data. As can be seen in Figure 4.3, this classification revealed that on average, larger vessels have become more popular.

The arrival pattern, representing the distribution of ship arrivals across different hours of the week, is determined using historical data, as depicted in Figure 5.2. No differentiation is made in the arrival patterns of different ship classes. Ship class parameters such as DWT, width, LOA and depth, speed limits, and load factors are used from SIVAK.

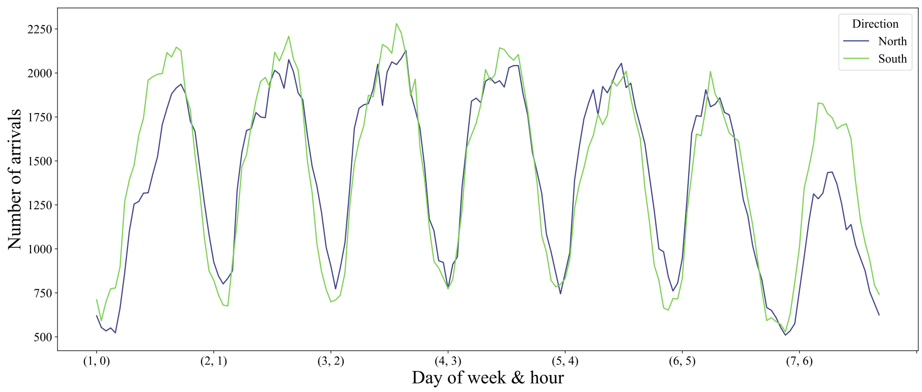
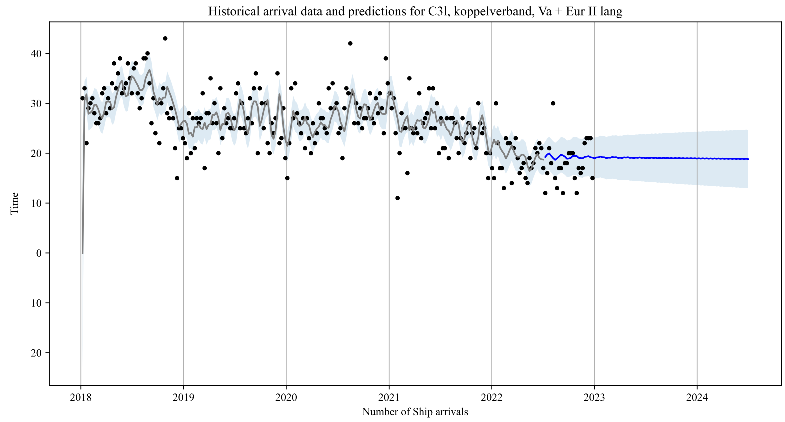


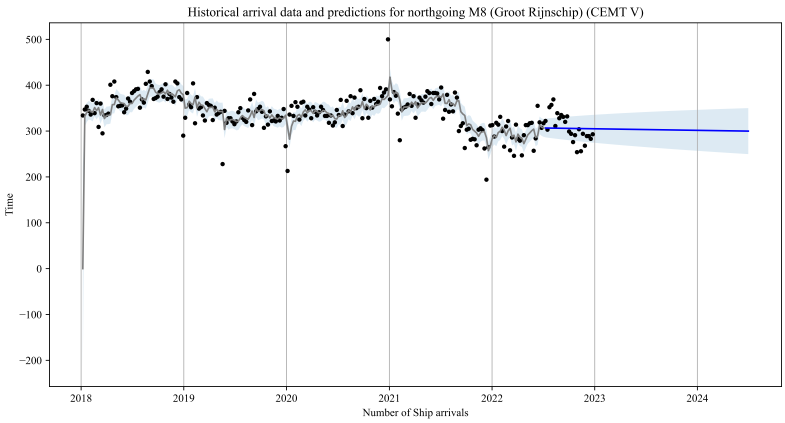

Figure 5.2.: Number of arrivals per day and hour of the week

The time series data for the weekly arrival of each ship class in both directions were analysed using Seasonal Autoregressive Moving Average (SARMA) models. These models were used to make predictions about future arrivals of ships. Figure 5.3 shows the visualised predictions for two examples. Appendix G.2.1 discusses this analysis in more detail.

These weekly arrival predictions serve as the basis for formulating fleet mixes. To study the period that is more challenging considering the capacity, these predicted weeks were inspected based on the number of arrivals, total area and total DWT statistics. Figure 5.4 is the resulting image of this inspection. Assuming that the area served is more likely to be the bottleneck of the service capacity, predictions corresponding to the 17th week of 2023 was selected as the baseline fleet mix.




(a) Southgoing C3l, koppelverband, Va + Eur II lang




(b) North-going M8 (Groot Rijnschip) (CEMT V)

Figure 5.3.: Historical arrival data and predictions for two different ship classes

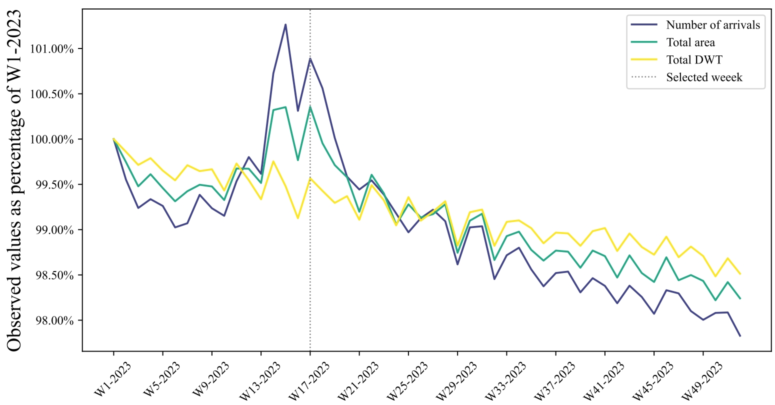



Figure 5.4.: Number of arrivals, DWT and area corresponding to predicted ship arrivals

### 5.2.2. Integral mobility analysis

As opposed to the time series analysis conducted in this study, (Rijkswaterstaat, 2021b) projects an increase in number of passages by anticipating changes in socio-economic conditions and policy agendas. To include this outlook in the analysis, predicted number of ship arrivals for the following year was calculated based on predicted increases in number of passages in the high growth IMA scenario. It is depicted in Figure 5.5.

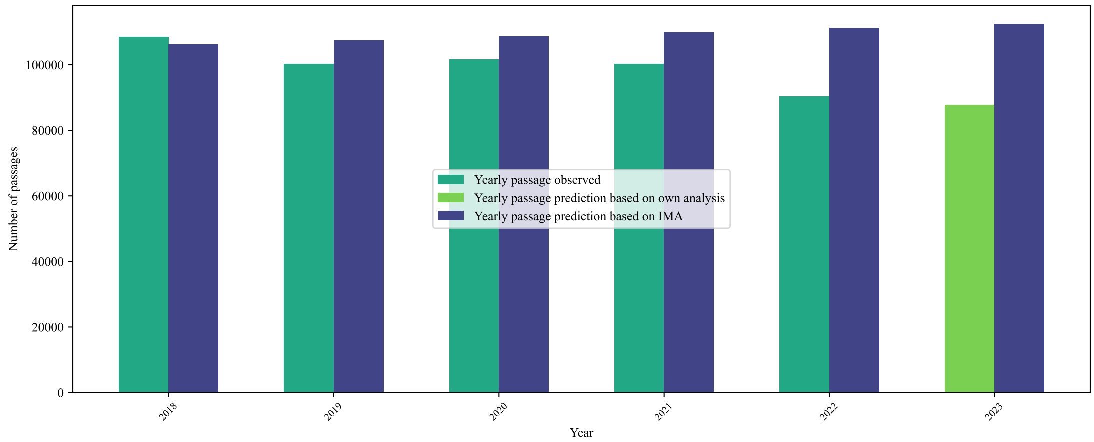



Figure 5.5.: Baseline vs. IMA-driven fleet mix

IMA also anticipates an increase in share of container transport. To account for this change in fleet composition, ship types that were recorded carrying containers in operational logs were identified. Based on IMA, (i) average predicted yearly container/total increase and (ii) average predicted yearly others/total decrease were calculated. Number of container-carrying ship type arrivals were scaled up by (i), and the others were scaled down by (ii). Resulting number of arrivals was normalised so that the number of ship arrivals is the same as predictions by IMA.

## 5.3. Experimentals

Three types of experiments have been conducted. The first one considers a set employing a factorial design, which aims to assess the significance of factors (Sanchez et al., 2020). The second one focusses on the formulation of stress scenarios, with varying degrees of lock condition deterioration and fleet intensity. The last one is univariate experiments, consisting of a total of four sets focussing on (1) traffic range, (2) chamber priority, (3) inspection start and (4) inspection duration.

### 5.3.1. Main experiments

Figure 5.6 summarises factors and levels used in the main experiment. Two scenarios were defined for the fleet mix: (1) Baseline fleet mix, corresponding to the predictions using Seasonal Autoregressive Moving Average (SARMA) (see Appendix G.2.1), (2) IMA-driven fleet mix, where (Rijkswaterstaat, 2021b). Taking into account the research objectives, five factors were selected to be included in the main experiments: fleet mix, lock condition, locking regime, periodic inspection and MTTR policies.

Table 5.3.: OCIR definition, runs for main experiments

| OCIR Definition | Description |
|---|---|
| *(d) Runs definition part* | *This part concerns definition of scenarios and experiments.* |
| Length of run | Four weeks, to allow for a sufficient number of observations of fluttering and slowdown events, as well as the necessary time for repairs and inspections. This timeframe ensures that these events occur frequently enough to be meaningful and representative of the lock's operational characteristics. It is assumed that the fleet intensity remains constant over the entire 4-week period. |
| Warm-up period | No warm-up period is defined for the experiments. This decision is based on the assumption that the lock complex will be empty at the starting time of the simulation. Regarding that the arrival patterns in Figure 5.2 suggests a low demand during this period, this can be considered as a valid assumption. Waterway length is kept at 2 kilometers both on the north and the south of the complex, assuring that the ships arrive at the traffic range only minutes after their generation. |
| Number of replications per design point | 10 replications. There are multiple sources of stocasticity in the model: vessel generation (both in terms of the time of generation and vessel characteristics), malfunctions and the repair (fluttering, slowdown, and repair). The presence of multiple lock chambers within each replication of the study increases the relevance of the statistical principle of the law of large numbers. This principle suggests that as the number of observations or samples increases, the more accurate and reliable the estimated outcomes become, converging towards the true expected values. As the preliminary runs resulted in visual and statistical differences between changing policies, 10 replications were assumed to be sufficient. |
| Scenarios | Fleet mix |
| | Condition of the lock, represented by five sets of fluttering probability. mean slowdown threshold and slowdown effect |
| Policy parameters | Locking regime |
| | Periodic inspection frequency |
| | MTTR |

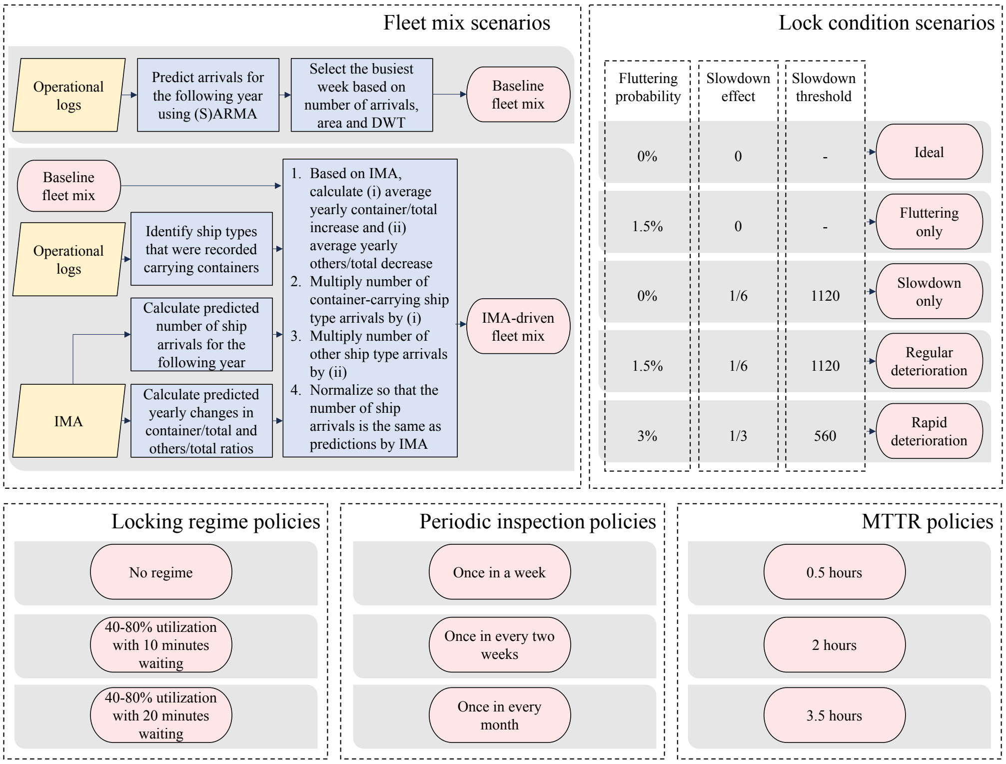



Figure 5.6.: Factors and levels in the main experiment

## 5.3.2. Stress testing experiment

As illustrated in Figure 5.7, Stress testing experiments are formulated by varying lock conditions and degrees of intensity of the baseline fleet mix. Decisions remain the same regarding the run length, no warm-up period and number of replications per design point. Policy parameters are in their baseline values with locking regime defined with ”40% and 80% with 10 minutes of waiting”, periodic inspection as once in a month and MTTR as 2.0 hours.

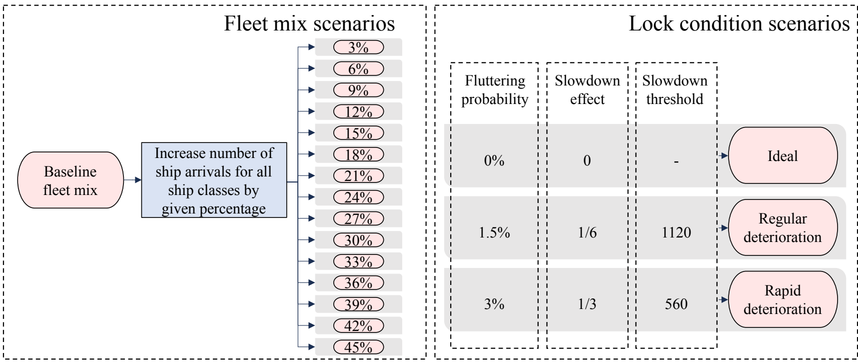



Figure 5.7.: Factors and levels in stress testing

### 5.3.3. Univariate experiments

Four sets of univariate experiments were conducted on the polic parameters (1) traffic range, (2) chamber priority, (3) inspection start and (4) inspection duration. IMA-driven scenario is used as the fleet mix under regular lock deterioration scenario. Policy parameters are kept their baseline values, same as in the stress testing experiments. Although number of replications per design point and the no warm-up period definition is shared among these sets of experiments, they differ in their run length based on their focus. Chamber priority is the only variable that is tested under the same run length as the main experiments. Run length is set to 1-day for the experiments with varying inspection start options. This decision is made to make sure that the focus remains on the ships that are affected by the inspection, trying to minimise the diminishing of the effect. Similarly, inspection duration was experimented in runs with length of 2 days, assuring that all the impacted ships complete their journey for recording purposes. Lastly, experiments with traffic range was of the run length of a week, so that the arrival pattern throughout the week is reflected in the results.

# Part III.

# Synthesising the findings

# 6. Results

As discussed in Section 4.4, only the KPIs are reported in this chapter. For general remarks on the complete set of performance indicators, see Appendix I.

## 6.1. Main experiments

The purpose of the feature scoring analysis, the result of which is available in Figure 6.1, is to quantify and compare the influence of factors on the KPIs. 1000 regression trees were fitted for each KPI using the extra trees algorithm to produce this figure (Geurts et al., 2006).

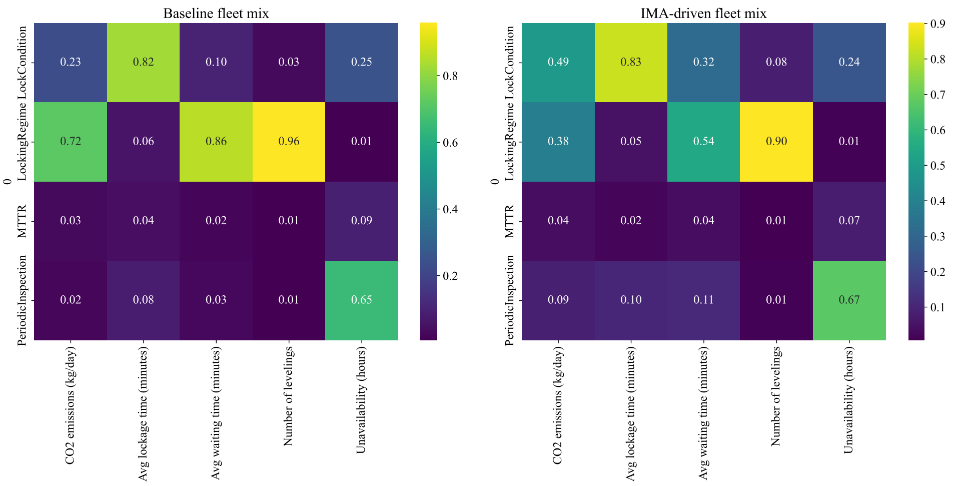
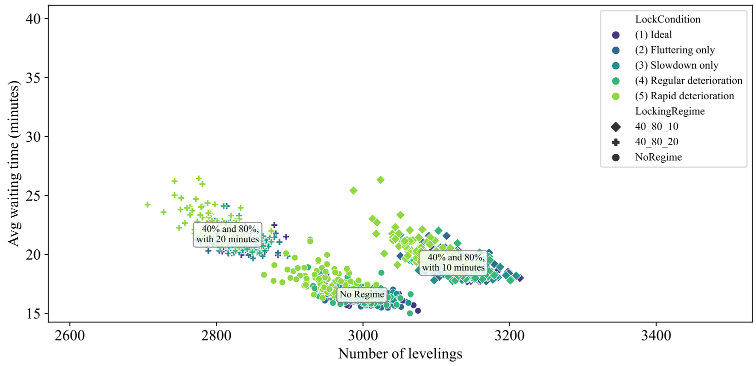


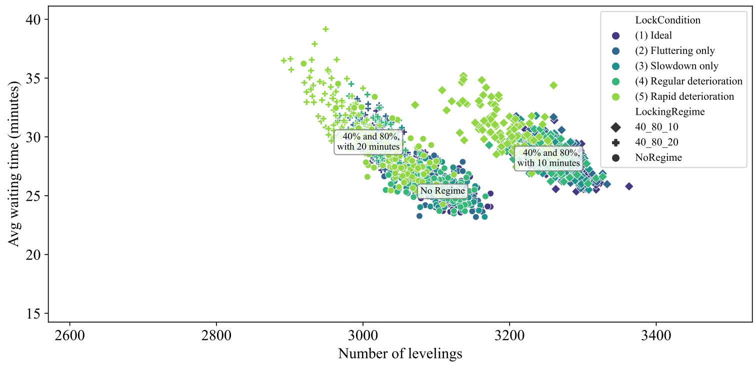

Figure 6.1.: Feature scoring table

Figure 6.1 provides insight into the underlying factors that cause the relationships between the KPIs. In both fleet mix scenarios, the locking regime factor has a significant influence on $CO_2$ emissions, average waiting time, and number of levellings. On the contrary, the locking regime is one of the least significant factors for the average lockage time and unavailability. While the former is mostly influenced by lock conditions, periodic inspection seems to be the key factor for the latter.

Figure 6.2 shows the resulting waiting times and the number of levellings from the experiments, coloured by the lock condition and styled by the locking regime. First, it is observed that for given locking regimes and fleet mix scenarios, there is a trade-off between waiting time and number of levellings. Second, it is seen that different locking regimes result in different




(a) Baseline fleet mix scenario

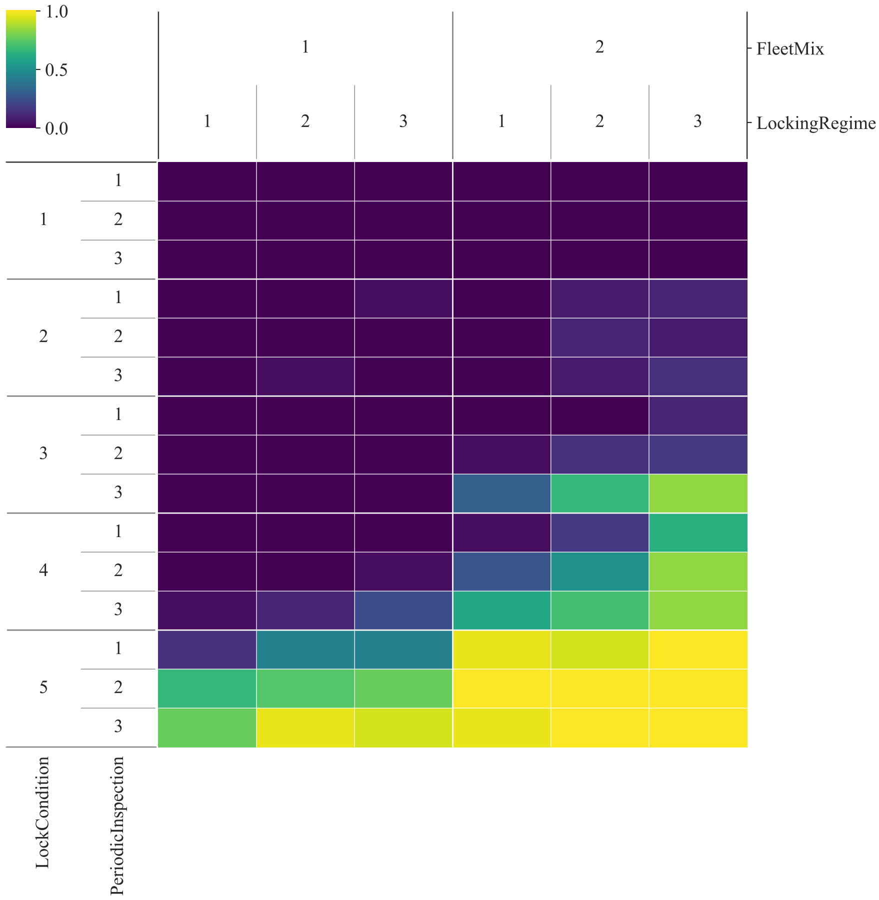



(b) IMA-driven fleet mix scenario

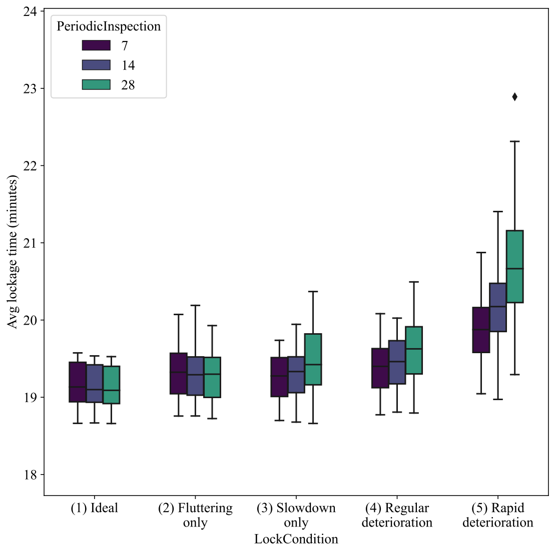
Figure 6.2.: Scatterplot

clusters of observations. As expected, locking regimes with higher waiting time allowances result in higher average waiting times. The number of levellings, on the other hand, shows a more complicated behaviour, where the locking regime with 10 minutes waiting results in a higher number of levellings compared to the ”No Regime” case. Although this behaviour might seem non-trivial, it comes from the choice of implementation that yields vessels to wait for the other arrivals reported in the range when the locking regime is ”No Regime”, while for the locking regimes identified by the utilisation rates and waiting times, levelling considers only the waiting time dictated by the regime. Refer to Appendix F.2.1 for further inspection of this difference in the model logs.

A detailed look into the average lockage time is presented in Figure 6.3. The dimensional stacking of four factors in Figure 6.3a shows the characteristics of the experiments that led to large outcomes in average lockage time (higher than 75th percentile). The number of high observations on the bottom-right corner shows that the experiments with the rapid deterioration lock condition, IMA driven fleet mix and the locking regime identified as ”40% and 80% with 20 minutes” characterise high average lockage time. Furthermore, when the lock condition is ”rapid deterioration”, the importance of periodic inspection frequency is more pronounced. Figure 6.3b shows that when the lock condition is severely deteriorated, a more frequent periodic inspection (once a week) leads to considerably lower average lockage time.




(a) Dimensional stacking




(b) Boxplot

Figure 6.3.: Average lockage time

## 6.2. Exploring capacity under stress

With stress testing experiments, KPIs were inspected under different scenarios of fleet intensity and lock conditions. Figure 6.4 shows the average waiting times. Dotted gray line in the figure is the waiting time threshold monitored by RWS. In the ideal and regular deterioration scenarios, most observations surpass this threshold when fleet intensity is above 33%, while in the rapid deterioration scenario, it's 27%. All observations exceed the threshold when the fleet intensity reaches 39%, 36%, and 33% for the ideal, regular deterioration, and rapid deterioration scenarios, respectively.

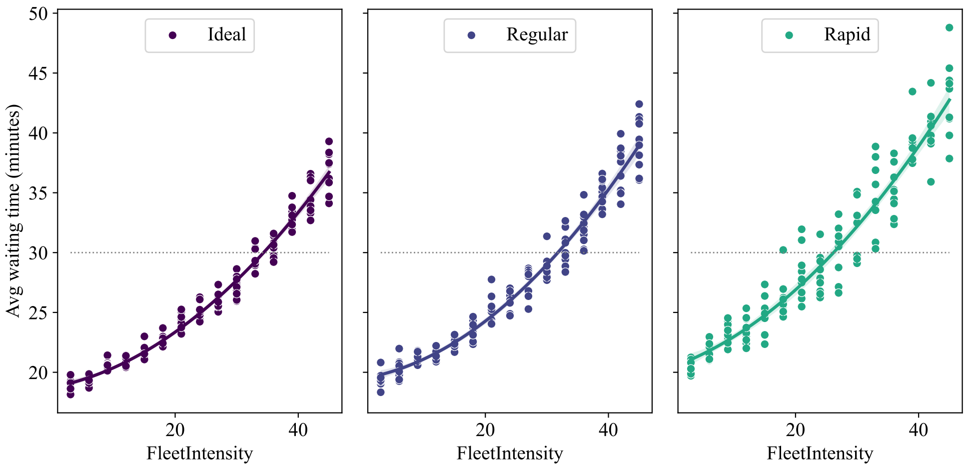



Figure 6.4.: Average waiting time under different lock and fleet intensity conditions

## 6.3. Univariate experiments

Figures 6.5 to 6.8 show the average waiting time and number of levellings resulting from the univariate experiments with traffic range, chamber priority, inspection start and inspection duration.

Figure 6.5 suggests that through an increase of traffic range from 1 km to 1.5 km, improvements can be achieved in both the average waiting time and the number of levellings, without any compromise. Although number of levellings can be further reduced with increased traffic range, this comes at the cost of additional waiting time. This improvement trend stabilises after a certain traffic range around 2 km.

Figure 6.6 shows that chamber prioritisations that consider the current state of the available area or the utilisation rate result in improvements both in waiting times and number of levellings. Using Kolmogorov–Smirnov and Levene tests with the significance level of 0.05, these improvements are evidenced to be statistically significant.

Figures 6.7 and 6.8 signify the importance of the timing and duration of the inspection activity. If the inspections are done during the night, where there are fewer arrivals given the arrival patterns (see Figure 5.2), ships wait less on average.

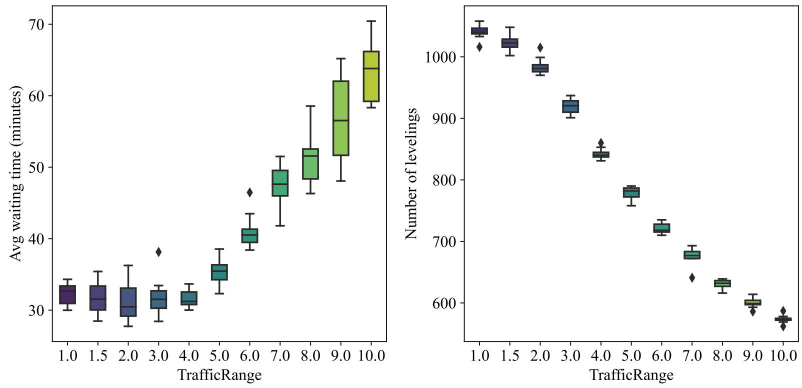



Figure 6.5.: Traffic range. Note that the run length is seven days.

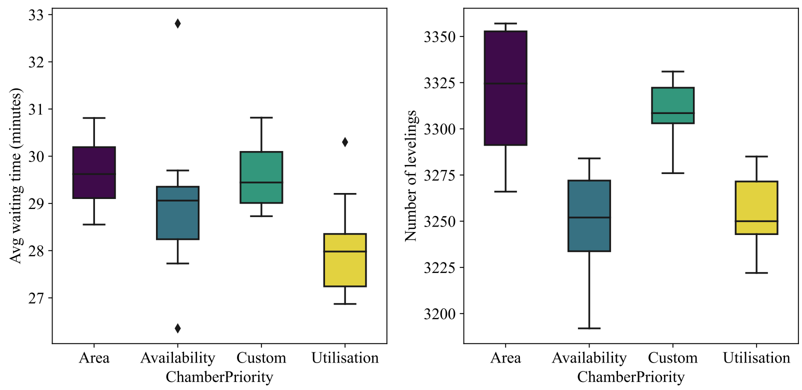



Figure 6.6.: Chamber priority

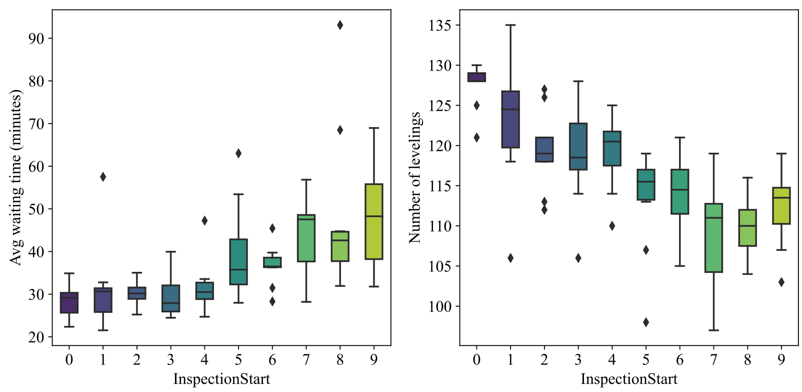



Figure 6.7.: Inspection start. Note that the run length is one day.

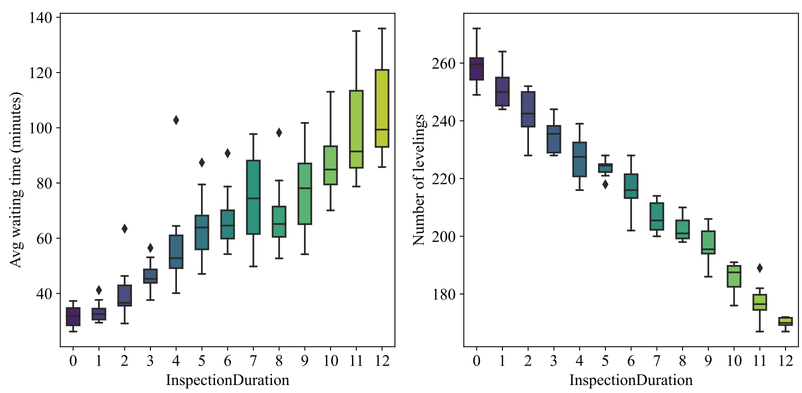



Figure 6.8.: Inspection duration. Note that the run length is two days.

## 6.4. Potential of OEE

Three alternative formulations of OEE, as discussed in Section 3.3.1, were employed in the main experiments, depicted in Figures 6.9, 6.10 and 6.11. These figures reveal that the OEE formulations have varying relationships between different KPIs.

Both the baseline and service-based OEE metrics are highly aligned with the average passage time and the $CO_2$ emissions. An apparent difference between the baseline OEE and the other two formulations is that the former is relatively independent of the fleet mix scenario and the locking regime, and the observed values remain approximately in the same range (85% to 100%) across these different combinations.

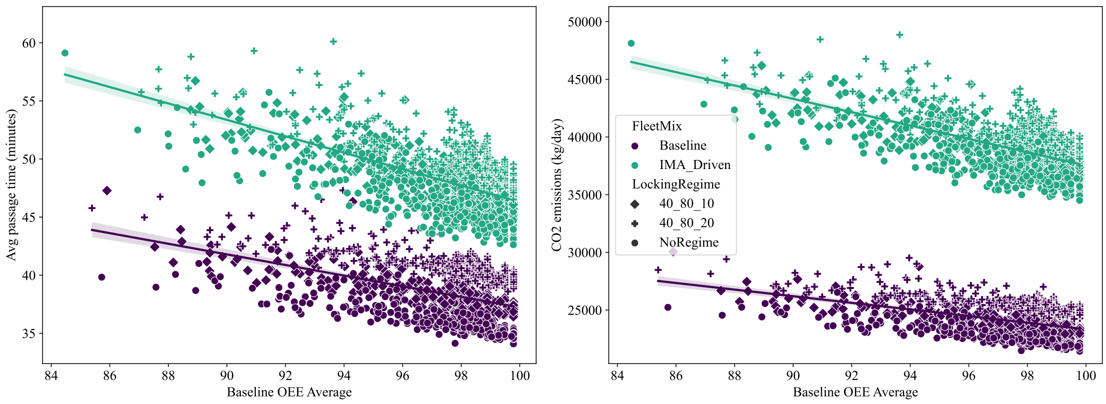
Nature of the relationship between the baseline OEE and the two performance indicators remain the same despite changing fleet mixes and locking regimes. Linear regression analyses using Baseline OEE as the dependent variable suggest that in the baseline fleet mix scenario, for any given locking regime, a 1-point improvement in the OEE score leads to an average boost of 1.2% in reducing both passage times and $CO_2$ emissions. These positive effects become more pronounced when the IMA-driven scenario is considered, where the improvements rise to 1.5%. The ability of these regression models to explain the data differs for these two performance indicators under different lock condition and locking regime combinations. The coefficients of determination ($r^2$) span from 0.55 to 0.70 for average passage time, and from 0.53 to 0.69 for $CO_2$ emissions. It is observed that the $r^2$ ranges point to an improvement in exploratory power for the baseline OEE when it is benchmarked with the individual components of the formulation, availability ($r^2$ ranges of 0.35-0.50) and speed ($r^2$ range of 0.37-0.55).

Outcomes for the service-based OEE, on the other hand, change based on the fleet mix and locking regime. Locking regimes that prioritise minimising passage times result in higher service-based OEE averages. When the number of arrivals is above capacity, and thus passage times are higher than acceptable terms, it is reflected in service-based OEE. Linear regression of Service-based OEE against KPIs shows that, in the baseline fleet mix, a 1-point OEE improvement yields a 1.1% reduction in both passage times $CO_2$ emissions. These gains amplify in the IMA-driven scenario to 1.3% for passage times and 1.4% for $CO_2$ emissions. The regression models' explanatory power varies, with $r^2$ ranging from 0.83 to 0.87 for passage times and 0.82 to 0.87 for $CO_2$ emissions. In comparison, $r^2$ values ranges from 0.72-0.87 when service level is used as the dependent variable for the linear regression.

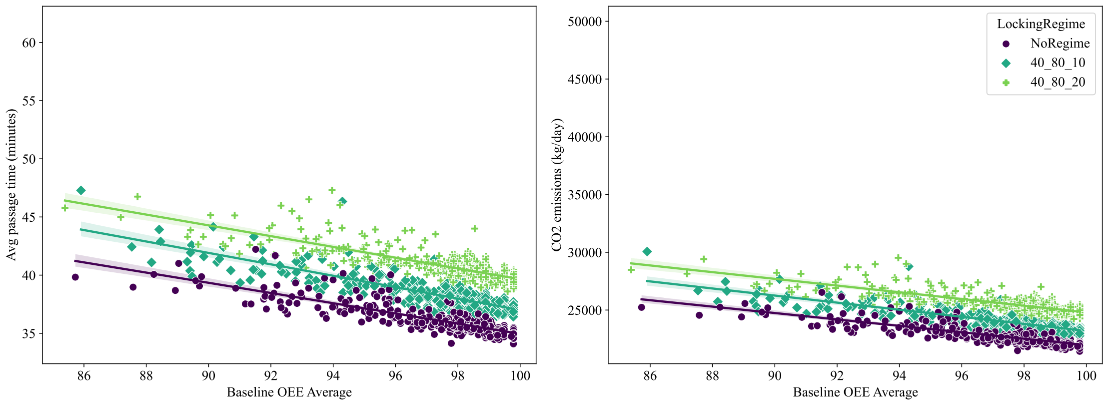
Efficiency-based OEE displays a clustered view across scenarios. Under both scenarios, the locking regime identified as "40% and 80% with 20 minutes waiting" results in higher scores of efficiency-based OEE.

### 6.4.1. MTTR

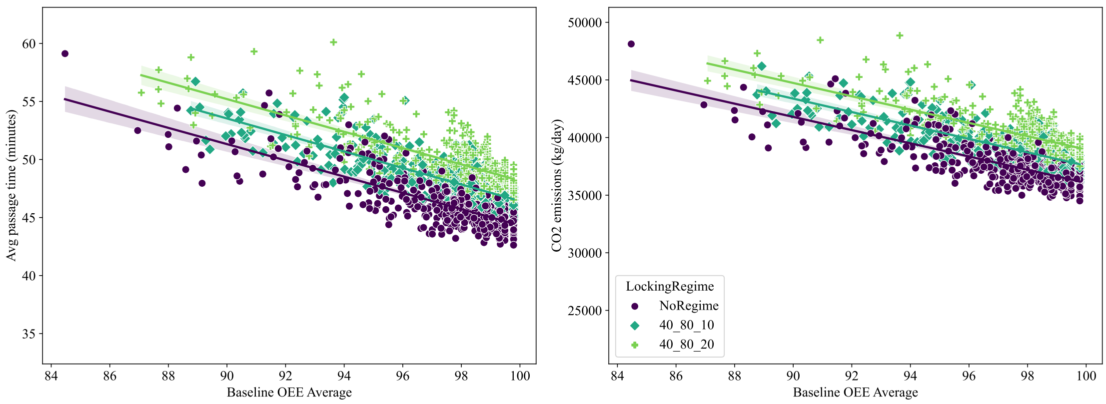
In both the regular and rapid deterioration cases under both fleet mix scenarios, solid evidence (at the 0.05 level) was found to claim that reducing MTTR to 0.5 hours brings a change in the distribution of baseline OEE. However, the hypothesis that baseline OEE distributions are indifferent to a change in MTTR from 2.0 to 3.5 hours could not be rejected.




(a) All observations

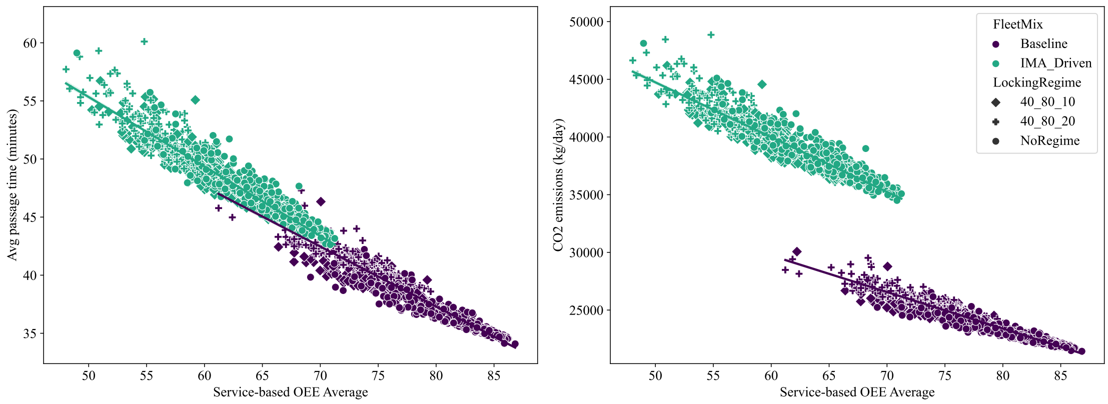



(b) Baseline fleetmix scenario

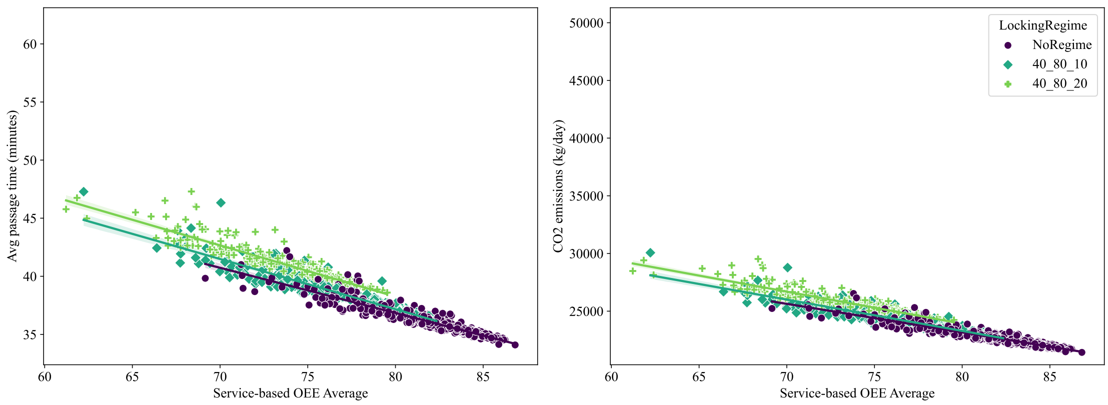



(c) IMA-driven fleetmix scenario

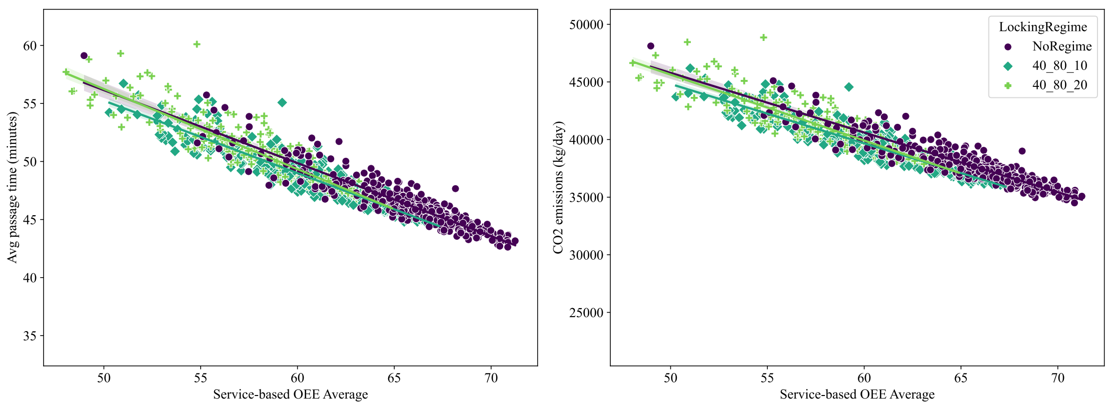
Figure 6.9.: Baseline OEE




(a) All observations

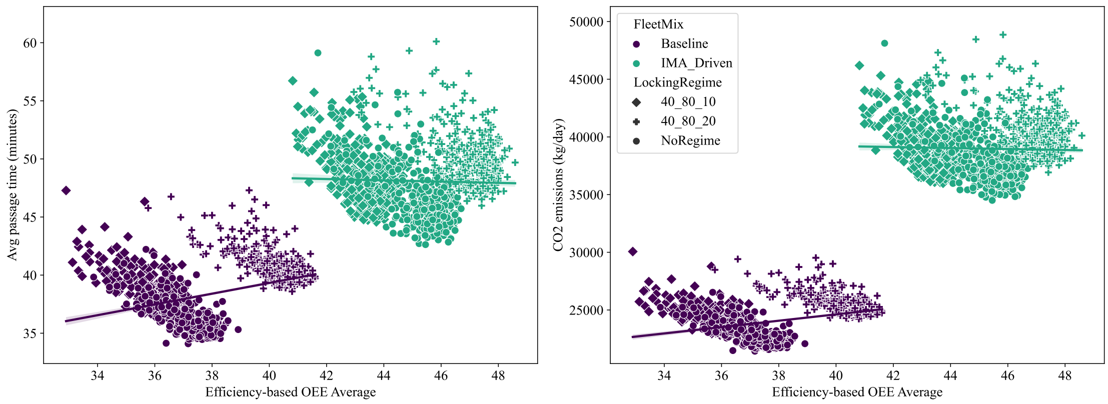



(b) Baseline fleetmix scenario

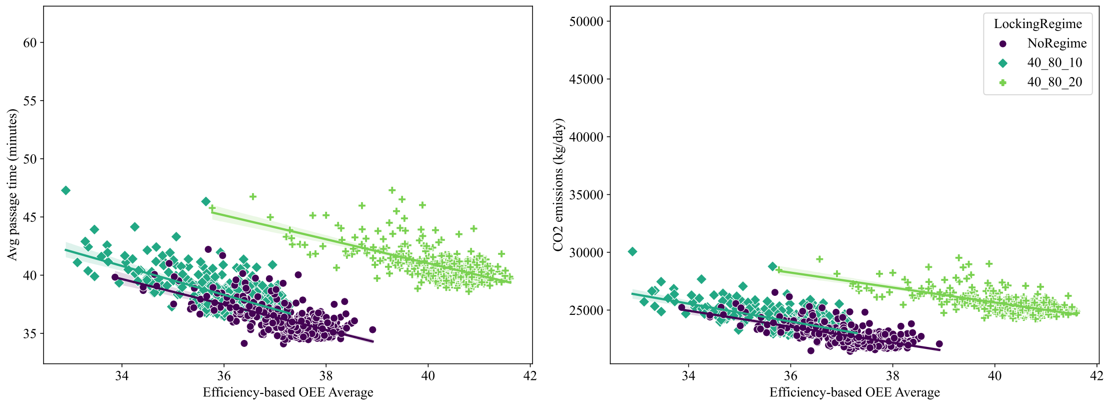



(c) IMA-driven fleetmix scenario

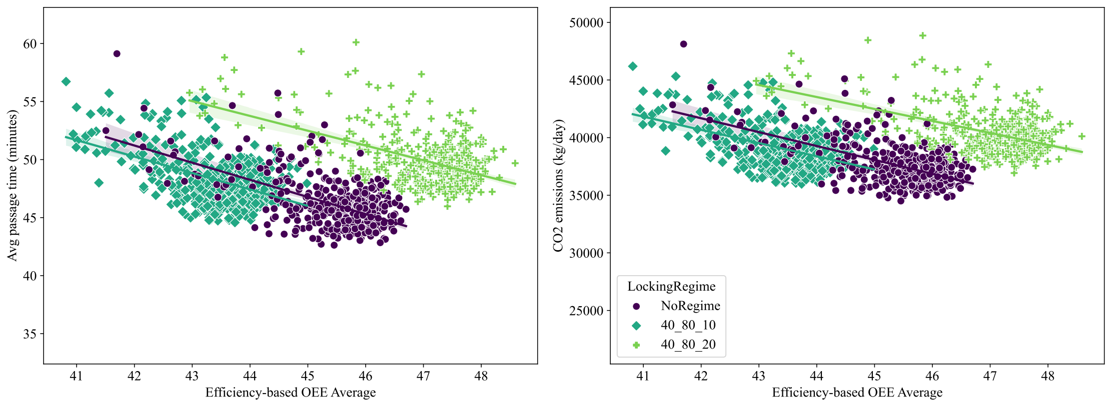
Figure 6.10.: Service-based OEE




(a) All observations




(b) Baseline fleetmix scenario




(c) IMA-driven fleetmix scenario

Figure 6.11.: Efficiency-based OEE

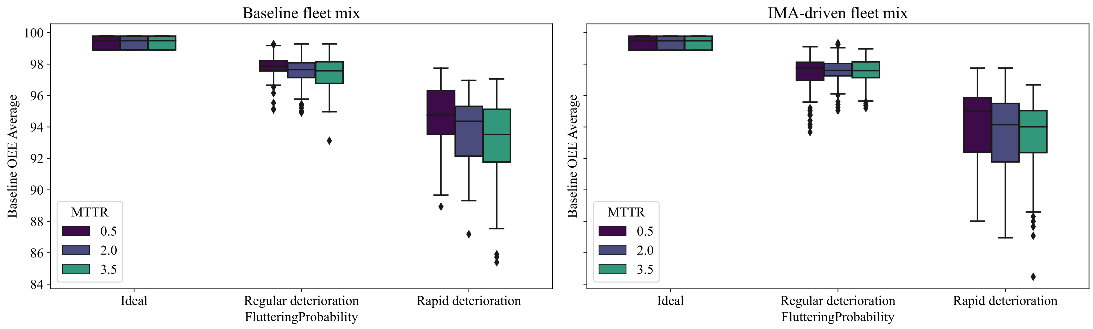



Figure 6.12.: Baseline OEE average fleet mix scenarios with changing MTTR policies

## 6.4.2. Frequency of inspection

Statistical evidence was found to state that for every fleet mix and lock condition scenario, frequency of inspection changes the baseline OEE distribution.

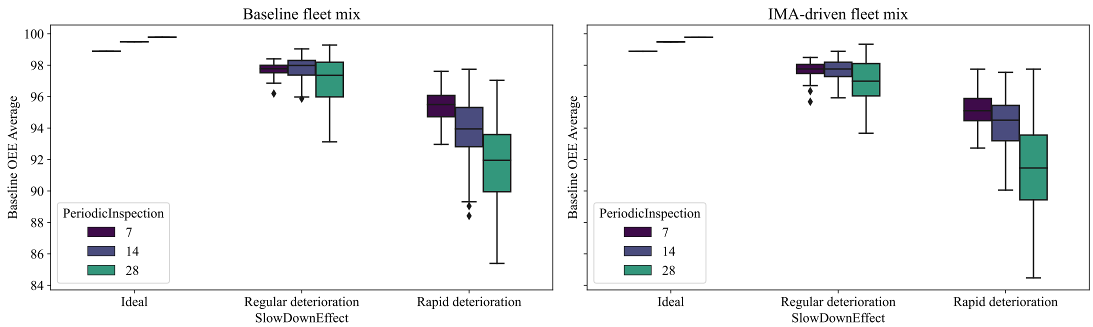



Figure 6.13.: Baseline OEE average fleet mix scenarios with changing inspection frequency policies

# 7. Discussion

## 7.1. Implications of results

### 7.1.1. Maintenance policy

The role of lock conditions gains prominence within the busier IMA-driven scenario, as highlighted in the analysis presented in Figure 6.1. This finding underlines the increasing importance of lock conditions under high demand. Additionally, when reviewing Figure 6.4, a clear pattern emerges: average waiting times exhibit increased unpredictability as lock conditions deteriorate. In particular, in addressing the challenge of rapid deterioration, improving infrastructure conditions to reduce slowdowns and fluttering probability results in notable improvements in handling capacity when the waiting time threshold is considered as the main criterion. Furthermore, scenarios with less favourable lock conditions emphasise the increased importance of corrective maintenance, as shown in Figure 6.3.

The concept of baseline OEE stands out as a maintenance-oriented metric that merges two critical performance indicators: availability and speed. Remarkably, this composite metric surpasses its individual components in explaining the variability in average passage time and $CO_2$ emissions. Its relative insensitivity to the number of ship arrivals and to different locking regime selections makes it comparable across various fleet mix and operational scenarios. By focussing on factors within the control of decision makers and remaining unaffected by demand fluctuations, this approach provides a benchmark that guides action-orientated maintenance decisions.

Lastly, insights from Figures 6.12 and 6.13 draw attention to the improvements of the baseline OEE that can be achieved through adjustments in MTTR and inspection policies. These observations point to the potential to optimise performance through strategic modifications in maintenance practises.

### 7.1.2. Operational policy

The results of the experiments reveal the following observations:

- **Trade-Off Management:** A notable trade-off exists between the number of levellings and average waiting time, as depicted in Figure 6.2. The choice of locking regimes plays a pivotal role in shaping this trade-off, as different regimes prioritise distinct aspects of this balance. Understanding how locking regimes interact with this trade-off is important for informed decision-making.

- **Traffic Range Optimisation:** The concept of traffic range highlights the potential gains in average waiting times and levellings through expansion of the traffic range, up to a certain threshold. However, beyond this point, it transforms into a nuanced balance that requires careful assessment. Striking the right balance requires a thorough evaluation of whether waiting for another ship within the range justifies the associated waiting times.
- **Chamber Priority Consideration**: Effective decision-making in chamber priority involves integrating the current state of chambers. Approaches centred solely on total chamber area or custom prioritisation, overlooking existing levelling plans, yield suboptimal outcomes for waiting times and levellings. Maximising utilisation or minimising available area, on the other hand, emerges as statistically superior.
- **Service-Based OEE**: Unlike baseline OEE, service-based OEE incorporates both operational and maintenance dimensions. Changes in the locking regime influence the service-based OEE, with those prioritising service level resulting in higher OEE scores. Changes in fleet mix also affect service-based OEE, highlighting cases where the capacity of a complex falls short of meeting the requirements. This aspect enables meaningful comparisons among different lock complexes, alarming the need for budget allocation. The metric is strongly correlated with $CO_2$ emissions and passage times, even to a degree that exceeds the explarotary power of the service level. This makes it easier to communicate potential improvements in the system and translate them into tangible results, such as reduced waiting times or emissions. Setting specific goals to increase OEE by a certain percentage can bring together different stakeholders to collaborate and work towards improving the performance of the system.
- **Efficiency-Based OEE:** Efficiency-based OEE provides a realistic indication of the efficiency with which the resources of the system are being utilised. By considering the chamber occupancy rate, efficiency-based OEE rewards efficient chamber filling practises. When the chamber is optimally used to serve a larger number of ships, the efficiency-based OEE increases. However, the components of this metric contradict with each other in some cases. For instance, when one lock chamber becomes unavailable, the other chambers become more occupied. Such contradictions result in ambiguity of the metric in relation with KPIs.

## 7.2. Limitations

In modelling, it is common to employ simplifications to reduce data requirements and facilitate the construction, use, and maintenance of the model (van der Zee, 2019). However, there is always a risk of oversimplification and of not accurately capturing real-world relationships. In this study, due to time limitations, simplifications were widely utilised in both input analysis and model development.

An example of a simplification can be seen in the prediction of ship arrivals. The occasional use of the recreational lock chamber by commercial vessels and vice versa (see Appendix G.2.2) were not taken into account in the observations, which could have impacted the accuracy of arrival predictions. Furthermore, arrival patterns were assumed to be the same across different ship classes, neglecting potential variations in their transit patterns during the week.

To minimise data requirements, fluttering, slowdowns, and inspections were modelled in a simplified manner. The impact of inspections on fluttering was ignored, and the effects of slowdowns were simplified. Some failures with more complicated consequences, such as those that would require the vessels to back out from the chamber, are left out of the modelling scope. However, it is crucial to acknowledge that these simplifications were made within the context of the exploratory nature of the study. Although they may have resulted in some level of inaccuracy, they served the purpose of the study in generating inefficiencies and providing initial insight and understanding.

# 8. Conclusion

## 8.1. Revisiting the research questions

> **❓ 1st Sub-question**
>
> How can we operationalise the performance measurement of lock complexes?

Through literature research, we conducted an extensive exploration of KPIs that have been used previously to assess the effectiveness and performance of waterway lock systems. We classified these indicators into five main categories: (1) economic and financial, (2) environmental, (3) capacity and reliability, (4) information and communication and (5) safety and security. To further refine the category of capacity and reliability, we practically decomposed it into descriptive, ratio, and total aspects.

It became apparent that each KPI places different levels of priority on the perspectives of stakeholders involved in IWT systems. We found that focussing on a specific indicator often resulted in conflicting interests and trade-offs between stakeholders, as their values and priorities tend to misalign.

We also observed a recent increase in attention given to the environmental performance of IWT, which consequently elevated the significance of environment-related KPIs. One commonly used metric to assess effectiveness from an environmental perspective is the measurement of $CO_2$ emissions.

Additionally, we adopted the OEE concept from the domain of industrial systems and applied it within the context of waterway locks. The operationalisation of OEE in this context aims to incorporate various factors that impact availability, speed, and quality, providing a comprehensive numerical overview condensed into a single figure.

> **❓ 2nd Sub-question**
>
> What are the main sources of data that can be used to monitor the effectiveness of lock systems?

Several data sources are utilised to monitor the performance of lock systems. To start with, the physical characteristics of the lock chambers play a crucial role in accurately representing the system within a simulation environment. These characteristics enable the calculation of the physical processes involved in the interaction between ships and the lock complex.

Another important data source is the composition of the fleet mix and the seasonal patterns of various fleet types. These factors are critical in testing the capacity bottlenecks concerning the lock system. Operational logs provided by organisations such as RWS are leveraged to generate plausible scenarios for future fleet compositions. Additionally, for future studies, AIS data holds a great potential in capturing real-time fleet movements and providing valuable insights into lock system performance.

Furthermore, maintenance reports and the personal experiences of maintenance personnel are vital sources of information. These reports offer insights into the condition of the lock infrastructure, potential issues, and maintenance requirements. By incorporating these data, decision makers can gain a comprehensive understanding of maintenance needs and their impact on the effectiveness and performance of the lock system.

By utilising a combination of physical characteristics, fleet data, maintenance reports, and personal experiences, researchers and stakeholders can establish a robust monitoring framework for assessing the effectiveness of waterway lock systems. These data sources enable a comprehensive analysis of the system's capacity, operational patterns, and maintenance requirements, facilitating informed decision-making and proactive measures to ensure the optimal functioning of the lock system.

It is worth noting that determining the speed of operations in locks has posed a challenge during the course of this study. This challenge arises from the limited availability of data sources that capture the time aspect of key operational activities, such as the duration required to open or close the doors and to level the water in the lock chambers.

**3rd Sub-question**

What is the impact of deficiencies in effectiveness in lock systems on the performance of the IWT system?

Simulation modelling provides a valuable approach to assess the impact of effectiveness deficiencies on performance. By developing a simulation model that incorporates the relevant policy levers and exogenous factors, it becomes possible to establish the relationship between performance measures and the specific settings within the model. To address the research question, it is crucial to ensure that the simulation model includes events and scenarios that represent deficiencies in effectiveness. A detailed explanation of the conceptual design of such a simulation model can be found in Section 4.3.

By designing experiments in accordance with the research objectives, as discussed in Chapter 5, the impact of deficiencies in the effectiveness of lock systems on the performance of the IWT system is explored. The following remarks can be made:

- As demand increases, the lock condition becomes more critical for maintaining low $CO_2$ emissions and acceptable service levels. This is also evidenced by the disparities in handling capacity observed across the three lock conditions formulated in this study.
- Deteriorating lock conditions are directly linked to increased unpredictability in average waiting times for ships. This highlights the importance of addressing the deficiencies in the lock system to ensure consistent and manageable waiting times, which are essential for user satisfaction and overall system efficiency.

- The concept of baseline OEE emerges as a robust maintenance-oriented metric. It emphasises that effective maintenance strategies can mitigate the negative impact of deficiencies in lock systems, leading to improved handling capacity, reduced passage times, and lower CO2 emissions. As a general rule of thumb, a 1-point improvement in baseline OEE corresponds approximately to 1.2%-1.5% improvement in waiting times and $CO_2$ emissions, This underlines the practical significance of baseline OEE as a benchmark for improving performance outcomes.

**❓ 4th Sub-question**

What are the right action points for RWS given budget considerations, deficiencies in effectiveness in Volkerak locks and their impacts on the IWT performance?

An important remark concerns the use of indicators. We argue that the baseline OEE formulation, which includes the speed of operation, is better suited to supporting maintenance decisions than the sole availability of the infrastructure. By recognising slowdowns as losses in effectiveness and extending the monitored indicator to include slowdowns, more informed decisions can be made about periodic inspections.

The results indicate a trade-off between preventive and corrective maintenance efforts. In more severe lock conditions, the need for faster repair and more frequent inspection strategies becomes more apparent, or the lock's handling capacity is challenged, with waiting times more likely to exceed acceptable levels.

A prominent dilemma of lock systems is the trade-off between transit times and the number of levels. The lock regimes examined in this study reflect this trade-off, and a shift towards reduced waiting times will result in more levellings, and therefore higher operating costs. However, we also report some points of consideration that can improve both indicators without compromise. Two of these points are (i) increasing the range of traffic and (ii) considering the current state of the system when selecting lock chambers for new arrivals.

**❓ Main Research Question**

How can the effectiveness of waterway locks be assessed to support lock maintenance and operation?

Performance measurement and the development of effectiveness metrics may provide valuable insights for decision-makers in waterway lock systems. The baseline OEE formulation, proposed and investigated in this study, serves as an exemplary metric. It offers an indication of potential improvements in KPIs, such as average passage times and emissions. By assessing the availability and speed of operations, the baseline OEE not only serves as an alarm mechanism to alert decision makers when performance falls below acceptable limits, but also triggers investigations into how to achieve performance enhancements. These investigations are closely related to decision-making processes related to lock maintenance and operation, such as inspection frequencies and locking regimes.

It is important to highlight that decision-making in waterway lock systems requires careful consideration and balancing of conflicting performance aspects. Rather than relying on a single numeric value, it is important to utilise a set of indicators that monitor and evaluate the various interests and priorities involved. This holistic approach allows decision makers to navigate the trade-offs and complexities inherent in optimising lock performance while considering multiple factors and stakeholder perspectives.

## 8.2. Policy recommendations

The first recommendation that can be made in light of the results of this study concerns inherently conflicting KPIs. This implies that optimising for an indicator, such as the occupancy, might have severe implications on the others, such as on the emissions. It is important to identify, for given lock and traffic conditions, where the desired balance lies. Simulation, offers benefits in seeking this balance.

Events that impact availability and speed in locks result in an increase in waiting times and emissions, two indicators that bring together the interests of several stakeholders such as the owner of the IWT infrastructure, fleet operators, and environmental groups. For example, if the baseline OEE is to be improved by 4% from 86% to 90%, this results in an overall reduction of 5-6% in average waiting times and emissions. The effect of OEE on waiting times and emissions becomes even more notable with increasing traffic intensity. The explanatory power of the baseline OEE exceeds those of the availability and speed components alone. There might be an opportunity to use baseline OEE requirements in maintenance contracts as a replacement of the widely-used availability score.

For operational policies, service-based OEE creates similar potential. Currently, the service level is monitored for the lock systems in the waterway network (Interview B. When the service level is below expectations, the lock complex receives more attention initially to diagnose the problem and later to solve it. Service-based OEE, offering a stronger alignment with waiting times and $CO_2$ emissions, can serve the same purpose. Such a composite index facilitates the recognition of losses due to unavailability and reduced speed.

## 8.3. Future research

In this research, we followed an exploratory approach to investigate the relationship between various factors and indicators. Future research can follow with more accurate measurements of input data to formulate precise action points to balance conflicting interests and improve the performance of the system in an intended direction.

A promising extension of this research would concern modelling multiple lock systems in a network, rather than focussing on one. In this way, it becomes possible to analyse rippling effects, the impact of which is even greater than isolated deficiencies in effectiveness (Ylipää et al., 2017). This could provide a ground for experiments that involve the optimisation of candidate indicators over the network, which would provide valuable insight for budget allocation decisions (Interview B).

Furthermore, in future research, it is essential to incorporate the impact of climate change on water levels and its consequences for lock systems. Low water levels pose an increasingly relevant threat linked to the severity of climate change. In 2018, the Rhine river experienced one of the most extreme low-water events in the last 50 years (CCNR, 2021). Some segments of the waterway became unavailable due to safety concerns related to UKC. It also reduced transport efficiency, as ships were forced to travel below their ideal speed and loading capacity (CCNR, 2021). Due to the increased draught-to-water depth ratio, the resistance to water and therefore the fuel consumption per kilometre rose. In this research, we used fixed water heights and did not

Another area of improvement lies in the proactivity of the maintenance action in waterway lock systems. This can draw inspiration from other fields, such as manufacturing and elevator systems, where scholars have successfully used technological equipment and mathematical techniques to detect and evaluate failure risks (Borucka & Grzelak, 2019; Dobra & Jósvai, 2022; Kozłowski et al., 2019; Yan & Lee, 2004).

In this research, we mainly reported averages of performance indicators, such as average waiting and lockage times. This approach, leading observations of short waiting times evening out extremes, overlooks variability, and no context remains available about the justness of the service. Future research can expand on variability of indicators, maximum values observed.

# Part IV.

# Bibliography and Appendices

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# A. Literature Review Strategies

## A.1. Metrics in IWT

| | Scopus | Web of Science | IEEE Xplore | ScienceDirect [1] |
|---|---|---|---|---|
| transport* OR logistic* OR navigat* OR ship* OR freight* | TITLE | Title | Document Title | Title |
| waterway OR waterborne OR maritime OR river* | TITLE-ABS-KEY | Topic | All Metadata | Title, abstract or author-specified keywords |
| metric* OR indicator* OR measurement* | TITLE-ABS-KEY | Topic | All Metadata | Title, abstract or author-specified keywords |
| effectiveness OR performance OR efficiency OR reliability OR resilience OR productivity OR utilization | TITLE-ABS-KEY | Topic | All Metadata | Find articles with these terms |
| lock* OR infrastructure | TITLE-ABS-KEY | Topic | All Metadata | Find articles with these terms |
| Number of resulting entries | 48 | 73 | 14 | 61 |
| Number of new entries | 45 | 49 | 8 | 55 |

The list of entries was filtered on the basis of abstract relevance. Snowballing was used to include new articles.

[1] Advanced Search function of ScienceDirect allows for extensive searching of the entire documents excluding references (Elsevier, 2021). However, this function has two limitations compared to other more established search platforms like Scopus, Web of Science and IEEE Xplore. Firstly, it does not allow using more than 8 boolean connectors per search field. Therefore, the terms identified for the literature review were distributed across three search fields in an order of relevance: (1) Title, (2) Title, abstract or author-specified keywords and (3) All parts of the document. Secondly, wildcards are not supported in the query. For that reason, alternatives were generated for terms that were originally searched in a truncated form, such as explicitly searching for (transport OR transportation) instead of using transport*.

## A.2. OEE in transportation

| | Scopus | Web of Science | IEEE Xplore | ScienceDirect |
|---|---|---|---|---|
| transport* OR logistic* OR navigat* OR ship* OR freight* | TITLE-ABS-KEY | Topic | All Metadata | Find articles with these terms |
| oee OR ”overall equipment effectiveness” | TITLE-ABS-KEY | Topic | All Metadata | Find articles with these terms |
| Number of resulting entries | 85 | 88 | 10 | 52 [2] |
| Number of new entries | 82 | 49 | 8 | 51 |

[2]This query initially resulted in 2788 articles. An additional and stricter constraint was introduced to have the word ”transport” included in the title. After this constraint, number of resulting entries were reduced to 52

# B. Interview Summaries

## B.1. Maintenance contractor

Interview with the maintenance contractor Vialis B.V. took place in mid-May 2023 at the Volkerak Complex. The company is dedicated a building on the site where both white and blue collar employees can conduct their daily work. In this building, there are various bulky repair equipment as well as some displays for real-time surveillance of the lock chambers (see Figure B.1).

Figure B.1.: Displays for real-time surveillance of the lock chambers

In the first part of the interview, the participant gave some general information about the company and the facility. Vialis B.V. is in charge of the maintenance of Haringvlietcomplex & Volkerak Complex (HVVOS) for 15 years until the begining of February 2027. The contract is designed based on Probabilistic Management and Maintenance (ProBO, Probabilistisch Beheer en Onderhoud) methodology (Bakker et al., 2010). This methodology is mainly used for safety-critical complex objects, and requires analysis of the risk occurring in case of lack of maintenance and performing maintenance activities in intervals determined accordingly. As the contractor, Vialis B.V. makes operational maintenance decisions. Their aim is to minimize cost given constraints defined by the contract, which are mostly in the form of availability.

There are over 6600 detailed requirements defined in the contract. Most of these requirements are completed, during the realization phase in 2010-2012. Ongoing requirements are being monitored using daily dashboards (see Figure B.2).

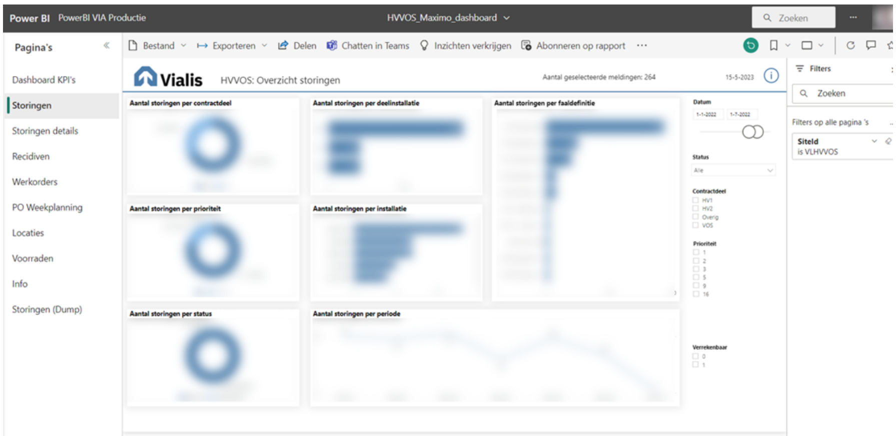



Figure B.2.: Daily dashboards

As with every project, HVVOS also presents opportunities and risks for Vialis B.V. Firstly, there is a potential for future partnerships with RWS. Another opportunity on a more operational basis is about extra work. If there is work demanded by RWS outside the contract scope, additional budget is allocated. Among the risks identified, the most concerning is the need faced for capacity higher than initially planned. As the facility gets older, number of malfunctions are getting higher. This results in additional burden to be born by Vialis B.V.

The second part of the interview related to inspections and workflow in cases of malfunction. Inspections are of two types: electronic and mechanic inspections. For the former, there are sensor installations on each electronic component of the system. These sensors can be inspected using displays (Figure B.3) and they alarm the operator in case of failures. The latter requires in-place evaluations.

Mechanical inspections are carried out periodically. Doors in commercial lock chambers are inspected monthly, quarterly, annually and bi-annually with varying emphasis and level of detail. Preventive maintenance is carried out annually on sliding gates. Software components and hardware installed in lock heads are inspected and serviced on an annual basis.

Vialis B.V. classifies failures into two categories based on priority. Prio 1 failures, which constitute 90% of all malfunctions, are those that result in a state where the system can't function until it is repaired. In those cases, the mechanics is obliged to be in the facility within 1 hour. An example to Prio 1 failure can be displacement of a lock door sensor. If the door is not recognized as closed, leveling can not be initiated. Prio 2 failures, which are around 10%, correspond to failures after which the operation can still continue. In these cases, the mechanics is notified, but receives the notification in the next morning. An example to Prio 2 failure is blurry vision on a redundant camera. Both of these types of failures are almost always easy to

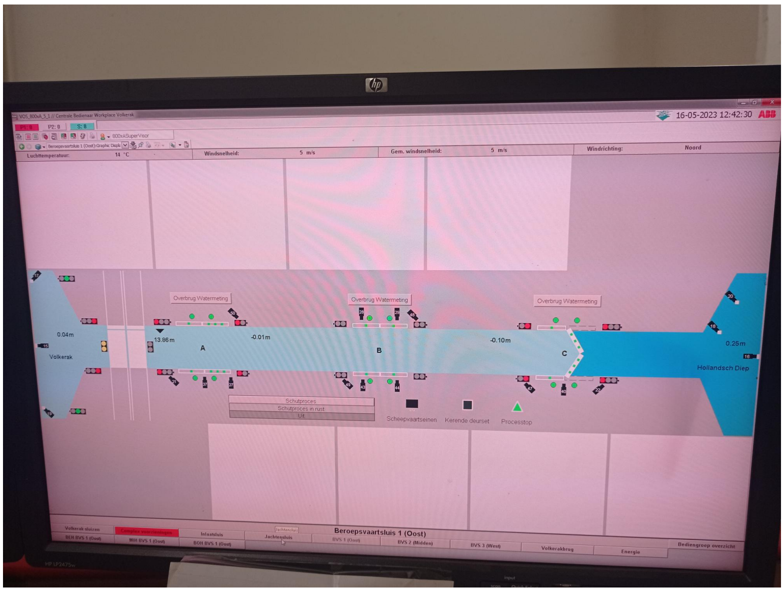



Figure B.3.: Sensors monitored

fix.

In case of malfunctions, the following workflow is executed:

- Lock operator calls the hot-line
- A mechanics is informed and is given a short description of the issue (e.g., one of the doors is not opening)
- The mechanics calls back the operator, has to be there in 1 hour
- The mechanics logs the error themselves on a shared system (see Figure B.4), and then decide on how to fix it
- The mechanics fills a form to register how long the repair took, what they did
- Service coordinator checks everything in the end

These logs are inspected by the maintenance engineer, and a report is compiled 2 times a year, explaining the malfunctions and conformance to the contract. Items in this report concern contractual requirements for commercial and recreational shipping (hours required, percentage) as well as some indicators that are of interest, such as percentage of maintenance performed on time and number of failures.

The last part of the interview concerned the causes of failures in the system. This discussion is used for the Ishikawa diagram shown in Figure 3.4. It was noted that one of the most recent and impactful disturbances in operation was related to door flutter. Particulary two of the door sets experienced significant unavailability in the second half of 2022. These malfunctions were often due to conflicting pre-notifications, where the sensor was no longer correctly positioned in front of the detection plate. In such cases, operators would try to open/close the door

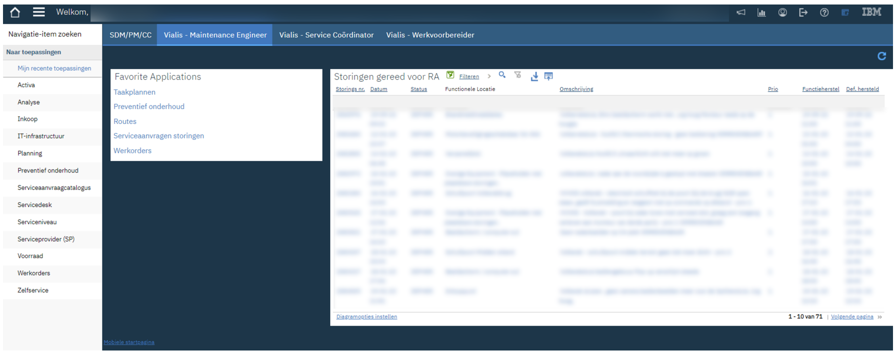



Figure B.4.: Malfunction registration system

again. If the fault reoccurs, maintenance is called and the above workflow is followed. After the mechanic has readjusted the sensor in relation to the detection plate, the fault would occur again after some time. This again results in a relatively long period of unavailability. These faults have occurred on these heads after the doors have been replaced. The doors appear to move slightly. On head F, a few centimetres of play were observed at the point of engagement.

## B.2. Rijkswaterstaat: Asset management

The main function of asset management is to provide a clear overview to support the allocation of the maintenance budget in the most efficient way, considering the whole network. Following workflow is adopted to generate insight (Rijkswaterstaat, 2023a):

- Step 1. Map the area
- Step 2. Dividing our area into network links
- Step 3. Analysis of the performance level of each component
- Step 4. Creating scenarios per network link
- Step 5. Risk Analysis
- Step 6. Cost analysis
- Step 7. Presenting the scenarios to the client
- Step 8. Execution of the choices made
- Step 9. Deployment and management of market parties

One of the main challenges is clustering the network into meaningful units, called network links ("netwerkschakels" in Dutch). For instance, the Volkerak complex is between the Sea and Delta and the South West Netherlands units. There are constant efforts to improve definitions of these network links, which are the working units of the maintenance strategies. By using network simulation tools, scenarios are formulated by changing the levels of maintenance in different network links. The scenarios that are ultimately selected are implemented by Rijkswaterstaat (Rijkswaterstaat, 2010). It is important to ensure that the decisions are made to optimise for the whole network.

Asset management also searches for new formulations for the indicators. Currently, they are monitoring availability for their relationship with the maintenance contractor, and service level for the lock performance. In cases of deviations from the acceptable ranges, they reach out to relevant parties to investigate the issue. From the asset management perspective, availability is the percentage of time where none of the chambers are available, which is a formulation that is recently being challenged. They also acknowledge that emission related objectives are likely to become more central in their analyses.

# C. Flow Diagram

## C.1. Lock passage

Below is a flow diagram reprinted from Waterway Guidelines by Rijkswaterstaat, Centre for Transport and Navigation (2011) depicting the passage of a vessel through a lock.

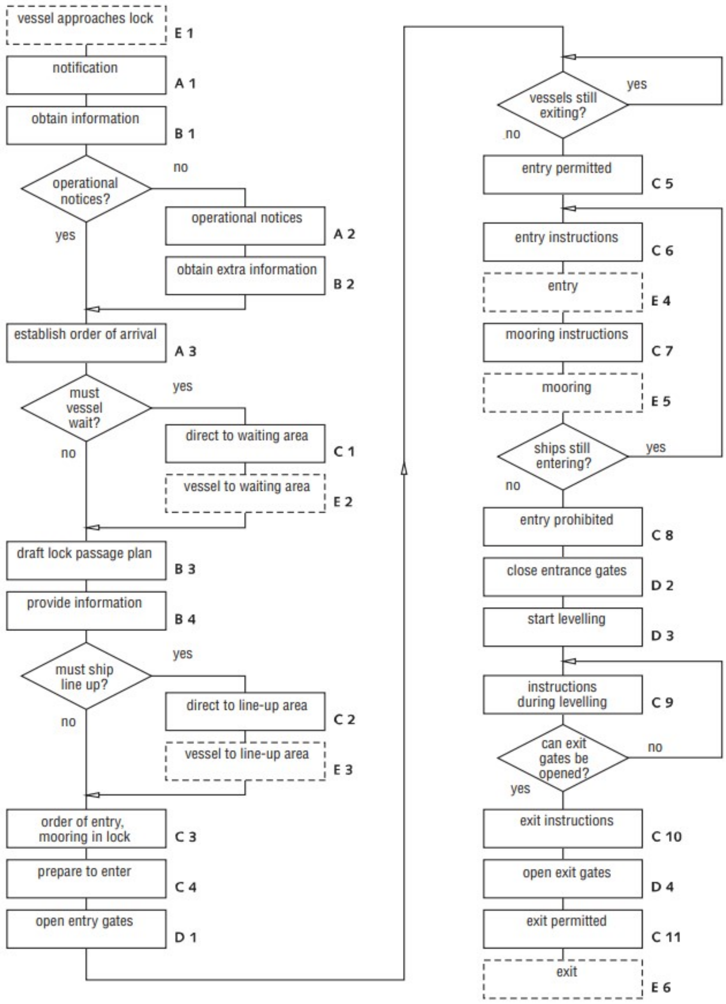
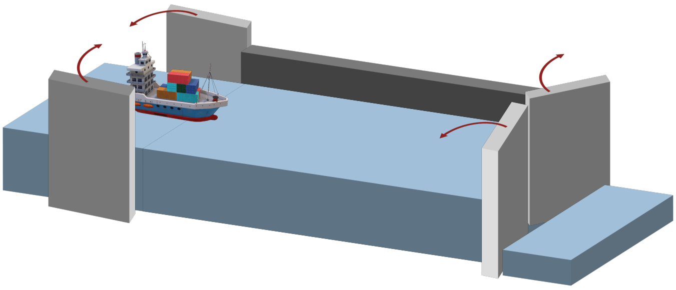


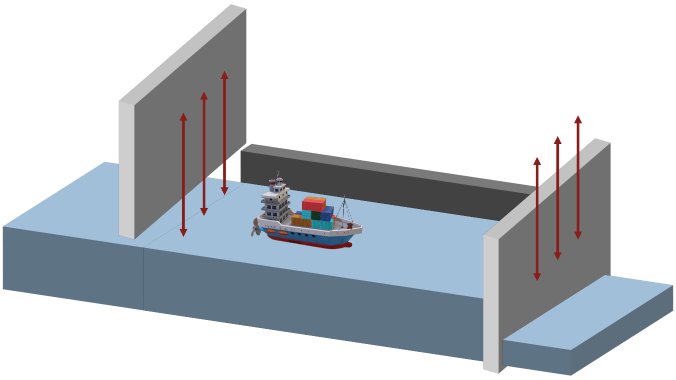

Figure C.1.: Flow diagram of lock passage of a vessel

# D. Technical design of the lock

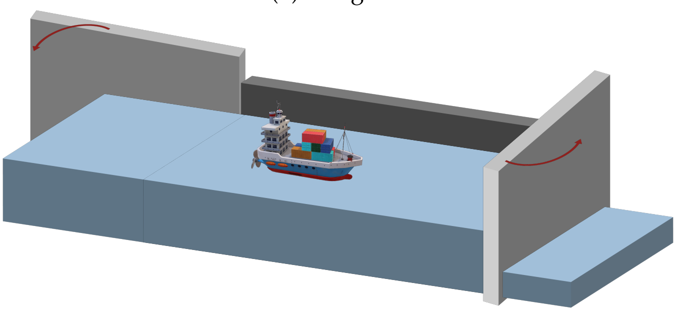
There are two main defining characteristics of lock designs: (Vrijburcht, 2000b).



(a) Mitre gates



(b) Lift gates



(c) Pivot gates

Figure D.1.: Types of gates

# E. Verification and Validation

## E.1. Verification

### E.1.1. Fluttering and repair

The fluttering event is modelled as a binomial distribution with a given probability. Using normal approximation to the binomial distribution, it is possible to calculate the expected number of fluttering events in a run, as well as the theoretical standard deviation. The following table is generated using a scenario where the probability of flutter $p = 0.015$. At the p-value 0.05, both Shapiro-Wilk and Kolmogorov-Smirnov tests do not provide enough evidence to reject the hypothesis that standardised values of observations (z-scores) are normally distributed.

Table E.1.: Fluttering observations in replications

| Rep. | Number of door opening & closing $N$ | Observed number of flutters $x$ | Expected number of flutters $\mu = p * N$ | Standard deviation $\sigma = \sqrt{N * p * (1 - p)}$ | Standardised value of observation $z = (x - \mu)/\sigma$ |
|---|---|---|---|---|---|
| 1 | 7228 | 122 | 108.42 | 10.33 | 1.31 |
| 2 | 7033 | 110 | 105.50 | 10.19 | 0.44 |
| 3 | 7184 | 128 | 107.76 | 10.30 | 1.96 |
| 4 | 7122 | 118 | 106.83 | 10.26 | 1.09 |
| 5 | 7137 | 79 | 107.06 | 10.27 | -2.73 |
| 6 | 7214 | 112 | 108.21 | 10.32 | 0.37 |
| 7 | 7142 | 113 | 107.13 | 10.27 | 0.57 |
| 8 | 7057 | 123 | 105.86 | 10.21 | 1.68 |
| 9 | 7064 | 111 | 105.96 | 10.22 | 0.49 |
| 10 | 7145 | 102 | 107.18 | 10.27 | -0.50 |
| 11 | 7109 | 91 | 106.64 | 10.25 | -1.53 |
| 12 | 7118 | 93 | 106.77 | 10.26 | -1.34 |
| 13 | 7179 | 117 | 107.69 | 10.30 | 0.90 |
| 14 | 7095 | 102 | 106.43 | 10.24 | -0.43 |
| 15 | 7180 | 114 | 107.70 | 10.30 | 0.61 |

Kolmogorov-Smirnov test is used for the duration of the repair events that took place during these 15 replications. At a significance level of 0.05, the Kolmogorov-Smirnov test did not provide sufficient evidence to reject the hypothesis that they follow an exponential distribution in accordance with the rate input.

Model traces and logs are also inspected to follow the execution of fluttering-related events. Table E.2 displays a selection of logs durin a replication

Table E.2.: Observation of fluttering in simulation logs

| Time | Chamber | Levelling ID | Ship | Description |
|---|---|---|---|---|
| 10:51 | West | 1029 | - | Doors open on side 2. |
| 10:51 | West | 1029 | Ship.6226 | Leaving chamber. |
| 10:53 | West | 1029 | Ship.6226 | Left chamber. |
| 10:53 | West | 1029 | Ship.6833 | Leaving chamber. |
| 10:55 | West | 1029 | Ship.6833 | Left chamber. |
| 10:55 | West | 1029 | Ship.6792 | Leaving chamber. |
| 10:57 | West | 1029 | Ship.6792 | Left chamber. |
| 10:58 | West | - | Ship.6085 | Ship has been added to leveling plan on side 2 |
| 10:58 | West | 1030 | Ship.6085 | Entering chamber. |
| 11:01 | West | 1030 | Ship.6085 | Entered chamber. |
| 11:04 | West | - | Ship.6619 | Maximum waiting time exceeded on side 1 |
| 11:04 | West | - | - | Leveling is triggered because maximum waiting time has been exceeded. |
| 11:04 | West | 1030 | - | Doors closing on side 2. |
| 11:07 | West | 1030 | - | Doors fluttered while closing. It will be tried one more time. |
| 11:09 | West | 1030 | - | Doors fluttered while closing. It will be tried one more time. |
| 11:12 | West | 1030 | - | Doors fluttering during closing requires maintenance. Operation stops until repair. |
| 13:58 | West | 1030 | - | Fluttering doors are repaired. |
| 13:58 | West | 1030 | - | Doors closed on side 2. |
| 13:58 | West | 1030 | - | Start Leveling |
| 14:08 | West | 1030 | - | Finished Leveling |
| 14:08 | West | 1030 | - | Doors opening on side 1. |
| 14:10 | West | 1030 | - | Doors open on side 1. |
| 14:10 | West | 1030 | Ship.6085 | Leaving chamber. |
| 14:12 | West | 1030 | Ship.6085 | Left chamber. |
| 14:12 | West | - | - | Leveling is triggered because maximum waiting time has been exceeded. |

### E.1.2. Slowdown and inspection

Animation can be used to monitor the behaviour in the simulation model (Kleijnen, 1995). In this study, status labels supported by display of ships and lock chambers are used as a means of verification for inspections. Figure E.1 shows a screenshot captured from Simio when the simulation clock reached 12:00 am on Monday morning during a scenario where inspections are set to begin at 8:00 AM and take 2 hours per chamber, starting with the East chamber. Visualisation reveals several observations:

1. The East chamber has completed its inspection and is already back in operation. The slowdown counter has been reset.
2. The Middle chamber is currently empty and under inspection. The inspection process is still ongoing as the chamber was occupied at 10:00 AM.
3. Although the West chamber's inspection is scheduled to start, it is currently on hold due to its ongoing activity. The inspection will begin once the levelling process in the chamber is completed.

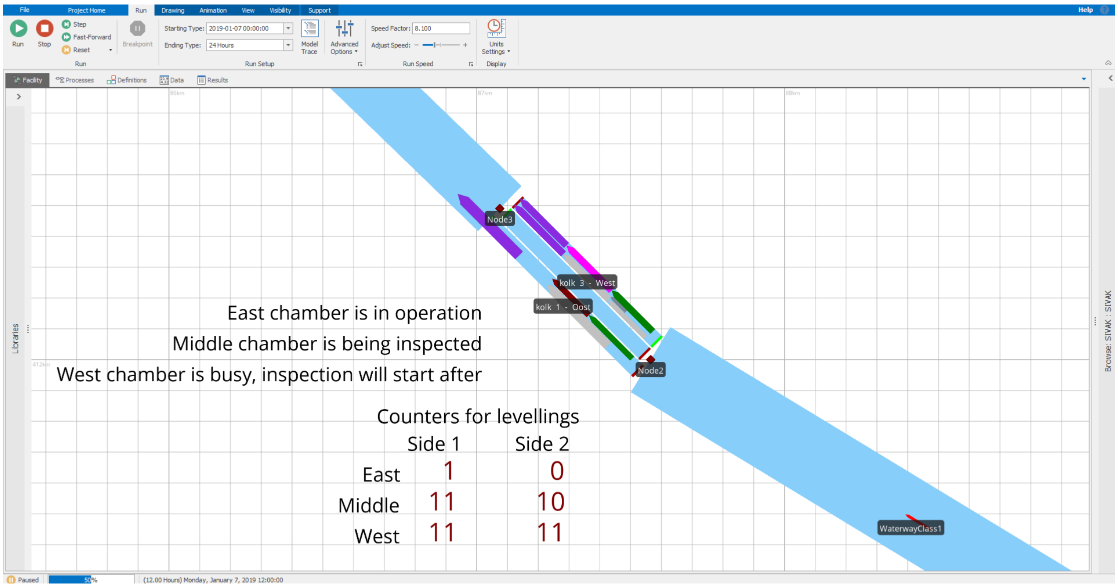



Figure E.1.: SIVAK animation

## E.2. Validation

Using baseline conditions identified in Chapter 5, ten different locking regimes were tested. Resulting histograms of number of ships were inspected. Based on Euclidean distance, the locking regime with 40% and 80% with 10 minutes waiting was selected as the with the closest distribution to the observed histogram.

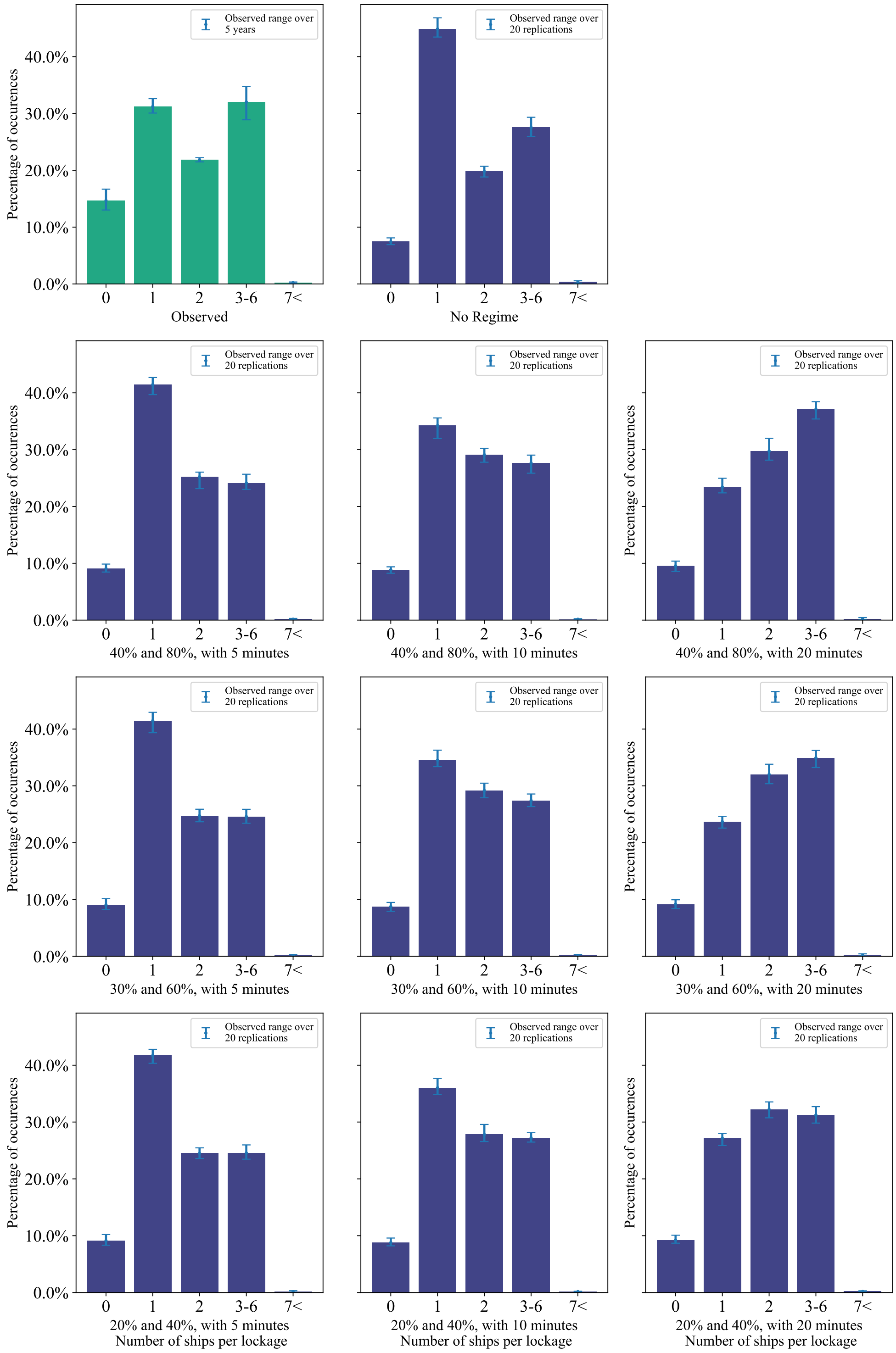



Figure E.2.: Histogram of number of ships per levelling in operational logs and experiments

# F. SIVAK

## F.1. UML Class diagram of SIVAK

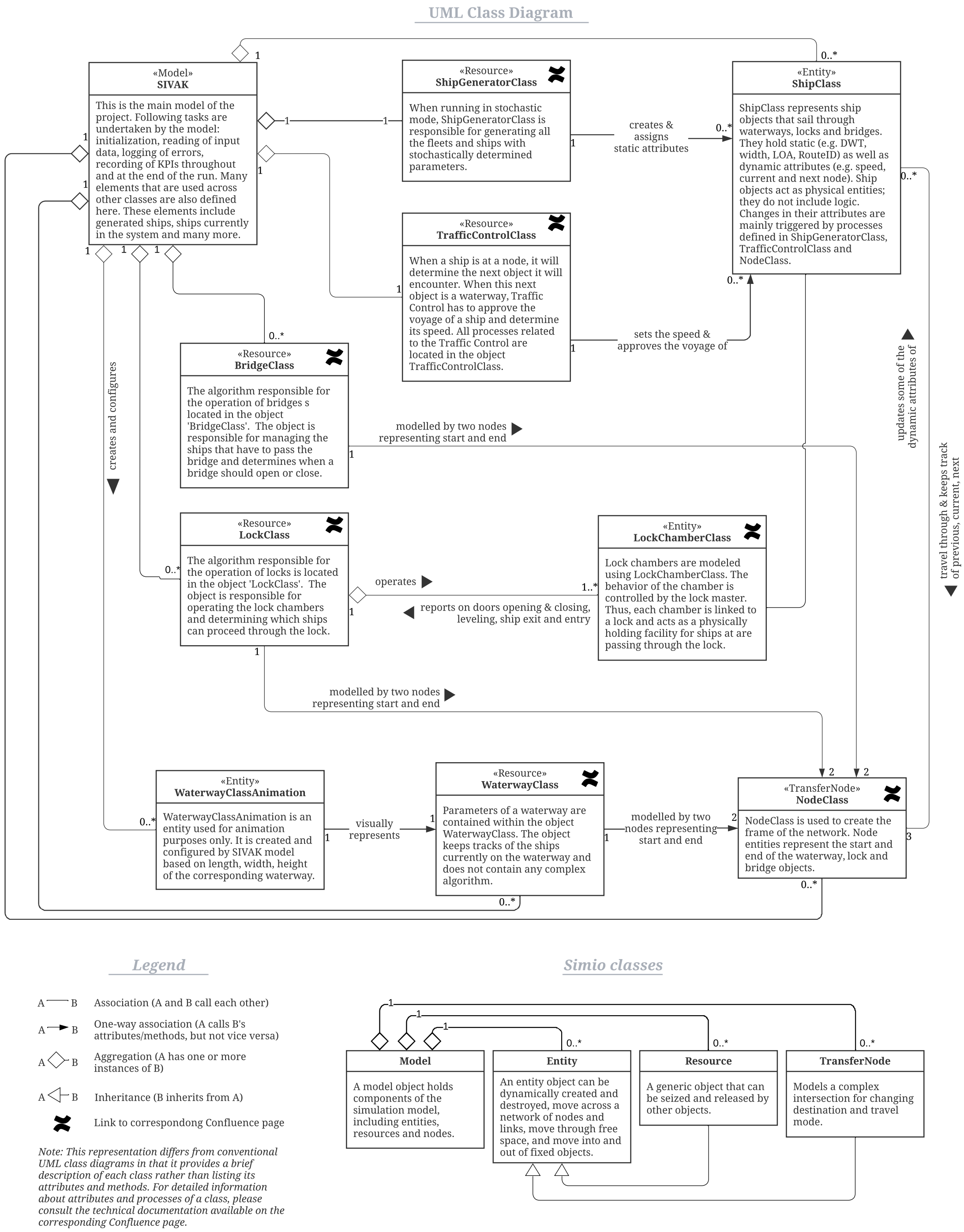



Figure F.1.: UML Class Diagram

## F.2. Modelling of the lockage

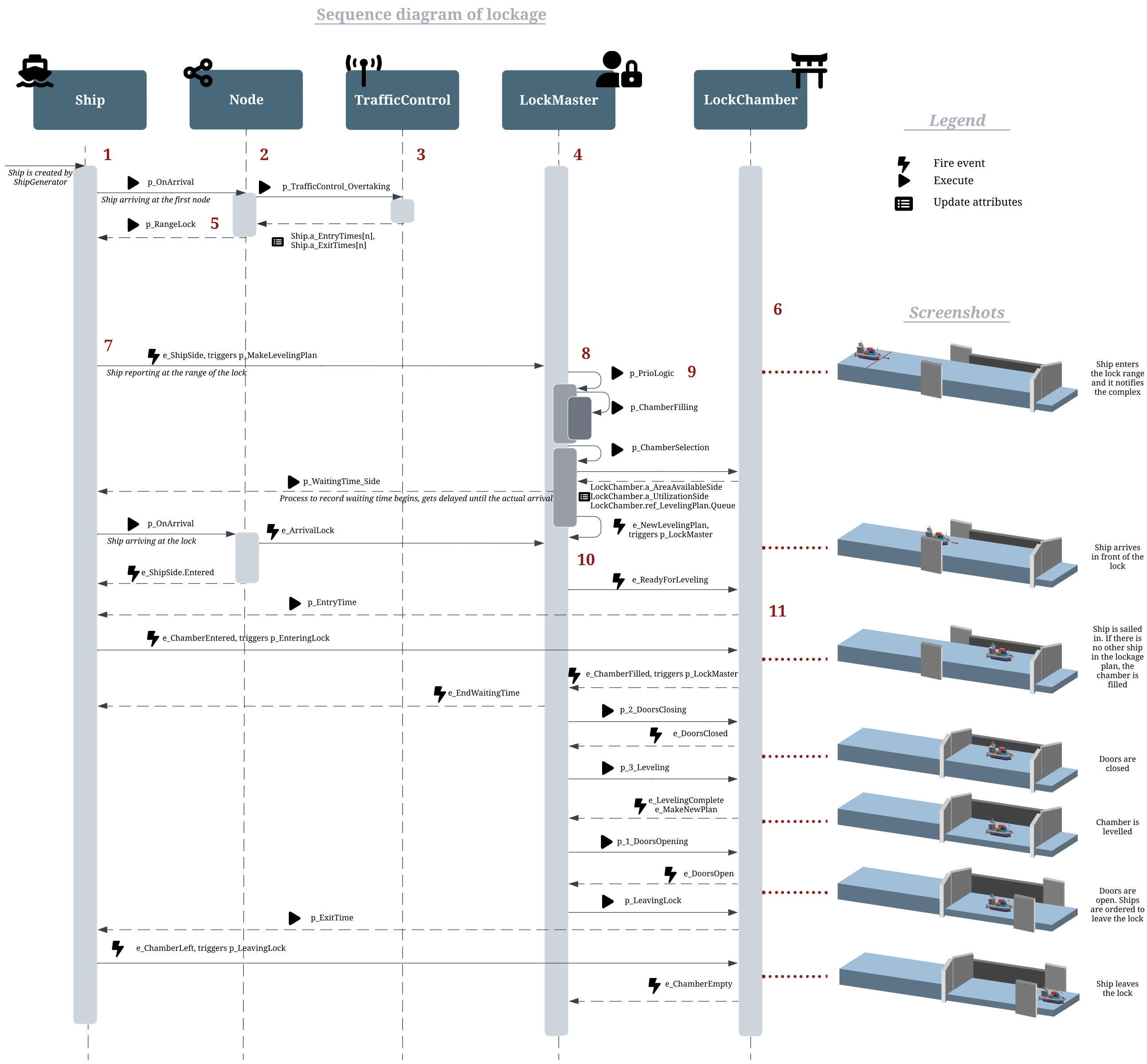



Figure F.2.: Sequence diagram of lockage

Table F.1.: Sequence diagram details

| No. | Explanation |
|---|---|
| 1 | • Ships are generated weekly by p_ShipGenerator_DeterministicRun or p_ShipGenerator, according to run settings. Furthermore, ships are assigned dimensions (DWT, width, LOA), speed (min, max, actual) and route ID.<br>• With SIVAK.p_FindRoute, associated nodes are put in ship's a_Nodes.Queue in the order of sequence. This process also triggers p_FindWaterways and p_LockEstimateArrivalTime.<br>• With SIVAK.p_FindWaterways, objects on the route (waterways, locks, bridges) are put in ship's a_Objects.Queue.<br>• SIVAK.p_LockEstimateArrivalTime calculates ETA based on minimum and maximum speed of the waterway and ship class. |
| 2 | • Node.p_OnArrival triggers one of the following based on the next object: Node.p_OnArrival_Waterway or Node.p_OnArrival_Lock.<br>• Node.p_OnArrival_Waterway executes several TrafficControl process, the most important being p_TrafficControl_Overtaking, where entry and exit times are calculated for all the objects on the route. |
| 3 | • With SIVAK. p_LockEstimateArrival, ShipClass.a_ArrivalTimeAtObject is assigned.<br>• p_TrafficControl_Waterway (using p_TrafficControl_SetShipSpeed) sets the ship speed.<br>• With p_TrafficControl_Overtaking process, TrafficControl calculates more accurate entry and exit times, kept in a_EntryTimes[n] and a_ExitTimes[n] vectors of the ship. |
| 4 | • Two processes are always active for a lock:<br>  – p_LockMaster: This process is initially triggered by LockChamber.OnCreated. Tokens representing lock chambers loop through the process. p_LockMaster is in charge of orchestrating lock chamber operations (opening of the doors of the lock chamber, letting ships leave and enter, closing). Whenever there is a new leveling plan sketched by p_MakeLevelingPlan, p_LockMaster checks whether the criteria is met for the plan.<br>  – p_MakeLevelingPlan: This process is executed twice by Lock.OnRunInitialized, one for each side. Tokens corresponding to sides loop through p_MakeLevelingPlan throughout the simulation. This process looks at the lock complex from a higher perspective, overseeing all the chambers. It is in charge of selecting chambers based on prioritization and inserting ships into leveling plans, by orchestrating processes such as p_PrioLogic and p_ChamberSelection. |
| 5 | • A simple interpolation is used to calculate the duration of the trip between the start of the waterway and the reporting range based on<br>  – the length of the waterway,<br>  – duration of the trip between the start and the end of the waterway (calculated by a_EntryTimes[n] and a_ExitTimes[n]),<br>  – the length between the start of the waterway and the reporting range |
| 6 | • Token representing the chamber waits in p_EnteringLock until new ship arrivals or criterion reached. |
| 7 | • p_CheckAllowed and p_CheckDimensions are executed before reporting event takes place.<br>• Reporting at the lock occurs through e_ShipSide1 or e_ShipSide2 events. |
| 8 | • e_ShipSide1 and e_ShipSide2 events trigger p_MakeLevelingPlan process.<br>• Based on priority selection for the lock, this process calls p_PrioLogic1Area, p_PrioLogic2Avai, p_PrioLogic3Fill or p_PrioLogic4Cust.<br>• p_PrioLogic processes search through Ship.a_AllowedChambers.Queue. This search aims at finding the chamber with the best fit given priority selection and conditions. For instance, if the prioritization criteria is area, the search step minimizes the expression LockChamber.a_Area for chambers with matching conditions. Matching conditions are as follows:<br>  1. Chambers with available area greater than the ship area<br>  2. Side is not blocked<br>  3. Ship class is allowed for the chamber<br>  4. Chamber is levelled at the side of the ship<br>• If there is no chamber meeting all these requirements, the fourth rule is waived and the search is repeated. |
| 9 | • Before concluding that the chamber can be selected, p_ChamberFilling process is executed. This process is needed, because areas of the chamber and the ship are not enough to conclude that the ship would fit.<br>• If addition of the ship into the chamber is not immediately possible, p_ChamberOptimization process is executed. This process looks for alternative formations in the chamber.<br>• Either 1 or 0 is returned by p_ChamberFilling, indicating whether chamber can be selected. |
| 10 | • p_LockMaster checks whether the criteria are met for the leveling plan. If there is no regime, this check is done directly in p_LockMaster. If there is a locking regime defined, p_LockRegime process is called.<br>• If criteria are met, e_ReadyForLeveling event is fired, and the token starts waiting for chamber to be filled. |
| 11 | • For each ship in the leveling plan queue, there is a token created in p_EnteringLock. This token executes p_EntryTime process and cause delays corresponding to ship's entrance in the chamber.<br>• After the delays, e_ChamberEntered event is fired by the token.<br>• When all the ships in the leveling plan are inside the chamber, e_ChamberFilled event is triggered by the token representing the lock chamber. |

### F.2.1. Difference in behaviour between locking regimes

Table F.2.: Locking regime with no requirements

| Time | Chamber | Levelling ID | Ship | Description |
|---|---|---|---|---|
| 0:00 | Middle | | - | Doors opening on side 1. |
| 0:02 | Middle | | - | Doors open on side 1. |
| 0:05 | Middle | | Ship.458 | Ship has been added to leveling plan on side 1 |
| 0:05 | Middle | | - | Leveling is triggered because 1 ships are waiting on side 1 and 0 ships on side 2 |
| 0:13 | Middle | | Ship.458 | Maximum waiting time exceeded |
| 0:13 | Middle | 1 | Ship.458 | Entering chamber. |
| 0:16 | Middle | 1 | Ship.458 | Entered chamber. |
| 0:16 | Middle | 1 | - | Doors closing on side 1. |
| 0:19 | Middle | 1 | - | Doors closed on side 1. |
| 0:19 | Middle | 1 | - | Start Leveling |
| 0:23 | Middle | | Ship.1198 | Ship has been added to leveling plan on side 2 |
| 0:29 | Middle | 1 | - | Finished Leveling |
| 0:29 | Middle | 1 | - | Doors opening on side 2. |
| 0:30 | Middle | | Ship.1198 | Maximum waiting time exceeded |
| 0:31 | Middle | 1 | - | Doors open on side 2. |
| 0:31 | Middle | 1 | Ship.458 | Leaving chamber. |
| 0:33 | Middle | 1 | Ship.458 | Left chamber. |
| 0:33 | Middle | | - | Leveling is triggered because 0 ships are waiting on side 1 and 1 ships on side 2 |
| 0:33 | Middle | 2 | Ship.1198 | Entering chamber. |
| **0:36** | **Middle** | **2** | **Ship.1719** | **Ship has been added to leveling plan on side 2** |
| 0:38 | Middle | 2 | Ship.1198 | Entered chamber. |
| 0:42 | Middle | | Ship.1719 | Maximum waiting time exceeded |
| 0:42 | Middle | 2 | Ship.1719 | Entering chamber. |
| 0:44 | Middle | 2 | Ship.1719 | Entered chamber. |
| 0:44 | Middle | 2 | - | Doors closing on side 2. |
| 0:46 | Middle | 2 | - | Doors closed on side 2. |
| 0:46 | Middle | 2 | - | Start Leveling |
| 0:56 | Middle | 2 | - | Finished Leveling |
| 0:56 | Middle | 2 | - | Doors opening on side 1. |
| 0:59 | Middle | 2 | - | Doors open on side 1. |
| 0:59 | Middle | 2 | Ship.1198 | Leaving chamber. |
| 1:00 | Middle | 2 | Ship.1198 | Left chamber. |
| 1:00 | Middle | 2 | Ship.1719 | Leaving chamber. |
| 1:01 | Middle | 2 | Ship.1719 | Left chamber. |

### F.2.2. Sailing in and out

When a ship enters/leaves the lock chamber, sail-in/-out time is determined based on its resistance. Resistance is calculated as illustrated in Figure F.3. Sail-in and -out times, in both loaded and unloaded cases, are defined for multiple resistance cases, and the exact sail-in/out time of the given ship through the given lock chamber is calculated by using linear approximation of the value from these definitions. Let us assume that there is a loaded BO1 barge, for which the entering times are defined as 5.9 minutes if the fraction is 0.2, 10.0 minutes if the fraction is 0.6 and 13.6 minutes if the fraction is 0.8. This shows that as the vessel's fit into the chamber becomes more challenging given its dimensions, it takes more time to sail in. If the resistance for the barge is 0.7, sailing in will take 11.8 minutes.

Table F.3.: Locking regime with 40% and 80% utilisation requirement, 10 minutes waiting

| Time | Chamber | Levelling ID | Ship | Description |
|---|---|---|---|---|
| 0:00 | Middle | | - | Doors opening on side 1. |
| 0:02 | Middle | | - | Doors open on side 1. |
| 0:05 | Middle | | Ship.458 | Ship has been added to leveling plan on side 1 |
| 0:13 | Middle | 1 | Ship.458 | Entering chamber. |
| 0:13 | Middle | | - | Leveling is triggered because maximum waiting time will be exceeded when next ship arrives. |
| 0:16 | Middle | 1 | Ship.458 | Entered chamber. |
| 0:16 | Middle | 1 | - | Doors closing on side 1. |
| 0:19 | Middle | 1 | - | Doors closed on side 1. |
| 0:19 | Middle | 1 | - | Start Leveling |
| 0:23 | Middle | | Ship.1198 | Ship has been added to leveling plan on side 2 |
| 0:29 | Middle | 1 | - | Finished Leveling |
| 0:29 | Middle | 1 | - | Doors opening on side 2. |
| 0:31 | Middle | 1 | - | Doors open on side 2. |
| 0:31 | Middle | 1 | Ship.458 | Leaving chamber. |
| 0:33 | Middle | 1 | Ship.458 | Left chamber. |
| 0:33 | Middle | | - | Leveling is triggered because maximum waiting time will be exceeded when next ship arrives. |
| 0:33 | Middle | 2 | Ship.1198 | Entering chamber. |
| **0:36** | **West** | | **Ship.1719** | **Ship has been added to leveling plan on side 2** |
| 0:38 | Middle | 2 | Ship.1198 | Entered chamber. |
| 0:38 | Middle | 2 | - | Doors closing on side 2. |
| 0:40 | Middle | 2 | - | Doors closed on side 2. |
| 0:40 | Middle | 2 | - | Start Leveling |
| 0:50 | Middle | 2 | - | Finished Leveling |
| 0:50 | Middle | 2 | - | Doors opening on side 1. |
| 0:53 | Middle | 2 | - | Doors open on side 1. |
| 0:53 | Middle | 2 | Ship.1198 | Leaving chamber. |
| 0:55 | Middle | 2 | Ship.1198 | Left chamber. |

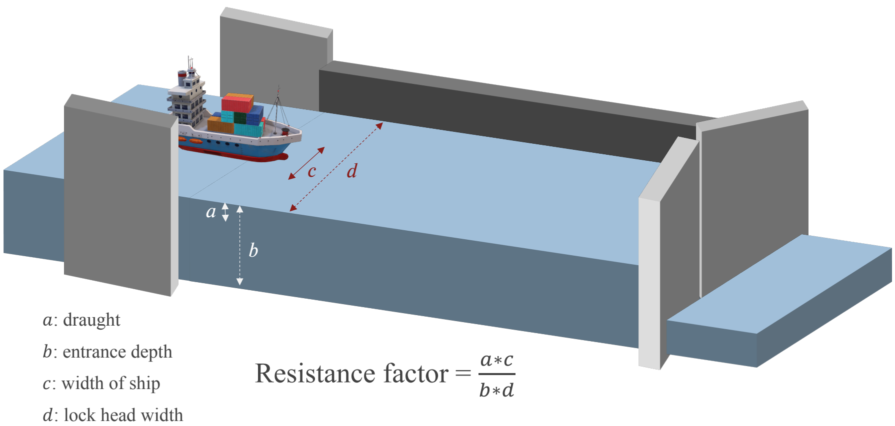



Figure F.3.: Resistance factor during lock entrance

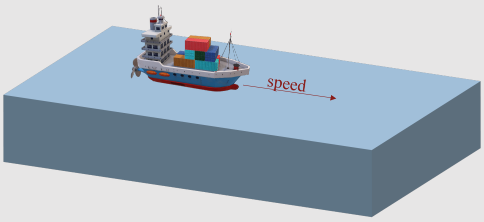
## F.2.3. Cone ships

Ships that are loaded with flammable or potentially harmful goods are required to sail in with 1 cone or 2 cones, respectively, Higher safety allowances are given to those ships while placing them in the chamber.

## F.3. Emission calculations

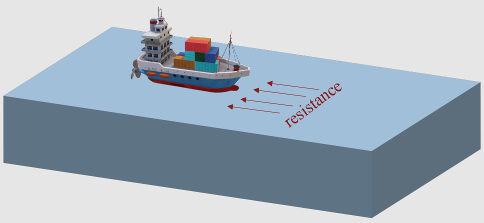
**1. The sailing speed through the water**

Expected speed through the water is given as the minimum of:
- desired speed, which is the maximum speed determined by either the channel requirements or the characteristics of the vessel
- low water speed,
- 90% of theoretical maximum speed (limit speed)



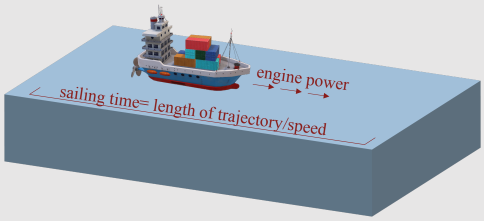

**2. Resistance of the ship at that speed in the given link**

Total water resistance is sum of the following components:
- Friction: calculated using length, width and draft of the vessel
- Resistance increase in shallow water: calculated using decrease in water level, ratio of the vessel cross-section (width × draft) to the channel cross-section, water density
- Residual resistance: calculated using water density, vessel speed, width and maximum draft




**3. Motor power used x the time duration**

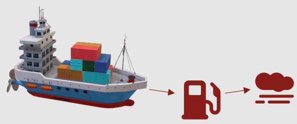
Energy used is calculated as the multiplication of sailing time and engine power.




**4. Amount of fuel and the emissions of fuel-dependent substances**

To convert energy to fuel consumption, the row corresponding to “Fuel type” in “Emission load factor” data table is used.
- Fuel = Energy × diesel factor × partial load factor(Fuel type)

For every substance defined for the given fuel type, fuel factor is retrieved from “Emissions fuel dependent” data table.
- Emission(substance) = Fuel × factor(substance)



**5. Emissions of fuel-independent substances**

It is also possible to define substances that are emitted irrespective of the fuel quantity used, directly linked with energy consumption. This is done through defining new rows corresponding to such substances in “Emission load factor” data table.
- Emission(substance) = Energy × partial load factor(substance)

Figure F.4.: Emission calculation

# G. Model inputs

## G.1. Ship classes

The classification of inland waterway vessels took a significant step forward in 1954 with the adoption of the first international classification system known as the Conférence Européenne des Ministres des Transports (CEMT) (Rijkswaterstaat, Centre for Transport and Navigation, 2011). This system was primarily concerned with commercial navigation and introduced a framework based on the importance of the waterways and the dimensions of the vessels they could accommodate. The classification included two main groups: (1) motor vessels and barges and (2) pushed convoys. Within each group, specific designation guidelines were provided to classify vessels according to the type of waterway for which they were suitable.

| | Type de voies navigables Type of inland waterway | Classe de voies navigables Class of navigable waterway | Automoteurs et chalands Motor vessels and barges | | | | | Convois poussés Pushed convoys | | | | | Hauteur minimale sous les ponts Minimum height under bridges |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Type de bateaux: caractéristiques générales Type of vessel: générales characteristics | | | | | Type de convoi- Caractéristiques générales Type of convoy- Générales characteristics | | | | | |
| | | | Dénomination Designation | Longueur Length | Largeur Beam | Tirant déau Draught | Tonnage Tonnage | | Longueur Length | Largeur Beam | Tirant déau Draught | Tonnage Tonnage | |
| | | | | m | m | m | t | | m | m | m | t | m |
| D'INTERET REGIONAL | OF REGIONAL IMPORTANCE | I | Péniche Barge | 38.50 | 5.05 | 1.80-2.20 | 250-400 | | | | | | 4.00 |
| | | II | Kast-Caminois Campine-Barge | 50-55 | 6.60 | 2.50 | 4.00-650 | | | | | | 4.00-5.00 |
| | | III | Gustav Koenings | 67-80 | 8.20 | 2.50 | 650-1000 | | | | | | 4.00-5.00 |
| D'INTERET INTERNATIONAL | OF INTERNATIONAL IMPORTANCE | IV | Johan Welker | 80-85 | 9.50 | 2.50 | 1000-1500 | | 85 | 9.50 | 2.50-2.80 | 1250-1450 | 5.25/or 7.00 |
| | | Va | Grand bateaux Rhenands/Large Rhine Vessels | 95-110 | 11.40 | 2.50-2.80 | 1500-3000 | | 95-110 | 11.40 | 2.50-4.50 | 1600-3000 | 5.25/or 7.00/or 9.10 |
| | | Vb | | | | | | | 172-185 | 11.40 | 2.50-4.50 | 3200-6000 | |
| | | VIa | | | | | | | 95-110 | 22.80 | 2.50-4.50 | 3200-6000 | 7.10/or 9.10 |
| | | VIb | | 140 | 15.00 | 3.90 | | | 185-195 | 22.80 | 2.50-4.50 | 6400-12000 | 7.10/or 9.10 |
| | | VIc | | | | | | | 270-280 193-200 | 22.80 33.00-34.20 | 2.50-4.50 2.50-4.50 | 9600-18000 | 9.10 |
| | | VII | | | | | | | 285 195 | 33.00 34.20 | 2.50-4.50 | 14500-27000 | 9.10 |

Figure G.1.: Classification of ships based on CEMT, reprinted from Rijkswaterstaat, Centre for Transport and Navigation (2011)

Arguing that recent trends in inland navigation were challenging the validity and coverage of the CEMT, RWS designed a new classification for commercial vessels based on the CEMT.

**RWS 2010 Binnenvaartvloot Classificatie**

| CEMT Klasse | Motorvrachtschepen (Motorvessels) | | | | | | | Duwstellen (Barges) | | | | | | | Koppelverbanden (Convoys) | | | | | | | Doorvaart-hoogte* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | RWS Klasse | Karakteristieken maatgevend schip** | | | | Classificatie | | RWS Klasse | Karakteristieken maatgevend duwstel** | | | | Classificatie | | RWS Klasse | Karakteristieken maatgevend koppelverband** | | | | Classificatie | | incl. 30 cm schrikhoogte |
| | | Naam | Breedte | Lengte | Diepgang (geladen) | Laad-vermogen | Breedte en lengte | | Combinatie | Breedte | Lengte | Diepgang (geladen) | Laadvermogen | Breedte en lengte | | Combinatie | Breedte | Lengte | Diepgang (geladen) | Laadvermogen | Breedte en lengte | |
| | | | m | m | m | t | m | | | m | m | m | t | m | | | m | m | m | t | m | m |
| 0 | M0 | Overig | | | | 1-250 | B<= 5,00 of L<= 38,00 | | | | | | | | | | | | | | | |
| I | M1 | Spits | 5,05 | 38,5 | 2,5 | 251-400 | B= 5,01-5,10 en L>=38,01 | BO1 | | 5,2 | 55 | 1,9 | 0-400 | B<=5,20 en L= alle | C1l | 2 spitsen lang | 5,05 | 77-80 | 2,5 | <= 900 | B<= 5,1 en L=alle | 5,25* |
| | | | | | | | | | | | | | | | C1b | 2 spitsen breed | 10,1 | 38,5 | 2,5 | <= 900 | B=9,61-12,60 en L<= 80,00 | 5,25* |
| II | M2 | Kempenaar | 6,6 | 50-55 | 2,6 | 401-650 | B=5,11-6,70 en L>=38,01 | BO2 | | 6,6 | 60-70 | 2,6 | 401-600 | B=5,21-6,70 en L=alle | | | | | | | | 6,1 |
| III | M3 | Hagenaar | 7,2 | 55-70 | 2,6 | 651-800 | B=6,71-7,30 en L>=38,01 | BO3 | | 7,5 | 80 | 2,6 | 601-800 | B=6,71-7,60 en L=alle | | | | | | | | 6,4 |
| | M4 | Dortmund Eems (L < = 74 m) | 8,2 | 67-73 | 2,7 | 801-1050 | B=7,31-8,30 en L=38,01-74,00 | BO4 | | 8,2 | 85 | 2,7 | 801-1250 | B=7,61-8,40 en L=alle | | | | | | | | 6,6 |
| | M5 | Verl. Dortmund Eems (L > 74 m) | 8,2 | 80-85 | 2,7 | 1051-1250 | B=7,31-8,30 en L>=74,01 | | | | | | | | | | | | | | | 6,4 |
| IVa | M6 | Rijn-Herne Schip (L <= 86 m) | 9,5 | 80-85 | 2,9 | 1251-1750 | B=8,31-9,60 en L=38,01-86,00 | BI | Europa I duwstel | 9,5 | 85-105 | 3,0 | 1251-1800 | B=8,41-9,60 en L=alle | | | | | | | | 7,0* |
| | M7 | Verl. Rijn-Herne (L > 86 m) | 9,5 | 105 | 3,0 | 1751-2050 | B=8,31-9,60 en L>=86,01 | | | | | | | | | | | | | | | 7,0* |
| IVb | | | | | | | | | | | | | | | C2l | Klasse IV + Europa I lang | 9,5 | 170-185 | 3,0 | 901-3350 | B=5,11-9,60 en L=alle | 7,0* |
| Va | M8 | Groot Rijnschip (L <=111 m) | 11,4 | 110 | 3,5 | 2051-3300 | B= 9,61-11,50 en L=38,01- 111,00 | BII-1 | Europa II duwstel | 11,4 | 95-110 | 3,5 | 1801-2450 | B=9,61-15,10 en L<=111,00 | | | | | | | | 9,1* |
| | M9 | Verlengd Groot Rijnschip (L >111 m) | 11,4 | 135 | 3,5 | 3301-4000 | B= 9,61-11,50 en L>= 111,01 | BIIa-1 | Europa IIa duwstel | 11,4 | 92-110 | 4,0 | 2451-3200 | B=9,61-15,10 en L<=111,00 | | | | | | | | 9,1* |
| | | | | | | | | BIIL-1 | Europa II Lang | 11,4 | 125-135 | 4,0 | 3201-3950 | B=9,61-15,10 en L=111,01-146,00 | | | | | | | | 9,1* |
| Vb | | | | | | | | BII-2l | 2-baksduwstel lang | 11,4 | 170-190 | 3,5-4,0 | 3951-7050 | B=9,61-15,10 en L>=146,01 | C3l | Klasse Va + Europa II lang | 11,4 | 170-190 | 3,5-4,0 | 3351-7250 | B=9,61-12,60 en L>=80,01 | 9,1* |
| VIa | M10 | **Maatg. Schip 13,5 * 110 m** | **13.50** | **110** | **4,0** | **4001-4300** | **B=11.51-14.30 en L=38.01- 111.00** | BII-2b | 2-baksduwstel breed | 22,8 | 95-145 | 3,5-4,0 | 3951-7050 | B=15,11-24,00 en L<=146,00 | C2b | Klasse IV + Europa I breed | 19,0 | 85-105 | 3,0 | 901-3350 | B=12,61-19,10 en L<=136,00 | 7,0* alleen voor klasse IV koppelverband |
| | M11 | **Maatg. Schip 14.2 * 135 m** | **14.20** | **135** | **4,0** | **4301-5600** | **B=11.51-14.30 en L>= 111.01** | | | | | | | | C3b | Klasse Va +Europa II breed | 22,8 | 95-110 | 3,5-4,0 | 3351-7250 | B>19,10 en L<=136 | 9,1* |
| | M12 | Rijnmax Schip | 17,0 | 135 | 4,0 | >= 5601 | B>= 14.31 en L>= 38.01 | | | | | | | | | | | | | | | |
| VIb | | | | | | | | BII-4 | 4-baksduwstel (incl. 3-baks lang ) | 22,8 | 185-195 | 3,5-4,0 | 7051-12000 (7051-9000) | B=15,11-24,00 en L=146,01-200 | C4 | Klasse Va + 3 Europa II | 22,8 | 185 | 3,5-4,0 | >=7251 | B>12,60 en L>=136,01 | 9,1* |
| VIc | | | | | | | | BII-6l | 6-baksduwstel lang (incl 5-baks lang) | 22,8 | 270 | 3,5-4,0 | 12001-18000 (12001-15000) | B=15,11-24,00 en L>=200,01 | | | | | | | | 9,1* |
| VIIa | | | | | | | | BII-6b | 6-baksduwstel breed (incl. 5-baks breed) | 34,2 | 195 | 3,5-4,0 | 12001-18000 (12001-15000) | B>=24,01 en L=alle | | | | | | | | 9,1* |

* Bij de klasses I, IV, V en hoger zijn de doorvaarthoogtes aangepast voor 2 respectievelijk 3 en 4-laags containervaart. (doorvaarthoogte op kanalen t.o.v. Maatgevend Hoog Water = 1% overschrijding/jaar)
** De karakteristieken van het maatgevend schip hebben in de lengte een marge van ± 1 meter en in de breedte van ± 10 cm

Opm: 1: Een maatgevend schip is een schip waarvan de afmetingen bepalend zijn voor de dimensionering van de vaarweg en de kunstwerken daarin.
2: Bij nieuwbouw of vaarwegverruiming wordt uitgegaan van het grootste maatgevende schip binnen een CEMT-klasse.
3. Klasse M3, M4, M6, M8, M10 en M11 mag alleen worden toegepast bij renovatie van bestaande vaarwegen, sluizen en bruggen.
4: De kleinste afmetingen van een maatgevend schip vormen de ondergrens om een vaarweg in een bepaalde gestandaardiseerde klasse in te delen.

Figure G.2.: Classification of ships based on RWS, reprinted from Koedijk (2015)

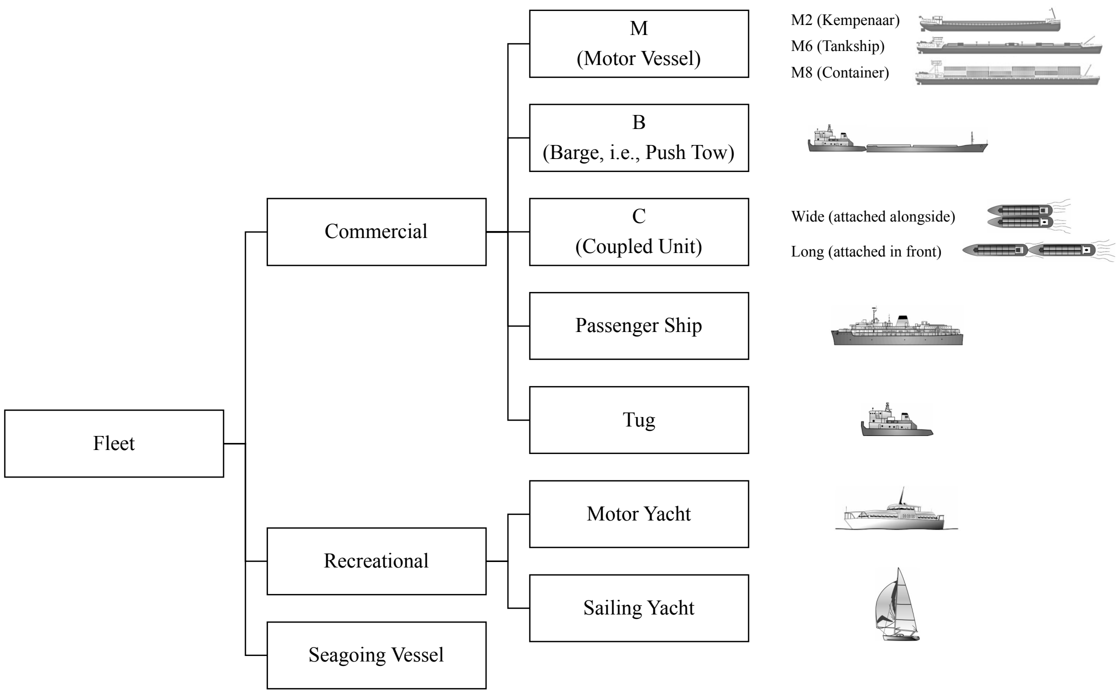



Figure G.3.: Ship groups in SIVAK, graphics reprinted from RWS Dir. Zeeland (2004)

For the operational logs obtained upon request from RWS, the m

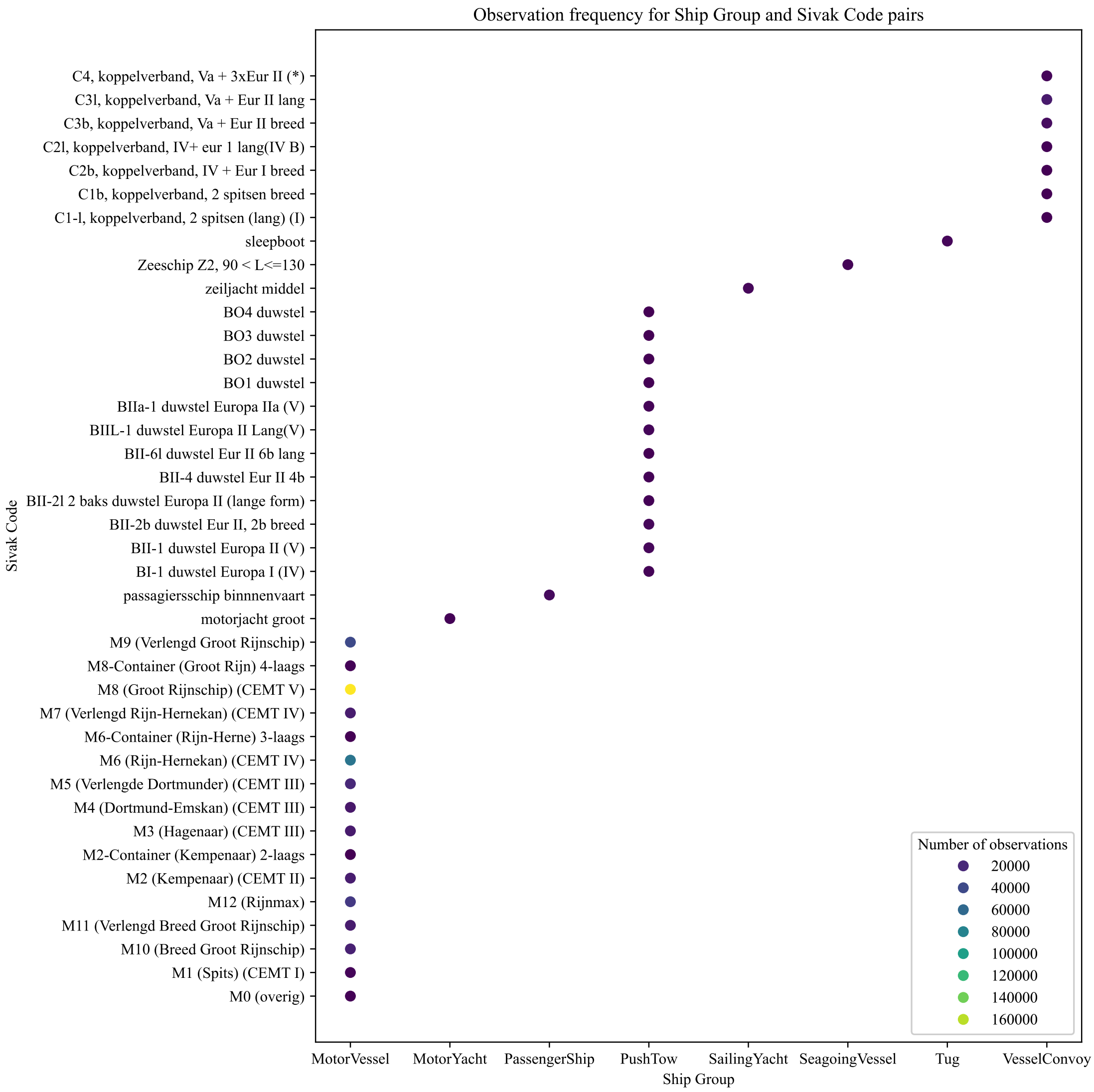



Figure G.4.: Mapping between SIVAK ship groups and ship classes

## G.2. Fleet mix

### G.2.1. Predicting future arrivals

The first step of the prediction concerns an investigation of seasonality in observations. Weekly arrival intensities are laid out for the years for every ship class, and clustering is performed on these ship classes. The elbow method suggests that the ship classes can be clustered into three groups based on their seasonality.

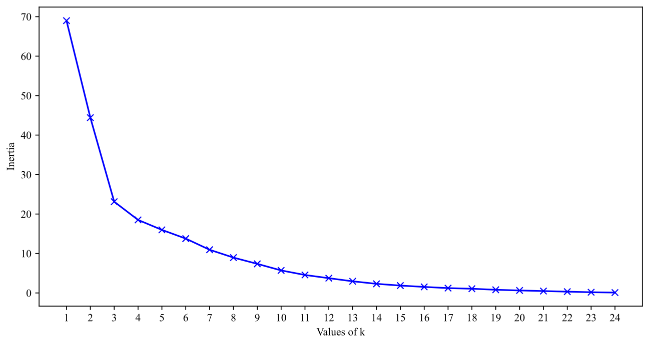



Figure G.5.: Clusters

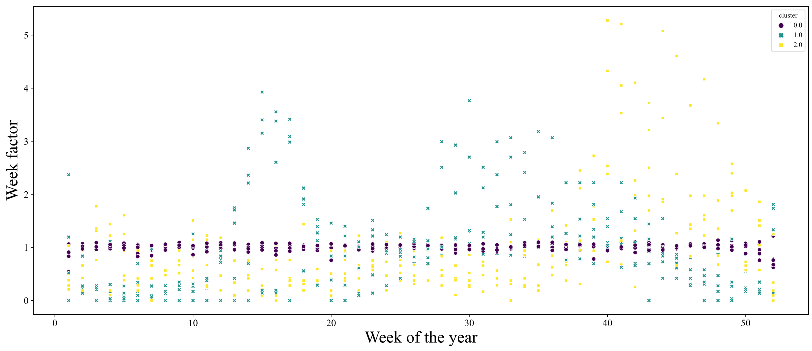
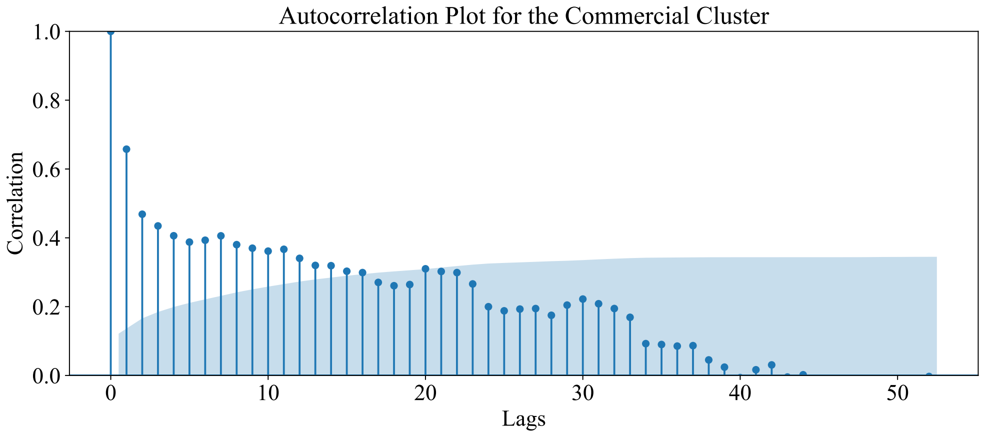
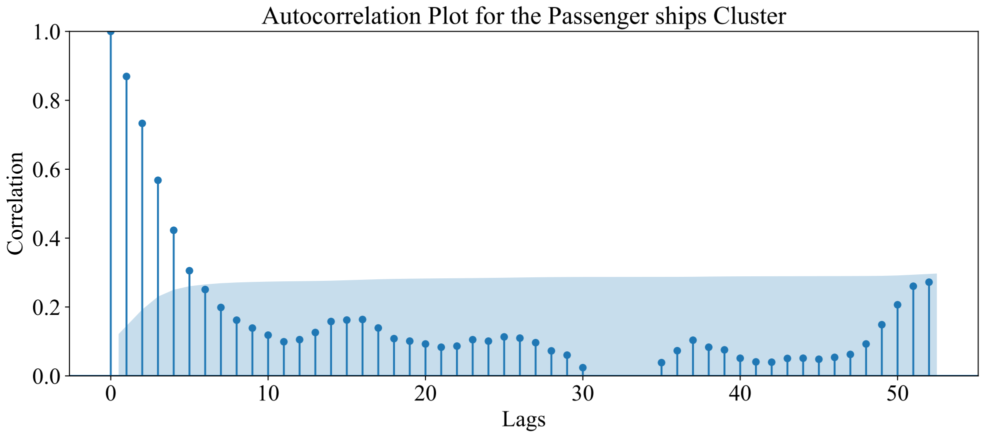



Figure G.6.: Week factors of clusters

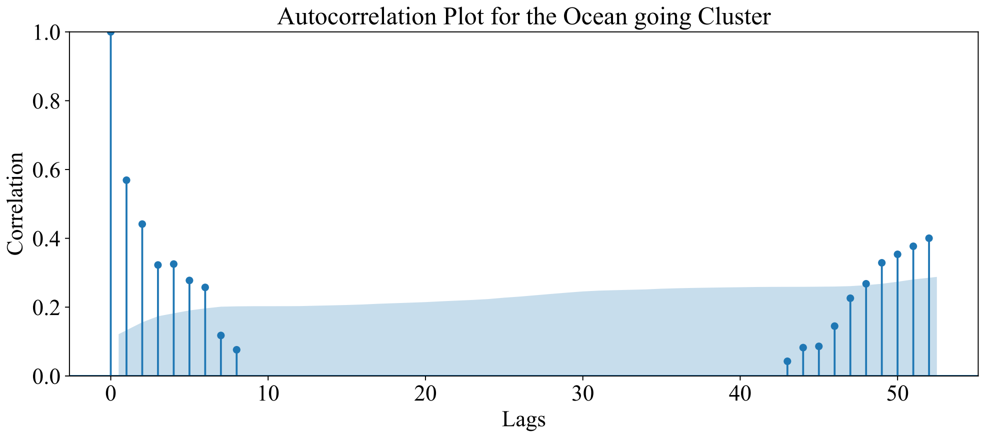
For these clusters, plots of Autocorrelation Function (ACF) are generated. It is seen that the first cluster, which includes most of the ship classes, do not exhibit seasonality. where as the uni-observation clusters of passenger and ocean going ships have significant auto-correlation. Accordingly, for the ship classes that belong to the first cluster, Auto Regressive Moving Average (ARMA) models are fitted, and the Seasonality component is introduced only for the passenger and ocean going ships.




(a) ACF of the IWT cluster




(b) ACF of the passenger ship




(c) Scatter plot

Figure G.7.: ACF

## G.2.2. Unallowed passages

It is seen in Figure G.8 that recreational passages through the commercial chamber is a more common phenomenon compared to commercial passages through the recreational chamber. Figure G.9 suggests that recreational passages use the commercial chamber more in the first quarters of the year, or at times when there are few recreational vessels as in the year 2019, due to Covid-19. This can be explained by the preference of the lock operator to refrain from levelling the recreational chamber for only a few vessels.

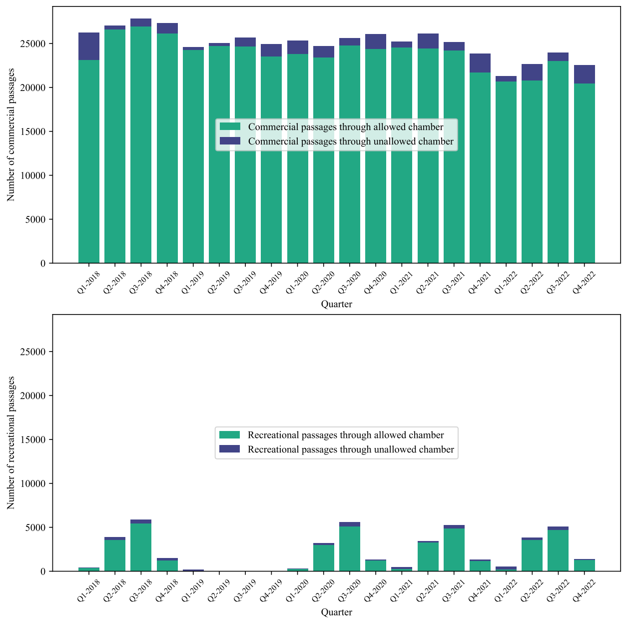



Figure G.8.: Allowed and unallowed passages

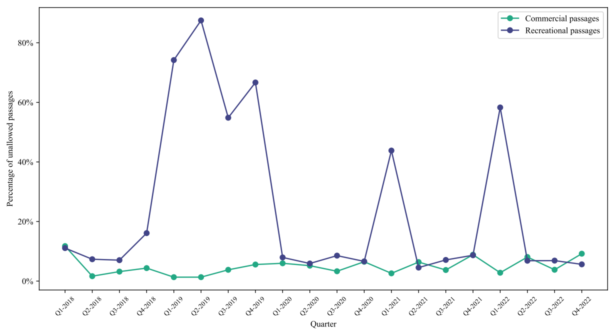



Figure G.9.: Percentage of unallowed passages

# H. KPI Selection

Table H.1.: Performance indicators

| Indicator | Stg. | Act. | Inf. | KPI | Justification |
|---|---|---|---|---|---|
| $CO_2$ **emission** | ↑ | ✔ | ✔ | ● | $CO_2$ emission is the only environmental performance indicator that can be calculated using the model. It is actionable as it is affected by the policies such as the lock condition, locking regime, and inspection frequency. |
| **Average waiting time** | ↑ | ✔ | ✔ | ● | Average waiting time is an important indicator that provides insight into the objectives of the ship operators. |
| **Average lockage time** | ↑ | ✔ | ✔ | ● | Average lockage time is influenced by different maintenance policies. |
| **Number of lockages** | ↑ | ✔ | ✔ | ● | Number of lockages is an important performance indicator that points to the operational cost of the lock complex. |
| **Hours of navigation interruption** | ↑ | ✔ | ✔ | ● | Losses in availability due to planned and unplanned maintenance. This indicator is the basis of the contractual agreements between the RWS and the maintenance contractor. |
| **Number of ships** | ↓ | ✖ | ✔ | | It is a direct result of the fleet mix scenario parameter and therefore is not actionable. |
| **Total tonnage** | ↓ | ✖ | ✔ | | See above. Although it quite related with the number of arrivals of ships, total tonnage still provides additional information about the fleet composition. |
| **Condition of the lock** | ↓ | ✔ | ✔ | | Modelled as a scenario parameter. |
| **Mean time between failures** | ↓ | ✔ | ✔ | | Modelled as part of the lock condition scenario set. |
| **Mean time to repair** | ↓ | ✔ | ✔ | | Modelled as a policy parameter. |
| **Average passage time** | ↑ | ✔ | ✖ | | Average passage time comprises two components, waiting time and levelling time. In this study, we choose to breakdown these components and report them individually. |
| **Max queue length** | ↑ | ✔ | ✔ | i | Although there is a strong alignment expected between maximum queue length and average waiting time, maximum queue length provides additional information on the experience of the ships and lock operators. It is not prioritised and is kept out of the set to limit the number of KPIs. |
| **Service level** | ↑ | ✔ | ✔ | i | See above. |
| **Average DWT per levelling** | ↑ | ✔ | ✖ | | For a given fleet mix, average DWT per levelling is determined solely by the number of lockages. |
| **Average number of ships per levelling** | ↑ | ✔ | ✖ | | See above. |
| **Average number of ships per filled levelling** | ↑ | ✔ | ✖ | | See above. |
| **Speed level** | → | ✔ | ✔ | | It is a proces-oriented performance indicator, therefore not included in the list of KPIs. |
| **Occupancy** | → | ✔ | ✔ | | See above. |
| **Number of empty lockages** | → | ✔ | ✔ | i | See above. |
| **Notification range of ships** | ↓ | ✔ | ✔ | | Modelled as a parameter for sensitivity analysis. |

Stg. refers to the stage described by the indicator. This classification is based on Joumard and Gudmundsson (2010) and Carter et al. (1995). ↓: input (resources, conditions), →: process (how the service is delivered), ↑: output (results).
Act. refers to the extent of actionability. If RWS can change policies to impact the variable, the indicator is considered actionable. ✔: actionable, ✖: not actionable.
Inf. refers to whether the indicator provides additional insight. ✔: additional information, ✔: information already covered by other selected KPIs.
KPI refers to whether the indicator is considered a key performance indicator and selected to be systematically reported in the main text. The rest of the performance indicators are inspected and are only reported in case they reveal an interesting relationship. ●: selected.

# I. Results for the complete set of performance indicators

Figure I.1 shows the correlations between different metrics, only presenting statistically significant correlations with a p-value lower than 0.05 and an absolute value of the correlation coefficient greater than 0.5.

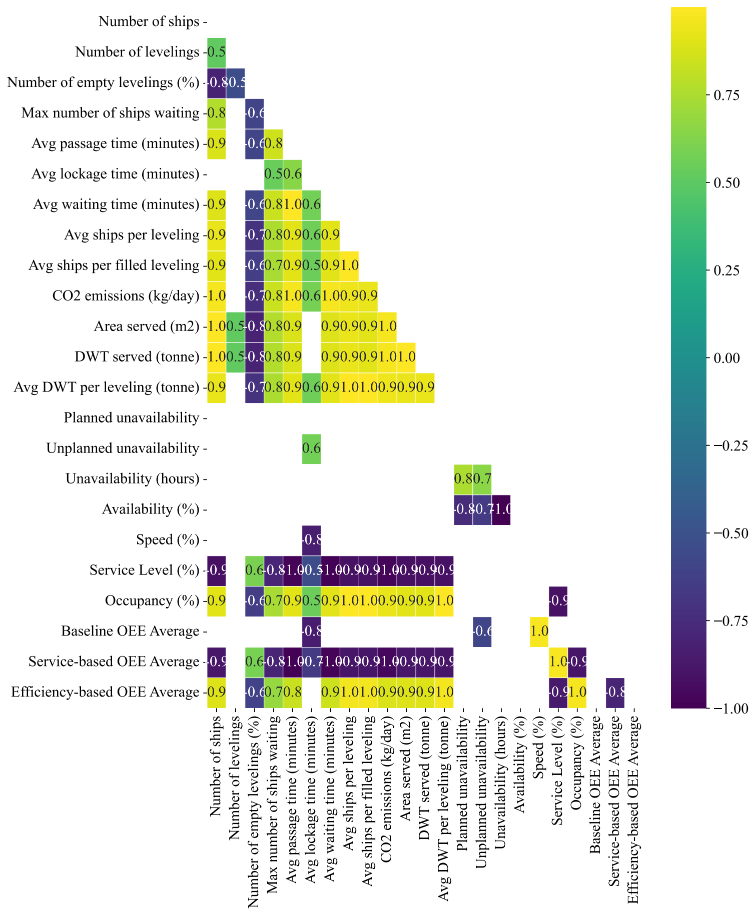


Figure I.1.: Correlation plot

The conflict of interest between two groups of KPIs can be observed in Figure I.1. The first group includes the number of ships, maximum number of ships waiting, average passage time, levelling and waiting times, average ships per levelling and per filled leveling, emissions, area and DWT served, occupancy, and average efficiency-based OEE. On the other hand, the second group consists of KPIs such as the number of empty levelings, service level, and average service-based OEE.

Within each group, there is a strong positive correlation among the KPIs, indicating that they are commonly influenced by similar factors. However, there is a high negative correlation between the two groups, highlighting the conflicting nature of their objectives. This suggests that improving KPIs in one group may have adverse effects on KPIs in the other group.

Planned and unplanned unavailability, availability and speed levels, and the baseline OEE average do not correlate as strongly with the two groups of KPIs. However, there are notable correlations between some of these factors and the average levelling time.

To shed light on the underlying factors causing these relationships, results of the feature scoring analysis can be found in I.2. To produce this figure, extra trees algorithm (Geurts et al., 2006) was used to fit 1000 regression trees for each KPI.

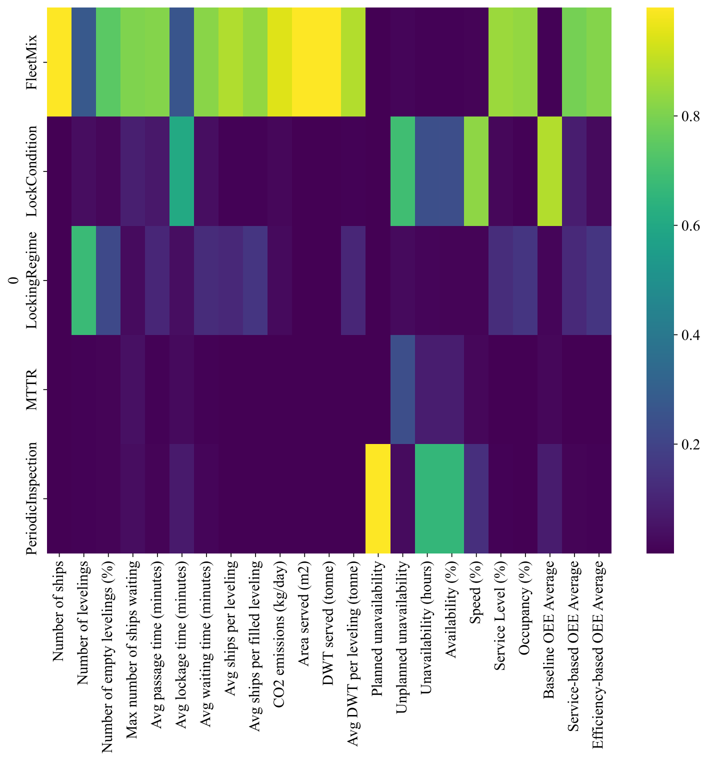



Figure I.2.: Feature scoring table

It is observed that for most of the KPIs, fleet intensity is the most significant input factor in explaining the variance. Referring back to the two groups of objectives observed in the correlation analysis, increasing fleet intensity also increases the first group. However, it has a negative causal relationship with the second group.