AALBORG UNIVERSITET

PROBABILISTIC RESILIENCE MODEL FOR MANAGEMENT OF WATER SUPPLY SYSTEMS.

MASTER OF SCIENCE IN TECHNOLOGY IN RISK AND SAFETY MANAGEMENT

By Tom Andersen

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TITLE PAGE

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ABSTRACT

This research investigates economic strategies to boost the resilience of TREFOR utility company's water supply system in Middelfart, focusing on key critical components. The study extensively evaluates two principal models: the probabilistic resilience model and a renewal model.

The probabilistic resilience model is demonstrated as an effective tool for identifying potential failure scenarios in utility infrastructure, particularly addressing internal degradation processes in system components like pumps and valves. However, the study also acknowledges that the model's utility could be significantly expanded through future research integrating considerations of external hazards, thus providing a more comprehensive and robust strategy for system resilience.

On the other hand, the renewal model's strength lies in its ability to examine and assess various renewal strategies and their respective temporal economic implications. It offers predictive capabilities that present a depiction of the future state of the water supply system and the financial resources necessary for sustained resilience.

Despite annual cost variations across different renewal strategies, the study uncovers practical economic thresholds that can guide TREFOR in their decision-making processes. However, it also highlights potential inaccuracies in the model due to variable lengths of pipe segments selected for renewal.

The research recommends that TREFOR should ideally combine both models to optimally improve their system's resilience. However, the need for further exploration and refinement of these models is highlighted, including the integration of external hazards and a more in-depth investigation of model assumptions, to improve predictive accuracy and support more comprehensive strategic decisions.

Unfortunately, the study was somewhat hampered by incomplete data on economic consequences. Nevertheless, assumptions based on discussions with TREFOR, along with insights into the current rate of pipe degradation and burst data, proved valuable for understanding system risks.

In conclusion, this research emphasizes the utility of both the probabilistic resilience model and the renewal model in enhancing the resilience of TREFOR's water supply system in Middelfart. Despite some data limitations, it delivers insights about system degradation, risk types, and response times to failure events, all of which can help inform strategic decision-making.

Overall, the research illustrates a pathway towards creating more resilient utility infrastructures grounded in solid economic rationale, while also underlining the importance of continuous research and refinement of these models.

PREFACE

The pursuit of knowledge and its practical application has always been a driving force in my academic journey. This thesis investigated the intersection of theory and practice, represents the culmination of my Master's degree in Risk and Safety Management at Aalborg University.

The primary motivation behind this work was to bridge the academic knowledge from my coursework, specifically classes on risk resilience and sustainability, with practical insights derived from real-world problem-solving.

One of the core objectives of this thesis was to gain hands-on experience and proficiency in python programming, probabilistic modelling techniques, Geographic Information System (GIS), and hydrodynamic software. These tools, while being diverse in their applications, came together to a certain extent in this work to provide solutions for the enhancement of resilience in utility infrastructure.

Collaborating with TREFOR utility company and the consultancy firm Envidan was a rewarding experience that provided valuable insights into the economic dimensions of water supply systems. The opportunity to work alongside seasoned professionals allowed me to witness first-hand the challenges faced by the industry.

The focus of the thesis, enhancing the resilience of TREFOR utility company's water supply system in Middelfart, provided a rich context for my research. By addressing this real-world problem, I was able to see how the theories I learnt could translate into outcomes that can be applied in the context of risk informed decision making. It is my belief that the principles of risk resilience and sustainability, combined with robust economic measures, can aid in the design and maintenance of resilient utility infrastructures.

It is my hope that the findings and recommendations provided in this thesis will contribute to the ongoing discourse on resilience in utility infrastructure and offer beneficial insights for TREFOR and other similar companies.

As I present this thesis, I look forward to using the knowledge and experience I have gained from not only these past months, but provision the value of this degree, to contribute meaningfully to the field of Risk and Safety Management, and to continue my journey of learning and **remaining curious!**

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INTRODUCTION

The TREFOR water supply system in Middelfart, a fundamental pillar of infrastructure, forms the primary focus of this master's thesis. The aim is to integrate and apply risk management methodologies within the context of Asset Integrity Management (AIM) to assess the system's resilience and the risks it faces.

The capacity of a water supply system to resist, respond to, and recover from potential threats or disruptions is a vital consideration in its operation and maintenance. Accordingly, the primary objective of this study is to interrogate the resilience of TREFOR's water supply system in the face of such challenges, focusing particularly on selected component.

The primary concern is to conduct a risk assessment and developing probabilistic models of system components. The ambition is to deepen the comprehension of the system's resilience and the economic repercussions of component degradation and failure, applied specifically to pipes, valves, and pumps currently operating in Middelfart.

To achieve these objectives, the study will undertake a comprehensive review of relevant literature, identification and analysis of system components and associated hazards, construction and evaluation of probabilistic models, and consultations with industry experts. In conclusion, the hope is that the findings and recommendations generated from this study will provide a meaningful contribution to TREFOR's decision-making processes, informing strategies to enhance the resilience and performance of their water supply system.

PROBLEM FORMULATION

"What economic measures can be undertaken to enhance the resilience of TREFOR utility company's water supply system in the city of Middelfart, specifically focusing on selected critical components?"

To this end, the study poses five research questions:

1. Which components constitute TREFOR's water supply system in Middelfart, and what are the potential economic consequences in case of their failure?
2. What is the current rate of degradation of pipes within the water supply system?
3. Which types of hazards are imposed on the system?
4. What is the response time to failure events?
5. What economic capacity do TREFOR need to sustain to prevent resilience failure?

The research questions will help address issues and support recommendations to TREFOR's decision-makers based on the risk assessment and probabilistic modeling results. Which aim at enhancing the water supply system's performance and resilience.

SCOPE

This thesis scope is centered on applying risk management and AIM for the TREFOR water supply system, with a primary focus on conducting a risk assessment and implementing probabilistic modeling of critical components.

The study aims to enhance the understanding of the system's resilience and associated economic consequences in the context of component degradation and failure, which will be applied to pipes, valves, and pumps currently operating in Middelfart.

This process will involve a comprehensive literature review, system identification, hazard identification, model building and assessments. Also, consultations with experts will be conducted to determine the essential elements that significantly impact the overall performance the system.

Also interviews and analysis of maintenance records and cost projections provided by TREFOR's asset management department will be conducted. The aim is to quantify the financial impact of various failure scenarios.

The project will require the application of statistical methods and expert judgment to gain a thorough knowledge of the system. Understanding the rate of degradation is necessary for predicting the system's long-term performance and in informing maintenance and replacement strategies.

It is the hope that the project will be able to develop recommendations for TREFOR's decision-makers to enhance the water supply system's resilience based on the model outcomes.

There are certain aspects excluded from this project, these exclusions comprise:

- Modeling of external risks, such as environmental hazards, geotechnical considerations, that may impact the water supply system. While these risks are essential to consider, identify and mention, they are beyond the scope of this project, which primarily focuses on component degradation and failure of selected system components.
- Modeling of water facilities or structures, groundwater formation, ground movement and issues related to water abstraction and treatment.
- Calculations of scenarios from the Monte Carlo simulation in hydrodynamic software or creation of a Digital-Twin.
- Modeling of emergency scenarios, such as fire events, and the system's capacity to handle such incidents during a damage state is excluded but would be of interest in future study. While these scenarios are important in understanding the system performance, they fall beyond the focus of this project and its time limitation.
- Material processes, such as calculation material fatigue, determination of leak or burst types in relation to diameter of holes or pipeline rupture and resulting water loss flow rates.
- Extended consequence in terms of affected traffic or other socio-economic impacts.
- Human health considerations and water quality risks.

LIMITATIONS

The calculations of scenarios from the Monte Carlo simulation in hydrodynamic software, as was initially planned, are excluded due to software limitations from Aquis (Hydrodynamic software by Schneider Electric) and the associated model of Middelfart.

A significant amount of time was spend on investigating this option along with learning new software (Aquis and EPANET - both hydrodynamic software).

An Aquis model was provided by Envidan, however there was no way of determining how to connect it to the MC simulation within the resilience model. On the other hand EPANET facilitated this option through a Python extension called WNTR. This would require building the hydrodynamic model as part of the thesis, which would be a project on its own in the context of applying it to the full scale of Middelfart.

Instead, the study will focus on building the resilience model. This setback unfortunately will limit the scope of the thesis, however the insight still provides motivational for future work.

BIBLIOMETRIC LITERATURE REVIEW

BIBLIOMETRIC & STATE-OF-THE-ART LITERATURE REVIEW:

This chapter describes the literature search and review process undertaken as part of this master thesis. The literature review is an important step in identifying the current state of knowledge about the research problem and in shaping the research questions and methodology.

The process included identifying the problem, defining the search scope, selecting relevant search terms, grouping search terms, creating queries, generating bibliometric maps, selecting articles for review, visualizing data, and analyzing results as an iterative process (Jan van Eck & Waltman, 2017; Nielsen & Faber, 2021).

The literature review started with defining the research problem, which is to apply risk management and probabilistic modelling techniques in the context of Asset integrity Management for the water supply system at TREFOR.

The search scope was limited by the temporality of literature and selected database (Web of Science), where preference was given to newest literature in order to narrow the search (see Appendix I).

Relevant search terms were grouped into categories based on their relevance to the research problem (figure 1). Search queries were formulated to retrieve the most relevant articles, and bibliometric maps were used to uncover patterns and trends in the literature. The most relevant articles were selected for further review, and the data from these articles were visualized and analyzed to draw conclusions about the research problem.

This chapter provides a detailed explanation of the literature search and review process, including the methods used, the sources searched, and the results obtained.

Additionally, this chapter discusses the strengths and limitations of the literature review and how the findings informed the development of the research questions and methodology.

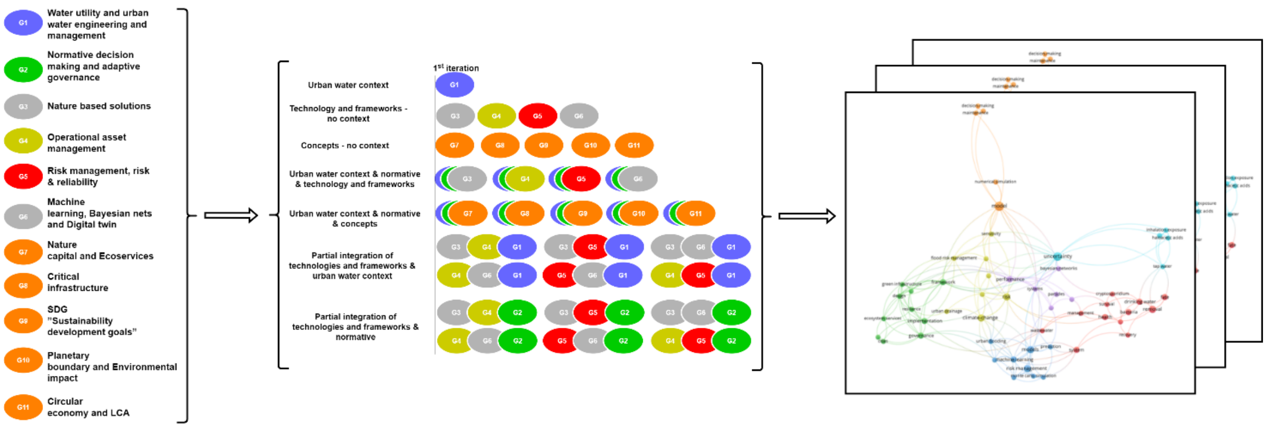

Figure 1. illustrating workflow process and combination of search groups (See Appendix I for enlarged version).

The work of Michael H. Faber and Linda Nielsen has been influential in inspiring the adoption of bibliometric methods for this thesis (Nielsen & Faber, 2021). These methods have been instrumental in various fields to examine scientific literature.

When two or more scientific papers share at least one reference, they can be considered to have a meaningful relationship with each other.

This is referred to as "coupling." This idea of bibliographic coupling, where two publications are connected through a third publication, is discussed in Kessler and Van Eck and Waltman and serves as a basis for the constructed maps (Jan van Eck & Waltman, 2017; Kessler, 1963).

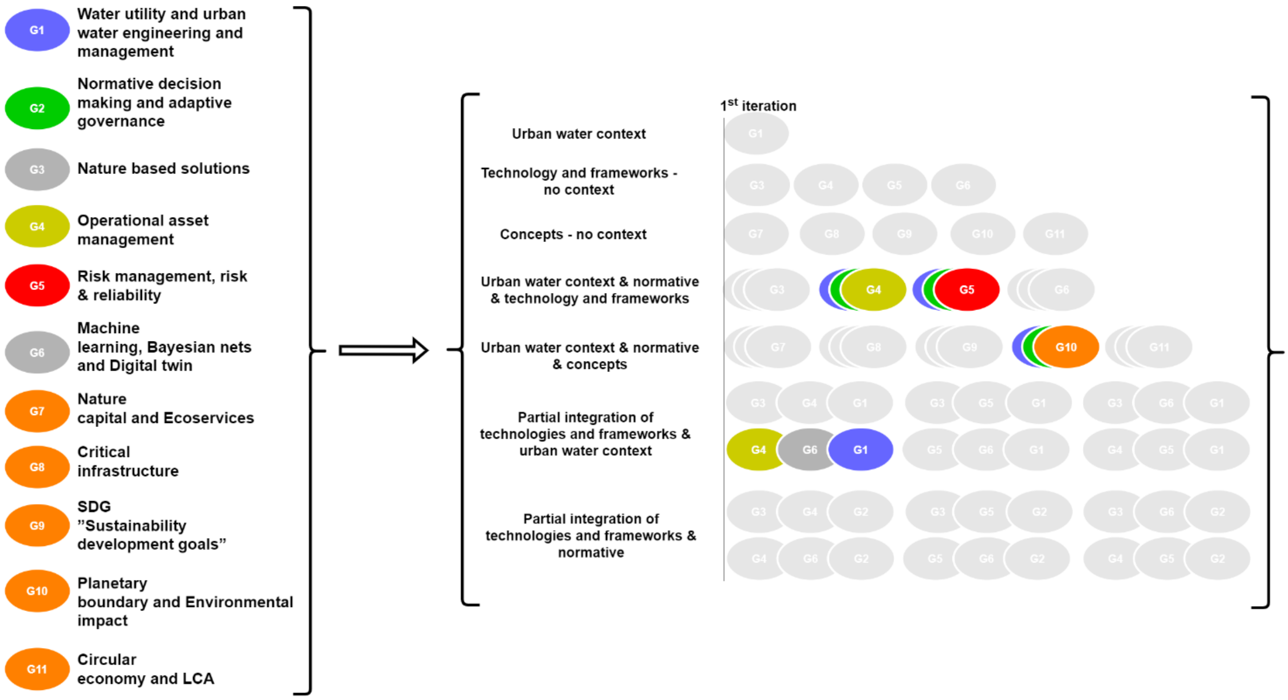

Figure 2, Group selection (highlighted) to inform the research problem, after extensive discussion with TREFOR utility company and the consulting company Envidan. Other searches were used for the purpose of exploratory research and pattern identification associated with the context (see Appendix I for high resolution bibliometric maps of all queries).

Certain groups were chosen and highlighted to provide information on the research problem (see figure 2), following discussions with TREFOR and Envidan. Other searches were conducted for exploratory research purposes and to identify patterns related to the context (high resolution bibliometric maps of all search queries can be found in Appendix I).

Figure 3 shows the ranking of relevant categories of science for this research, with a particular focus on risk and asset/integrity management in the context of water utility and its associated infrastructure.

Environmental Sciences ranks first in the figure, followed by Water Resources, Engineering Environmental, Engineering Civil, Green Sustainable Science Technology, Engineering Chemical, Environmental Studies, and Operations Research Management Science. Accounting for these categories of science is essential in understanding the interdisciplinarity of the problem context.

Here an explanation of the domains are presented:

Environmental Sciences and Environmental Studies focus on understanding the natural world and the impact of human activities on systems, including water utility systems and their associated infrastructure, which is crucial for identifying potential risks and vulnerabilities (Bill Kte'pi, 2022).

Water Resources is concerned with managing and protecting water resources, which are critical assets in many water utility systems (T. Editors of Encyclopaedia, 2021).

Engineering Environmental and Engineering Civil are involved in developing systems that protect the environment and the built environment, respectively, while also managing assets and mitigating risks associated with natural disasters and other hazards (Jerry A. Nathanson, 2020).

Green Sustainable Science Technology combines scientific knowledge with engineering principles to create sustainable solutions for environmental problems (Duc Long Nghiem, 2023).

Engineering Chemical is focused on designing and optimizing chemical processes and systems, which requires careful risk management (T. Editors of Encyclopaedia, 2003).

Operations Research Management Science uses mathematical modeling, statistics, and optimization techniques to solve complex problems in various industries (Erhan Kozan, 2002).

Understanding the ranking and relevance of these categories of science is important for effectively managing risks and assets in water utility systems. For the purpose of this thesis and a general risk management perspective,

In this respect it is worth considering which experts to draw upon in terms of domain knowledge, in professional risk management.

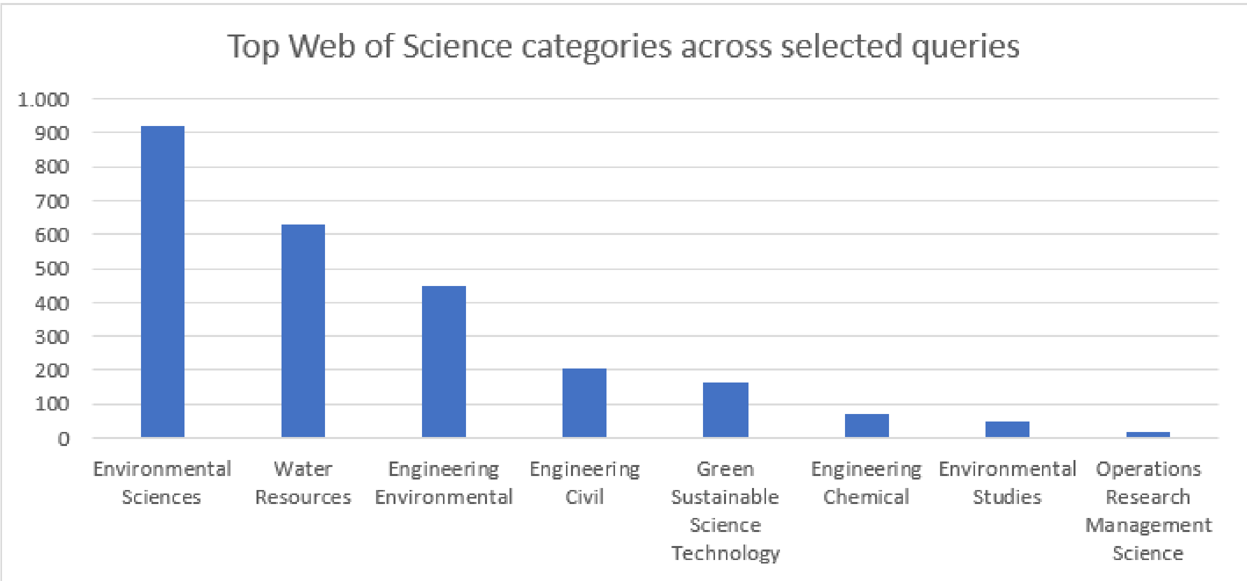

Figure 3. top record counts and knowledge domains represented in query #2, #3 #8 and #13. The categories in figure 3. is retrieved from the sum of searches in figure 4.

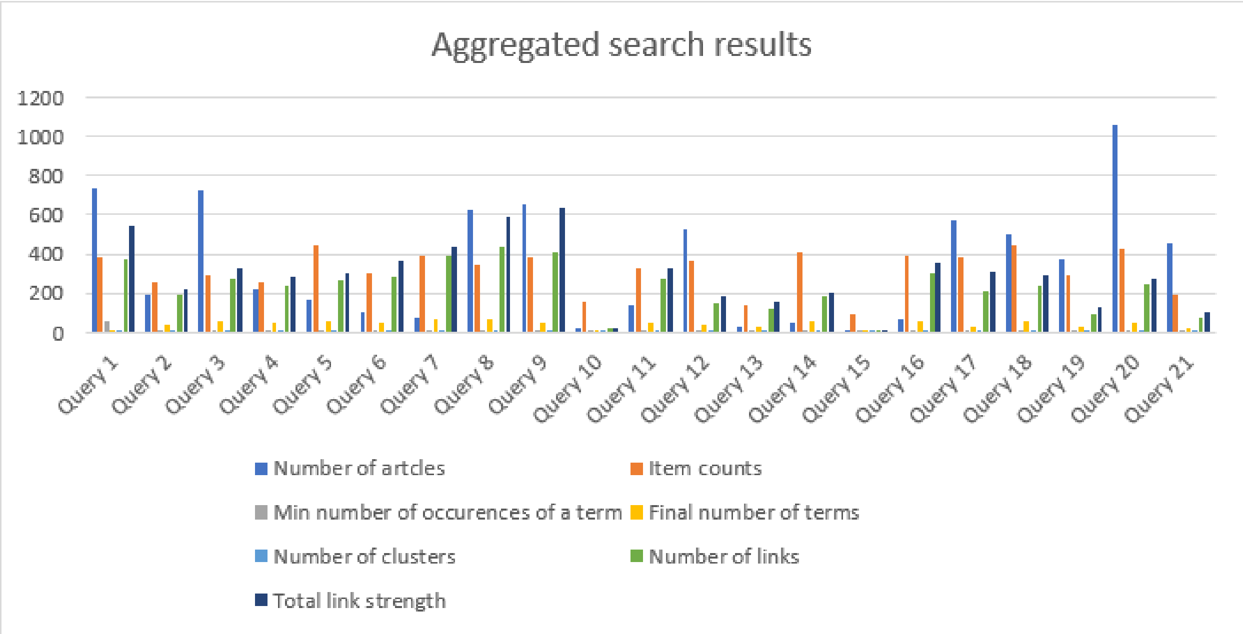

Figure 4. Showing the aggregated search results from all combined searches.(see appendix I for enlargement in excel file “Bibliometric info”).

QUERIES:

Query #2 - Water utility and urban water engineering and management & Normative decision making and adaptive governance & Operational asset management - (G1 + G2 + G4):

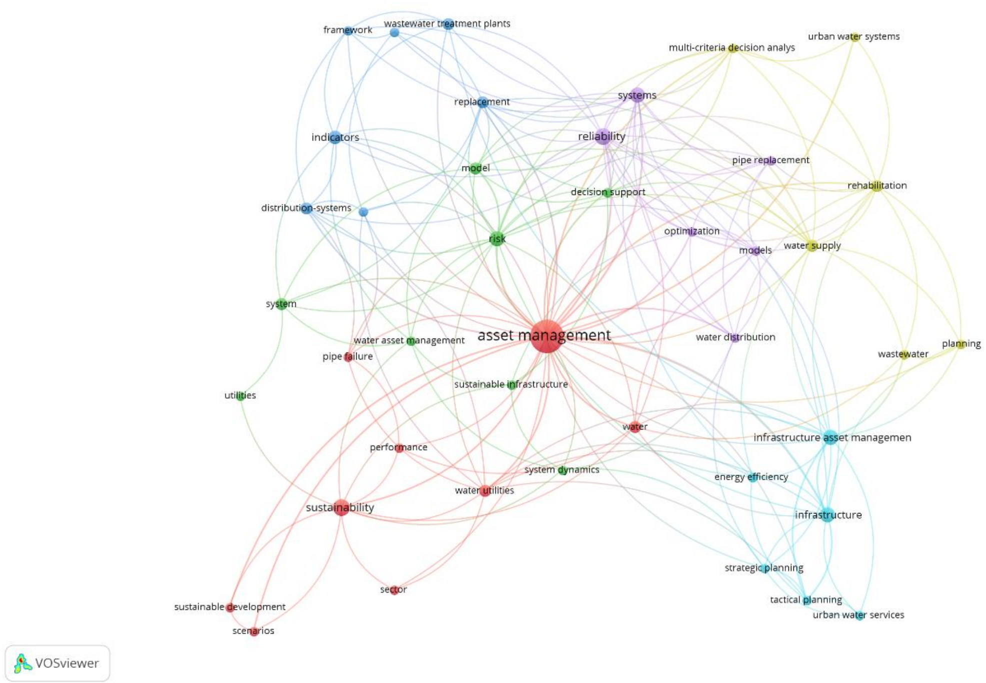

Figure 5. Network map of bibliometric clusters of query #2 (G1 + G2 + G4) (see appendix I for enlargement)

This query (figure 5) focuses on exploring the literature on the current practices of managing water supply, wastewater, and stormwater in urban areas. The aim is to identify research, case studies, and best practices related to concepts such as reliability, risk, resilience, sustainability, and governance, including adaptive governance.

The investigation spans multiple disciplines, including engineering, business, and public policy. It specifically emphasizes asset management in an operational context and considers the financial aspects associated with it. The goal is to gain insights into the relationship between asset management and financial modeling in the context of water supply management.

The six clusters associated with query #2 consists of the following subjective themes, which were identified for each cluster, which can be summarized as follows:

Cluster one (blue): Infrastructure Maintenance - The cluster relates to the maintenance of physical infrastructure, including indicators, distribution systems, framework, wastewater treatment, and replacement.

Cluster two (green): Risk Management - The cluster is focused on managing risk in utilities, with an emphasis on decision support, modeling, and water asset management.

Cluster three (red): Performance Assessment - The cluster involves assessing the performance of water utilities and related sectors, including asset management, pipe failure, and sustainability, among others.

Cluster four (purple): System Optimization - The cluster is concerned with optimizing systems to improve reliability and efficiency, with a focus on models, pipe replacement strategy, and water distribution.

Cluster five (yellow): Decision Analysis - The cluster involves using multi-criteria decision analysis to inform decision-making related to urban water systems, including rehabilitation, water supply, and wastewater planning.

Cluster six (turquoise): Infrastructure Planning - The cluster relates to strategic and tactical planning for urban water services, with a focus on infrastructure asset management and energy efficiency.

The resulting literature which helped inform the research problem are:

- Optimal Intervention Planning: A Bottom-Up Approach to Renewing Aging Water Infrastructure
- Setting Future Water Rates for Sustainability of a Water Distribution System
- Comparison of automatic and guided learning for Bayesian networks to analyze pipe failures in the water distribution system
- Development of a risk-based tool for groundwater well rehabilitation and replacement decisions
- Strategic Water Utility Management and Financial Planning Using a New System Dynamics Tool
- Multi-criteria decision analysis in urban water asset management
- Performance Evaluation of Water Distribution Systems and Asset Management
- Using the multiple scenario approach for envisioning plausible futures in long-term planning and management of the urban water pipe systems

The reviewed papers offer insights and methodologies that contribute to the thesis on the resilience of water supply systems. These papers provide relevant information on risk management, intervention planning, asset management, sustainability, and decision-making in the context of water supply systems. While not all papers explicitly focus on specific metrics, they offer frameworks, methodologies, and approaches that can be applied to enhance the understanding and analysis of various aspects of water supply system resilience.

The paper on "Comparison of Automatic and Guided Learning for Bayesian Networks to Analyze Pipe Failures in the Water Distribution System" (Tang et al., 2019a) specifically induced the need for relevant data in terms of specific pipe types and types of failure and their occurrence such as in the system operated by TREFOR. However, it should be noted that the use of Bayesian networks was not applied in the context of the thesis, even though it was initially considered. (See Appendix I for reference to query and review).

Query #3 - Water utility and urban water engineering and management & Normative decision making and adaptive governance & Risk management, risk & reliability - (G1 + G2 + G5):

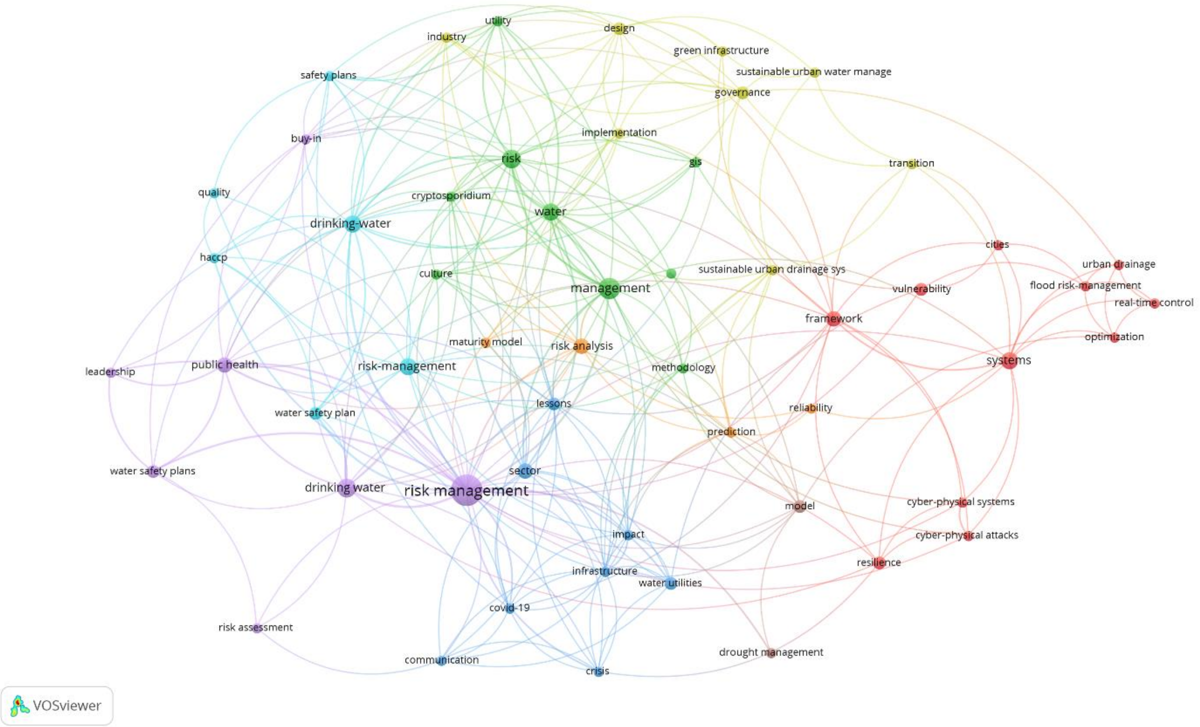

Figure 6. Network map of bibliometric clusters of query #3 (G1 + G2 + G5).(see appendix I for enlargement).

This search query was made to gain insights into the management of urban water supply systems and gather information to inform strategies for sustainable and resilient water supply management.

Additionally, the focus of the search is on exploring various methods and tools related to risk management and inspection techniques, such as risk-based inspection and reliability-based inspection. The goal is to gather insights on the application of these methods and tools in the context of urban water management.

This resulted in the eight clusters associated with query #3 (see figure 6), which consists of the following subjective themes for each cluster:

Cluster one (green): Risk management - The cluster focuses on risk management in the water utility sector, with keywords related to GIS, utility management, water. Hence it may have a stronger focus on risk assessment and management related to water quality and associated infrastructure.

Cluster two (yellow): Sustainable urban water management - The cluster is related to sustainable urban water management, with keywords such as green infrastructure, governance, and sustainable urban drainage systems. The focus seems to remain on developing sustainable water management strategies in urban areas.

Cluster three (red): Cyber-physical systems - The cluster is primarily concerned with the development of cyber-physical systems to manage urban drainage and mitigate flood risk, with a particular emphasis on keywords such as cities, cyber-physical attacks, and resilience. It proposes a strategic focus on the utilization of technologies to manage and mitigate flood risk in urban areas.

Cluster four (orange): Reliability - The cluster is related to risk analysis and reliability, with keywords such as risk analysis, maturity model, and prediction. The cluster seems to have emphasis on developing reliable risk analysis models to inform decision-making.

Cluster five (brown): Drought management modeling - This cluster focuses on drought management modeling, with keywords such as model and drought management.

Cluster six (blue): Crisis communication - The cluster focuses on crisis communication for water utilities, with keywords such as crisis, covid-19, and infrastructure. Hence effective communication strategies for managing crises in the water utility sector seems central in this cluster.

Cluster seven (purple): Drinking water safety - The cluster is related to risk assessment, with keywords such as risk management and public health. It suggests a focus on developing effective risk assessment and management strategies for ensuring the safety of drinking water.

Cluster eight (turquoise): Planning - The last cluster focuses on water safety plans for drinking water quality and safety management, with keywords such as HACCP (Hazard Analysis Critical Control Point). The cluster may converge upon the development of effective water safety plans aimed at managing the quality and safety of drinking water.

Resulting literature which help inform the research problem:

- "Costs for Water Supply Distribution System Rehabilitation"
- "A comprehensive framework to efficiently plan short and long-term investments in water supply and sewer networks”
- "Use of transient pressure data in a drinking water transmission system to assess pipe reliability"
- "A Risk-Based Approach in Rehabilitation of Water Distribution Networks"
- "Development of Multi-Objective Optimization Model for Water Distribution Network Using a New Reliability Index"

The reviewed papers in this query address key areas such as normative decision making, adaptive governance, risk management, risk and reliability.

The paper on "Costs for Water Supply Distribution System Rehabilitation"(Selvakumar et al., 2002) provides information on the costs associated with maintaining water distribution systems and the technologies used for rehabilitation and repair. It examines metrics including costs for different technologies, materials, equipment, and labor, providing budgetary cost estimation for utility managers. This paper's relevance will be aimed in this thesis at extending it to the Danish context, particularly at TREFOR’s system in Middelfart, as similar data will be sourced.

Additionally, the paper on "A comprehensive framework to efficiently plan short and long-term investments in water supply and sewer networks"(Ramos-Salgado et al., 2022) utilizes a specific metric, namely Average Network Age, which provides information on the age distribution of network components.

This metric aids in identifying areas that require renewal or replacement. The other papers also helped shed light on risk assessments based on remote sensors and data driven models for decision making in water supply systems. (See Appendix I for reference to query and review).

Query #8 - Water utility and urban water engineering and management & Normative decision making and adaptive governance & Planetary boundary and Environmental impact - (G1 + G2 + G10):

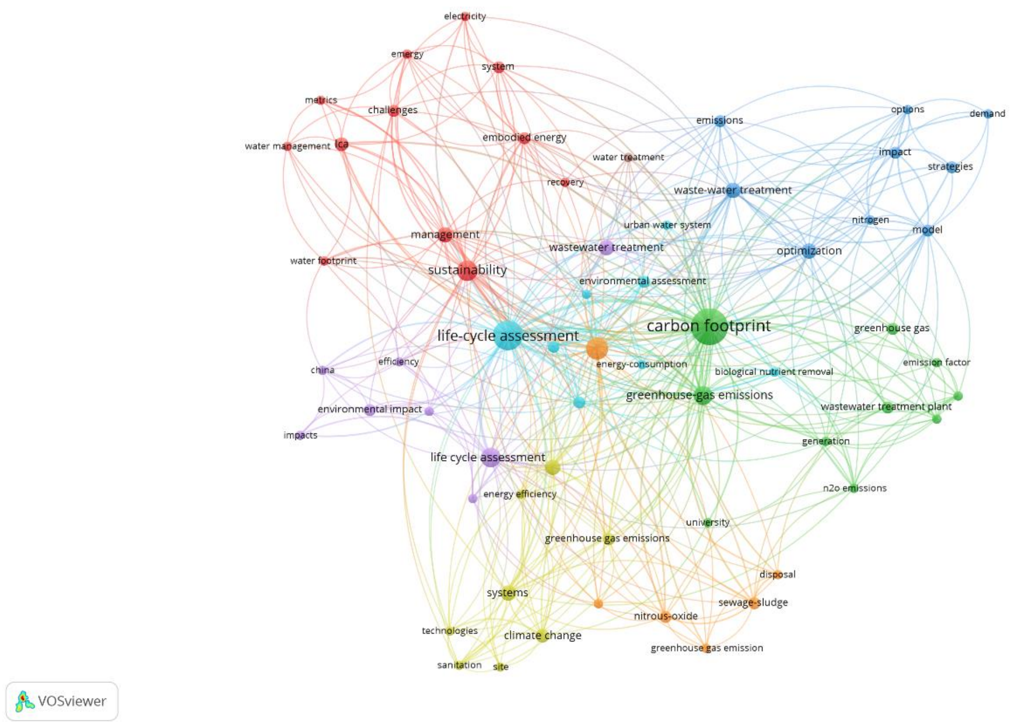

Figure 7. Network map of bibliometric clusters of query #8 (G1 + G2 + G10). (see appendix I for enlargement).

This search query (figure 7) aims to uncover, methods, tools, and strategies for addressing environmental issues such as climate change, biodiversity loss, land use change, and pollution. Even though this area of resilience was initially considered it was not included in the final scope of the project.

By exploring literature and findings in this area, it is an attempt to gain a better understanding of effective environmental management practices and decision-making approaches relevant to water utilities in relation to water supply networks.

The eight clusters where identified in associated with query #8:

Cluster one (red): Sustainability metrics - The primary focus of this cluster is on sustainability metrics in water management, with a specific emphasis on keywords related to embodied energy, recovery, and life cycle assessment. This suggests a strategic focus on comprehending and mitigating the environmental impact of water systems, as well as enhancing their overall sustainability.

Cluster two (purple): Environmental impact in China - This cluster centers around environmental impacts in China, with keywords related to efficiency and wastewater treatment. Hence this cluster is concerned with managing environmental impact in a specific geographic context.

Cluster three (green): Greenhouse gas emissions in wastewater treatment - This cluster is associated with the management of greenhouse gas emissions in wastewater treatment, with a particular focus on keywords related to nitrogen and emission factors. This suggests a deliberate weight on mitigating greenhouse gas emissions associated with wastewater treatment.

Cluster four (blue): Optimization of nitrogen emission in wastewater treatment - The focus of this cluster is the optimization of nitrogen emission in wastewater treatment systems, with a specific emphasis on keywords related to modeling and optimization.

Cluster five (turquoise): Environmental assessment - This cluster concentrates on environmental assessment of urban water systems, with keywords related to biological nutrient removal and life cycle assessment.

Cluster six (orange): Emissions management - Converges a strong emphasis on the management and mitigation of greenhouse gas emissions associated with sewage-sludge disposal, with particular attention given to keywords related to nitrous oxide. As a result, the management and mitigation of greenhouse gas emissions associated with the disposal of sewage-sludge seem key focal points of this cluster.

Cluster seven (yellow): Energy efficiency - This clusters focus is on energy efficiency in sanitation systems, with an emphasis on keywords related to climate change and site technologies.

Cluster eight (brown): Water treatment - Concentrates on water treatment, with keywords related to general water treatment processes. It suggests a focus on managing water quality through various treatment processes.

Reviewed literature:

“Nexus analysis and life cycle assessment of regional water supply systems: A case study from Italy”

The primary topic of the paper is a thorough assessment of how several water supply system activities, such as water treatment, extraction, distribution, and more, affect the environment.

The word "nexus" in the context of resource management refers to the links and relationships between various resources or sectors. The nexus approach acknowledges the interdependence of resources such as water, energy, food, and the environment and the potential for changes or actions in one area to cascade into others.

To achieve sustainable growth and efficient resource usage, it highlights the necessity of comprehending and managing these interlinkages, which is also emphasized in the theory section in this thesis in the context of systems thinking and their interdependence. Nexus theory emphasizes the value of holistic, integrated methods to solving complex problems and improving resource management plans (Arfelli et al., 2022a).

Nexus analysis and life cycle assessment (LCA) are used in the study to evaluate the sustainability of the system by analyzing the energy consumption and environmental effects of the processes involved. These analyses are intended to understand the relationships between various resources. Rather of directly studying the parts of pumps, pipelines, and valves, the research instead focuses on the larger issues of water management and offers information on the system's total environmental effect (Arfelli et al., 2022b). (See Appendix I for reference to query and review)

Query #13 - Water utility and urban water engineering and management & Operational asset management & Machine learning, Bayesian nets and Digital twin:

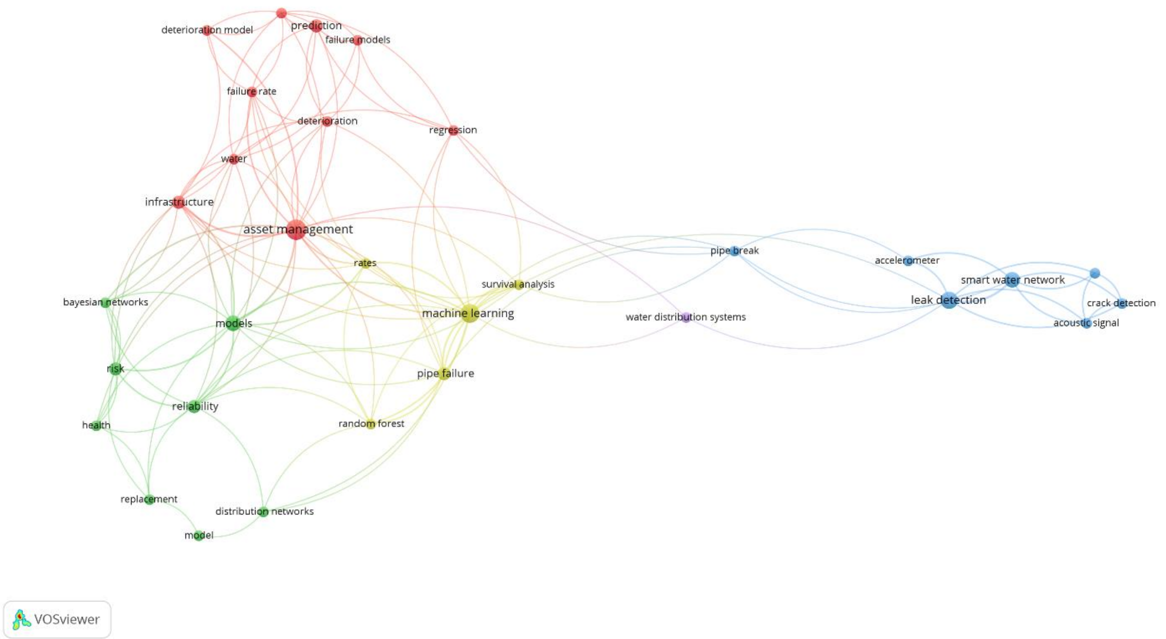

Figure 8. Network map of bibliometric clusters of query #13 (G1 + G4 + G6). (see appendix I for enlargement).

The intent of this query (figure 8) is to gain insights into asset management within operational contexts, and investigates the application of machine learning, probabilistic modeling, and digital twins in the field of urban water management.

The five identified clusters associated with query #13 are:

Cluster one (green): Bayesian networks - This cluster is primarily centered on improving distribution network reliability using Bayesian networks, with keywords related to model reliability and health risk. Emphasis seems to be leveraged towards advanced modeling techniques to enhance distribution network reliability.

Cluster two (red): Asset management - This cluster is related to asset management for water infrastructure deterioration prediction, with keywords related to regression and failure models.

Cluster three (yellow): Machine learning - The cluster is related to using machine learning for pipe failure prediction, with keywords related to random forest and survival analysis. It seems to suggest developing advanced machine learning algorithms to predict and manage pipe failure.

Cluster four (purple): Water distribution system - Converges on the water distribution system, with keywords related to general water distribution. It suggests a focus on managing and improving the overall water distribution system.

Cluster five (blue): Smart water network - This cluster is related to using smart water network technology for leak and pipe break detection, with keywords related to accelerometer and acoustic signal. It suggests a focus on developing advanced technologies to detect and manage leaks and pipe breaks in the water network.

The resulting literature which help inform the research problem are:

- "Asset management: Quantifying economic lifetime of large-diameter pipelines"
- "Monte Carlo Simulation Applied to Support Risk-based Decision Making in Electricity Distribution Networks"
- “Watermain breaks and data: the intricate relationship between data availability and accuracy of predictions”

The paper on "Monte Carlo Simulation Applied to Support Risk-based Decision Making in Electricity Distribution Networks" stands out in terms of management and the method could be applied in the context of water supply systems such as at TREFOR (Goerdin et al., 2015).

The paper introduces the use of Monte Carlo Simulation (MCS) as a tool for risk-based decision making in electricity distribution networks. By considering failure distribution models and historical data, it offers a practical approach to improving the reliability and performance of such networks. (See Appendix I for reference to query and review)

SUMMARY OF REVIEW AND ITS APPLICATION

Many of the metrics and methods derived from the reviewed literature, while providing insights, are generally comprehensive and beyond the scope of the time limitation of a thesis. They rely on a broad range of data and technical understanding. This broadness underlines the complexity and multifaceted nature of managing and improving the resilience of water supply systems.

For the purposes of this thesis, it is important to focus on more specific and manageable aspects that have a significant impact on system resilience. In particular, understanding the degradation processes or material behavior of various pipe materials over time due to wear and tear which can be a more focused and feasible area of study.

Pipes, valves, and pumps are critical components of the water supply system. They are constantly subjected to mechanical stresses, chemical reactions, and environmental conditions that can cause them to degrade over time (Abdel-Mottaleb et al., 2019; Tang et al., 2019a). This degradation can lead to failures that impact the reliability and efficiency of the water supply system. Therefore, developing an understanding of how these components degrade and fail can be crucial for improving system resilience.

Establishing a rationale for when to replace these components can also be essential (Selvakumar et al., 2002). This rationale could be based on various factors, such as the age of the components, the observed rate of degradation, the criticality of the components.

For instance, a pipe that is critical for system operation and shows a high rate of failure might need to be replaced sooner than a less critical pipe with the same level of failure. Similarly, a pump that is expensive to replace but has a low impact on system operation might be run to failure, while a cheaper but more critical pump might be replaced at the first sign of degradation.

While the broad and comprehensive insights from the literature are valuable, this thesis will focus on more specific and tangible aspects related to the degradation and replacement of critical components. This focus will allow for a more manageable and practical study that can still provide a contribution to improving the resilience of the water supply system at the TREFOR utility company.

With guidance from the thesis supervisors, three research papers were identified as significant sources of information, essential in establishing the groundwork for this thesis. In the following sections, these papers will be summarized in breif and their applicability to the thesis topic will be discussed.

- "An Exact Multiobjective Optimization Approach for Evaluating Water Distribution Infrastructure Criticality and Geospatial Interdependence"
- "Towards resilience of offshore wind farms: A framework and application to asset integrity management"
- "Probabilistic resilience model for management of road infrastructure systems subject to flood events"

The papers offer critical insights into the principles and methodologies used to assess and improve the resilience of different infrastructure systems, including water distribution, road networks, and offshore wind farms. Even though the papers focus on different types of infrastructures, the fundamental methodologies and concepts discussed in these papers can be adapted and applied to the water supply system at TREFOR utility company.

The first paper, "An Exact Multiobjective Optimization Approach for Evaluating Water," introduces a multiobjective optimization approach for evaluating the criticality and geospatial interdependence of water distribution infrastructure. The paper utilizes a hydrodynamic model developed in EPANET, which served as inspiration in the pursuit of model coupling for this thesis.

The second paper, "Probabilistic Resilience Model for Management of Road Infrastructure Systems Subject to Flood Events," presents a probabilistic resilience model for managing road infrastructure systems during flood events. The paper's contribution to the thesis is twofold.

Firstly, it presents a comprehensive framework for risk and resilience modeling that enables the ranking of different decision alternatives, a concept that could be applied to the management of water supply systems at TREFOR. Secondly, the paper's use of Monte Carlo simulations for probabilistic modeling and functionality metrics for quantifying resilience provides useful methods for examining the resilience of the water supply system in Middelfart. Although the context of the paper is road infrastructure systems, its approach to risk and resilience modeling can be applied to water supply systems, given the universal applicability of these concepts.

Although in relation to the two mentioned papers an Aquis model was provided by Envidan for simulating the water network physical behavior, it proved challenging to establish its integration with a Monte Carlo simulation. As a result, an adapted simulation approach was developed through a probabilistic resilience model, which specifically targeting the financial costs associated with systemic failures, while omitting the interlinking of the two models (i.e. a hydrodynamic coupled with the resilience model).

The third paper, "Towards Resilience of Offshore Wind Farms: A Framework and Application to Asset Integrity Management," offers a novel framework for modeling and analyzing the resilience of offshore wind farms. This paper's importance to the thesis lies in its proposal of a systematic approach for resilience assessment, which includes fault tree analysis (FTA), event tree analysis (ETA), and Monte Carlo simulation.

The hierarchical system-of-systems model used in the paper, which captures the complex interdependencies within infrastructure systems, can be applied to understand the interactions within the water supply system at TREFOR.

In conclusion, these papers provide methodologies, principles, and perspectives that can guide the formulation of the research question for the thesis, even if they need to be adapted to the specific context of the water supply system at TREFOR utility company.

THEORY & METHODOLOGY

Theory

The theories of ecological resilience by Holling and resilience of engineering systems offer valuable foundations for analyzing and enhancing the resilience of the water supply system such as at the TREFOR utility company.

Holling's ecological resilience theory (Holling, 1973) emphasizes the system's adaptability to disturbances and the need for flexibility in design and operation. It incites consideration of potential disruptions and their impacts on the system. In relation to resilience of engineering systems, focuses on the system's ability to sustainably adapt to long-term changes and emphasizes long-term planning and sustainability.

Hollinger suggests that understanding the behavior of ecological systems can be useful for designing and managing engineering systems. For example, if an engineer is designing a device to perform specific tasks under predictable external conditions, they may be more concerned with consistent consistent and stable level of performance that does not vary or fluctuate significantly over time.

However, if the system is intended to operate in a more complex and unpredictable environment, such as a natural ecosystem, then understanding the resilience and stability of ecological systems could help inform the design process. By considering the potential for unexpected events and disturbances, engineers can design systems that are better able to adapt and recover from disruptions. The theory is very much applicable when assessing the operational hazards as well as external which may instigate modes of failure in the water supply system at TREFOR.

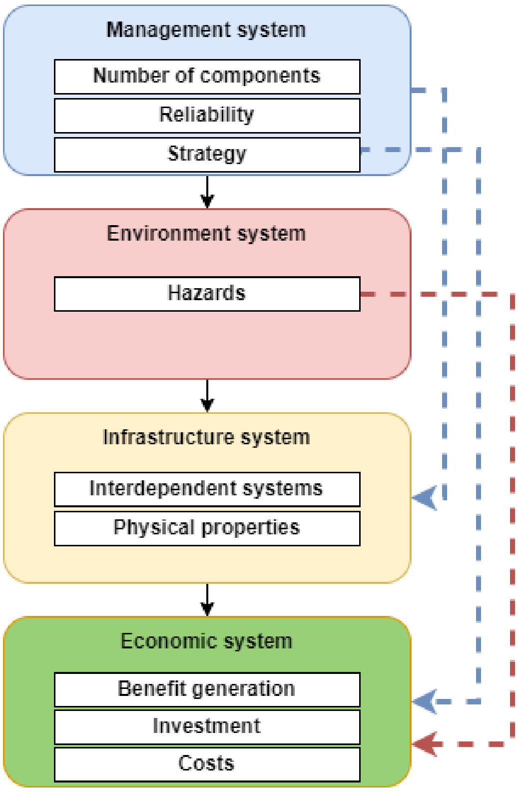

Figure 9. Interdependent water supply system hierarchical model inspired by (Liu et al., 2022).See appendix II for enlargement.

The System-of-Systems (SoS) theory mentioned in (Liu et al., 2022), is a collection of individual systems that work together to achieve a common goal.

In figure 9, a proposes a hierarchical system-of-systems model proposed by(Liu et al., 2022) adapted as a theory in this thesis for water supply systems, which comprises four interconnected systems: infrastructure system, economic system, environmental system, and management system.

The water supply system in this example may be seen as a complicated network of connected components aiming to provide a dependable source of water. It is important to consider their interdependence to effectively manage the pipes, pumps, and valves.

On the management system level, the organization TREFOR is responsible for considering system design, current and future renewal strategies, types of components along with their reliability. The strategies developed considering different system scenarios, which may consider different types of operability or system states such as modes of failure depending on the types of hazards. The management system may have to consider the requirements in terms of legal and live up to consumer requirements. This makes the management system directly interconnected with the other mentioned systems.

The environmental system considers the types of hazards that may act upon the system on all levels. Hazards can materialize and cause negative effects to the economic system in terms of added damages to system constituents as mentioned by Hollinger. They can both be of natural or anthropogenic character.

The infrastructure system considers the system constituents and their interdependence. Such as if a contamination at a water treatment facility may result in the downstream pump to be shut down, resulting in different pattern of distribution water through the system. This change in water distribution may affect the physical properties of the pipes, if some are more vulnerable to change in pressure, this may lead to leaks of pipe bursts, as indirect consequences of the treatment facilities being shut down.

The economic system considers the generation of benefit over time, in this case the sale of water to the consumers in Middelfart. Management strategies also impose the need to make new investments to the maintenance and renewal of the system. Which then relate to the operational cost of operating the system.

As mentioned, the main focus will be to consider the management system and economic system with consideration of the material properties on the system level of the infrastructure system.

The performance of the system will not be assessed in terms of modes of failure in relation to the effects on performance.

Methodology

Bibliometric study:

This master's thesis utilizes bibliometric techniques to analyze published literature and identify key research areas in the domains of water utility and normative decision making. By analyzing the frequency and co-occurrence of keywords, the study uses network and bibliographic coupling techniques to identify patterns in the literature.

The goal of this analysis is to provide a comprehensive understanding of the current state of research in the context of water utility and normative decision making, and to identify the key research areas and disciplines related to the study. To achieve this, the study uses cluster analysis techniques and creates visual representations of networks.

These networks provide a multidisciplinary perspective on the use of keywords in the literature and highlight clusters and the strength of connections between them. It is important to note that interpreting these visualizations is subjective, but the method is believed to offer an overview and quick screening of the most frequently used keywords in current literature for each domain.

The bibliometric analysis was conducted in the following process. The steps for a literature search and review in the context of problem identification are the following (Jan van Eck & Waltman, 2017; Kessler, 1963; Nielsen & Faber, 2021):

Problem identification: The first step in conducting a literature search and review is to clearly define the research problem or question. This involves identifying the specific area of interest, the gap in knowledge that needs to be filled or explored, and the objectives of the study. Define the search boundary:

Once the research problem has been defined, the next step is to define the search boundary. This involves determining the scope of the literature search, including the time frame, language, and databases to be searched.

Identify relevant search terms: The next step is to identify relevant search terms and keywords that will be used to search for literature. These terms should be specific to the research problem and should be chosen from the title, abstract, and keywords of relevant articles. Categorize search terms into groups: The search terms can be grouped into categories based on their relevance to the research problem. This will help to refine the search and reduce the number of irrelevant articles. The groups should be mutually exclusive and collectively exhaustive.

Define queries: Once the search terms have been identified and grouped, the next step is to define the search queries. These queries should be formulated in such a way as to retrieve the most relevant articles from the databases.

Create bibliometric maps: The next step is to create bibliometric maps of the literature. This involves creating a visual representation of the literature, such as a VOS map, to identify patterns and trends in the literature.

Select records for review: Once the bibliometric maps have been created, the next step is to select the records that will be reviewed. This involves reviewing the abstracts of the articles and selecting those that are most relevant to the research problem.

Visualize data: The next step is to visualize the data from the selected articles.

Analyze results: The final step is to analyze the results of the literature review. This involves synthesizing the findings from the articles, identifying patterns and trends, and drawing conclusions which help inform the research problem (Jan van Eck & Waltman, 2017; Kessler, 1963; Nielsen & Faber, 2021).

For the literature reviewed, it was limited to the Web of Science (WoS) database, which offers the option to export search results as .txt-files. These files include a comprehensive record of the search, such as the full name, author(s), abstract, DOI, and other relevant publication information, excluding the complete text of the articles.

Probabilistic model:
(Faber et al., 2017) propose the modeling framework which in this case will be applied in the context of decision analysis of the water supply system at TREFOR.

This model focuses on the direct and indirect economic consequences of specific component failure events, their probability of failure and expected value of utility, which is based on Bayesian decision analysis (Michael H. & Faber, 2012; Santamaria-Ariza et al., 2023).

As is mentioned in the hazard identification the system may be exposed to different events with following negative consequences. Following the principles of the system representation proposed by the Joint Committee on Structural Safety (M. H. Faber, 2008).

The modelling of the system can be broken down into three parts namely, exposure events such as hazards and in this case components subject to degradation over time and its inherent risk, direct consequences which are related to the damages of failures, and indirect consequences which relate to the loss of service provided by the system to the residents and businesses in the area.

The model considers the network level, which relates to the hierarchical model mentioned in the theory. The network level in this case is the infrastructure assets, namely pipelines, pumps, and pressure reducing valves in relation to the management strategies applied to the system.

Hazard due to degradation or failure of components

The hazards of a pipe burst or component failure of pumps and valves, time and location need to be considered along with the probability of failure types. The scale of the effects on the water supply system performance should still be considered and not be neglected in future studies.

In terms of modelling the occurrence of failure of pipes leading to bursts as well as component failure of pumps and valves, a non-homogeneous Poisson process can be applied as a hazard function as proposed in (Wagner et al., 1986). The shape parameter of the Poisson distribution, representing the failure rate is known as λ. Hence λ0 is the initial failure rate at the beginning of the simulation.

$$\Pr[N(t) = n)] = \frac{(\lambda_0 t)^n}{n!}\exp(-\lambda_0 t)\,, n = 0,1,2,3,4, \ldots \quad (1)$$

The Poisson process, rate of failure varies with time (λ(t)), the λ values for the different constituents are presented in the chapter on the model.

Vulnerability of water supply infrastructure

Vulnerability refers to how susceptible or prone a system is to being negatively affected by hazardous events. It captures the connection between the hazards themselves and the immediate effects they have on the system. The concept of vulnerability helps in to understand the magnitude of potential harm or damage that can occur as a result of exposures to hazards. R_D quantifies the overall risk or susceptibility of the water supply network to hazards by considering all the potential direct consequences resulting from the system's infrastructure assets.

$$R_D = \sum_i \sum_j P\left(D_j \middle| H_i\right) P(H_i) C_{D,ij} \quad (2)$$

P(H_i) denotes the probability of hazard H_i, which can be any number of events (i = 1,2,3,4,...). $P\left(D_j \middle| H_i\right)$ denotes the probability of damage D_j given the hazard H_i, with (j = 1,2,3,4 ...) as the possible set of infrastructure damage states. $C_{D,ij}$ is the expected consequences or costs of damage D_j due to hazard H_i.

Functionality loss

Functionality loss refers to the impairment or reduction in the ability of a water pipe network system to perform its intended functions due to one or more infrastructure failures. When infrastructure assets within the system fail, it negatively impacts the system's functionality and leads to indirect consequences.

The unsupplied demand and water loss and associated monetary loss resulting from a component failure can be expressed in the following way:

$$R_{ID} = \sum_{k} \sum_{i} \sum_{j} P\left(S_k \middle| D_j \cap H_i\right) P\left(D_j \middle| H_i\right) P(H_i) C_{ID,ijk} \quad (3)$$

The first term, denoted $P\left(S_k \middle| D_j \cap H_i\right)$, is the probability of different states of the water pipe network system, denoted as Sk. When there is damage to infrastructure assets (D_j) caused by a specific hazard event (H_i).

The second term, deonted $C_{ID,ijk}$ refers to the expected consequences or costs of indirect damages that may arise due to the system being in a particular state (Sk). It quantifies the potential negative outcomes or expenses associated with indirect damages caused by the system's state.

To assess the hazard associated with indirect consequences R_{ID}, it is possible to calculate the expected value of the indirect consequences.

Resilience modeling

Resilience refers to the ability of a water supply network to withstand and recover from disturbances or disruptions which relates to Hollinger’s perspective in the theory section of this chapter. The economic capacity of the water supply network over time (denoted R_r) represents the accumulation of these reserves.

It signifies the network's ability to generate and maintain a financial cushion that can be utilized during times of disruptions or emergencies. This reserve is typically generated through the sale of water to the consumers connected to the network (see figure 10).

Hence, resilience failure in this context means that a water supply network is not only capable of recovering from disruptions but also has a mechanism to generate and accumulate financial resources over time.

These reserves can be used to effectively respond to disturbances and ensure the network's ability to provide uninterrupted water supply services, supporting economic growth and meeting consumer needs.

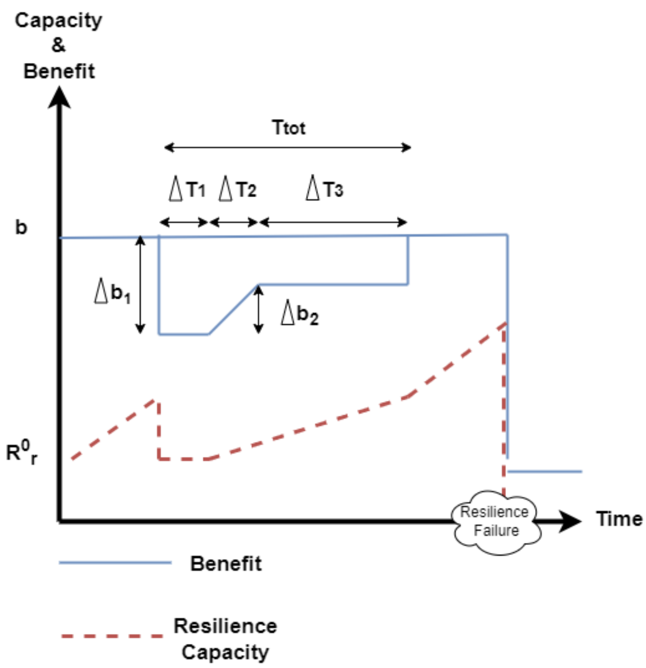

Figure 10, benefit and economic capacity generation over time and principle of resilience failure due to lack of capacity.

(K Nishijima & M H Faber, 2009; Santamaria-Ariza et al., 2023) suggested that the connection between investing applied in this case to water infrastructure can be done by employing macroeconomic production functions.

$$R_r(\mathrm{X}, a, \chi, t) = R_r^0 + \int_0^t \frac{\chi b(\mathrm{X}, a, \tau)}{(1 + r_\gamma)^t} d\tau \quad (4)$$

The starting capital reserve R_r^0 in a water supply network is a portion of the expected benefits generated by the system over its lifetime.

This reserve is determined by a percentage χ of the benefits saved. The function b(X, a, τ) describes how benefits are generated over time.

The discount rate r_γ considers the value of money over time. Figure 10 shows how benefits are generated, and economic capacity is built up in the water supply network. However, if a disturbance event occurs and damages the infrastructure, both benefit generation and the capacity of the system will decline.

$$S_r(\mathrm{X}, a, t) = \sum_{\tau\epsilon(\{t_F \cap (0,t)\}} \frac{C_T(\mathrm{X}, a, \tau)}{(1 + r_\gamma)^\tau} \quad (5)$$

When a disturbance event happens in a water supply network, it leads to economic costs during the recovery phase after the event. These costs, denoted as C_T(X, a, τ), represent the total expenses incurred during the process of restoring the network's functionality.

Disturbance events occur within the operational life of the infrastructure system is referred to as t_F.

If the economic resources or reserves of the water supply network are not enough to bring back its normal functioning, it is considered a resilience failure event. This means that the network is unable to recover due to insufficient financial capacity. Hence, the probability of resilience failure is denoted P_{RF} (Faber et al., 2017).

$$P_{RF}(a,\chi,t) = 1 - P\left[\{R_r(\mathrm{X},a,\chi,t) - S_r(\mathrm{X},a,t)\} > 0, \forall\tau \in [0,t]\right] \quad (6)$$

Risk-informed decision-making and management system
Monte Carlo simulations and hydraulic modeling techniques offer valuable tools for analyzing water supply systems. By utilizing Monte Carlo simulations, it is possible to probabilistically represent various failure scenarios for components such as pipes and valves.

This facilitates the means to calculate the expected direct costs associated with each scenario by considering the number of failures and the cost of the affected components.

$$C_D(k) = \sum U_r \cdot N_{BF}(k) \quad (7)$$

When considering a water supply system, the number of failed components in each scenario can be denoted as $N_{BF}(k)$, and the system scenario is denoted (k), which representing the total count of failed components. The cost associated with repairing each failed component is represented by the unit cost U_r for repair.

In terms of management and decision alternatives, the following is considered in the model (see chapter on model).

- Preparedness
- Accumulation of benefit

Several aspects are considered for managing a water supply system. This includes decision-making could also related to the target design reliability of pipes, valves, and pumps, where different failure rates can be chosen to achieve varying levels of reliability. Due to time limitations this has not been analyzed in great detail.

Another model is also proposed and will investigate renewal planning, this was meant as an attempt to establish a temporal model which could feed into the probabilistic model. More details on this are found in the model’s chapter.

Decisions regarding preparedness measures are crucial, with the duration of time required for finding leak or pipe bursts and the associated loss of water and potential damage effects to nearby infrastructure.

The impact of saving a portion of annual benefits for financing repairs and replacements is explored and quantified, with different decision alternatives considering various percentages of annual benefit savings denoted χ.

In conclusion various management strategies can be applied, however only few are investigated in this thesis, which leaves room for expansion upon this thesis.

It is important to note in terms of this thesis, that the event of failure is not conditioned on a specific hazard event such as natural disaster events. Therefore, the hazard represents the probability of a failure event, and achieving a state of damage is considered to occur when failure happens. In other words, once the failure has materialized, it is assumed that the damage will also take place. Calculating any types of limit states in relation to the mentioned components are beyond the scope of this thesis.

RISK ASSESSMENT

Risk assessment is the systematic procedure of identifying, examining, and assessing potential risks or hazards that have the potential to affect an organization, its constituent systems or projects.

It entails evaluating the probability and possible outcomes of a risk materializing and determining suitable actions to handle or minimize those risks (Aven, 2015; Nielsen et al., 2019).

Conditional risk assessments can be applied to quantify the level of speculation regarding the strength and adaptability of society or system at various levels. This entails conducting risk assessments on specific levels of damage to the system. "What if" scenarios are a type of conditional risk assessment that is used to evaluate the potential consequences of different levels of damage to critical systems.

These scenarios involve asking questions like "what if a certain system fails?" or "what if a certain event occurs?" (Nielsen et al., 2019). In the context of water supply system, it could entail the identification of a specific scenarios of failure and then simulate the effects of those modes of failure (see chapter on model).

The generic approach are the steps in risk assessment are:

Problem Definition and context: Clearly outline the purpose, scope, and objectives of the risk assessment.

Hazard Identification: Identify and document potential hazards or threats that have the potential to cause harm or damage.

Risk Analysis: Assess and analyze the probability and potential impacts of each identified hazard.

Risk Evaluation: Evaluate the significance of each identified risk by considering both its likelihood of occurrence and potential consequences.

Risk Treatment: Develop and implement strategies to manage, control, or mitigate the identified risks.

Monitoring and Review: Continuously monitor and review the effectiveness of the implemented risk management strategies, making necessary adjustments as needed and update knowledge as it becomes available such as by applying Bayesian updating.

Risk assessments support decision-making by providing valuable information and data for consideration in infrastructure investments.

They assist in managing risks, strengthening system resilience to withstand and recover from disruptions, and ensuring a reliable water supply even in the face of uncertainties. This chapter focuses on establishing the context and conducting system identification to understand the problem's scope and boundaries.

A hazard identification will be carried out, followed by the development of models to quantify the extent of the identified hazards. A risk analysis will be conducted, and the results will be evaluated. The decision-makers at TREFOR will then be responsible for risk treatment and monitoring based on the provided information.

CONTEXT

Middelfart

The town of Middelfart is positioned in central Denmark, on the island of Funen. As of January 2022, it was home to 16,277 people. TREFOR is the utility company servicing Middelfart, and contributes significantly to the community by offering necessities like heat, power, and clean water (Danmarks statistik, 2023).

According to estimates, the population is anticipated to expand by a total of 8.4%, from 39,970 in 2023 to 43,319 in 2035. This amounts to an annual rise of 279 people on average (Middelfart Kommune, 2023).

As Middelfart experiences gradual growth, it becomes important to address the aging water pipes and prioritize the maintenance and improvement of its water infrastructure for future system resilience. The following waterworks serve as the main water supply points in Middelfart, along with a pipeline connection that is established to the town of Fredericia across the little old belt bridge. The interdependence between the two towns are not expanded upon futher in this context.

Staurbyskov water treatment facility, located at Staurbyskovvej 15, Middelfart, is one of the waterworks. It was renovated in 1966 after being first constructed in 1900. It pumps around 300,000 m^3 of water annually from three operational producing wells (TREFOR, 2023). Though it has been closed since September 2017 due to the presence of the pesticide contamination, which poses a human health hazard.

Middelfart Municipality has given a concession to enabling it to be used as an emergency water supply when there is a scarcity of drinking water.

Svenstrup water treatment facility, located in Svenstrupvej 2, Middelfart, is the second water treatment facility in operation. It was built in 1978, and renovations were made in 1998. It pumps around 500,000 m^3 of water yearly from four operational producing wells.

TREFOR also looks after a number of water towers in addition to these waterworks. TREFOR owns three water towers, several storage facilities, and eleven waterworks in total, including the ones indicated above which are connecting the town of Middelfart (TREFOR, 2023).

The focus in this thesis will be on the distribution part of the water supply system in operation in Middelfart. In the following chapter a system identification will be conducted to describe the system level.

SYSTEM IDENTIFICATION

The water supply system in Middelfart is essential for the community's security, wealth, and general well-being. In this chapter the identification of the system will be conducted.

The system can degrade over time due to different factors, which can result in reduced performance and loss of functionality. Regular check-ups, maintenance, and repair are needed to ensure the infrastructure continued functioning well throughout its lifespan.

The information provided in this section has been acquired through meetings with TREFOR as well as experts at Envidan, as well as consulted related literature (Kim Brinck, 2014; Torben Larsen, 2007).

As part of the system identification process at TREFOR, the objective is to present an overview of the existing system. The primary focus will be on the different types of water pipelines that make up the distribution system. Additionally, attention will be given to the water supply pumps located at the two local water treatment facilities in Middelfart.

A principal illustration of the system concerned with this thesis is shown in figure 11. And in addition, a general network division structure of the system is illustrated in figure 12.

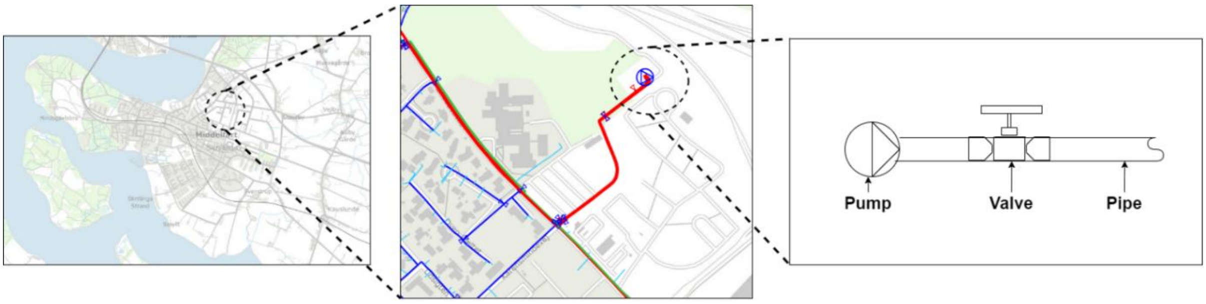

Figure 11, System representation of the distribution section of the water supply system.

As depicted in figure 11, the system is portrayed as a component of the integrated infrastructure of Middelfart. This view then narrows down to the pipe network's elements, consisting of different types of pipes, valves, and pumps, collectively referred to as the system level.

Finally, the focus is on the individual elements of a specific pump, valve, and pipe. The TREFOR water supply network division uses the following terms (TREFOR, 2023), see figure 12:

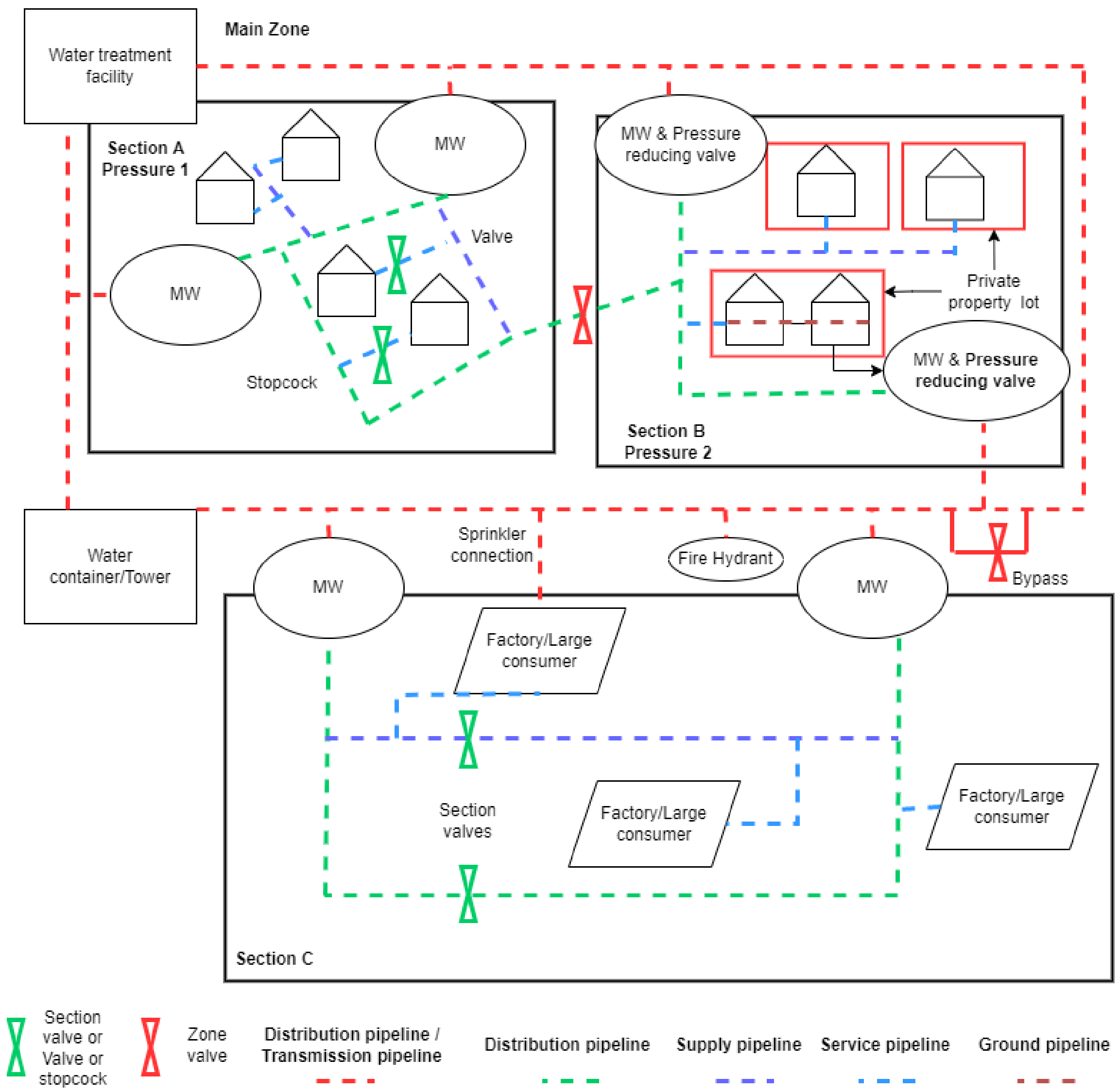

Figure 12, water supply network division principal components. For enlargement see appendix II. Please note Metering well is abbreviated (MW).

Main zone: A self-sufficient operational area in the water network, stretching from the source site to the consumers. Main zones don't typically exchange water but can do so during disruptions. Main zones may include one or more sections.

Section: A distinct part of the water network with its water balance and real-time monitoring provisioned by metering wells (MW).

Valve zone: The smallest hydraulic boundary in the network that doesn't require digging. It includes the pipelines and customers between two valves or between an endpoint and the closest valve.

Pressure zone: This term refers to areas with varying hydraulic pressures in the network, separated by valves or other structures that facilitate water exchange between them.

Structure: A structure is a facility like a measurement/metering well (MW) or pressure regulation system, pressure increase (PI) facilitated by a booster pump, or pressure reducing valve (PR) that affects hydraulics and enables water exchange between areas of low and high pressure.

Ring connection: A pipe system built as a hydraulically connected ring with water inflow from at least two sides. Closing a valve in this system won't cause a water supply failure as water can be supplied from the other side in this case.

There is also a division of water pipelines and valves based on their purpose and structural interconnections, hence the following distinctions are made:

- Transport and Transmission pipeline
- Distribution pipeline
- Supply pipeline
- Service pipeline
- Sprinkler Service pipeline
- Ground pipeline
- Shut off valves or Stopcock valve
- Zone valves
- Pressure reducing valves

In summary, valves are physical components used to regulate or block the flow of water in a pipeline. Their purpose is to control water flow and manage pressure within the network.

Valves are classified based on their functions, such as stopcocks which are used to completely shut off water supply downstream the pipeline from where the valve is fitted.

Transmission pipelines transport drinking water over long distances from the source to the distribution network. These normally have a larger diameter. They are not directly connected to customers and are designed to handle large volumes of water.

Distribution pipelines distribute drinking water within specific sections of the network. They directly connect to customers and transport smaller volumes of water over shorter distances compared to transmission lines.

Supply pipelines deliver drinking water to customers from the distribution network or supply line. Their purpose is to provide customers with water for their use.

Service pipelines establish a connection between the customer's property and the distribution network or supply line. They deliver drinking water directly to the customer's property, and customers are responsible for their maintenance.

Ground pipelines are private pipeline on private property. Carries drinking water from the service line to the meter and tapping point.

In figure 12, depicts that water pipelines can be structured as either ring-connected or one-sided.

A valve zone can be both ring-connected or one-sided. Ring connection means that the pipeline is connected in a loop, while one-sided means that the pipeline is connected to only one other pipeline which has a dead end (TREFOR, 2023).

Ring connections offer the advantage of allowing for selective shutdowns in the event of incidents such as pipe bursts. By isolating a portion of the network, the remaining sections can still be supplied with water from alternate directions. Middelfart´s water supply system is at large designed this way.

One-sided water pipelines are more susceptible to vulnerability since downstream consumers are disconnected from the point of shutdown under necessary circumstances, limiting their access to water supply.

There is a differentiation between section A and section B in figure 12, which operate at varying pressures based on their geographical locations and the relative elevation difference, commonly referred to as "head," between these areas.

There are currently three pressure zones in Middleford, which are further divided into sections. Two high pressure zones an one low pressure. The distinction is made where the water supplied at the each level should have a minimum pressure in the interval of 2.5-5 bar of pressure according to TREFOR.

The low-pressure zone is called “Harbor Zone K45”, which constitute only one section.

The high-pressure zone is called “Zone K59 in Middelfart”. This is the larger zone of the town, which is subdivided into 8 sections. The last high-pressure zone is named “"Staurby T-network K50 in Middelfart", which has only one section. Middelfart currently has a total annual consumption of 2,441,841 m^3 of water.

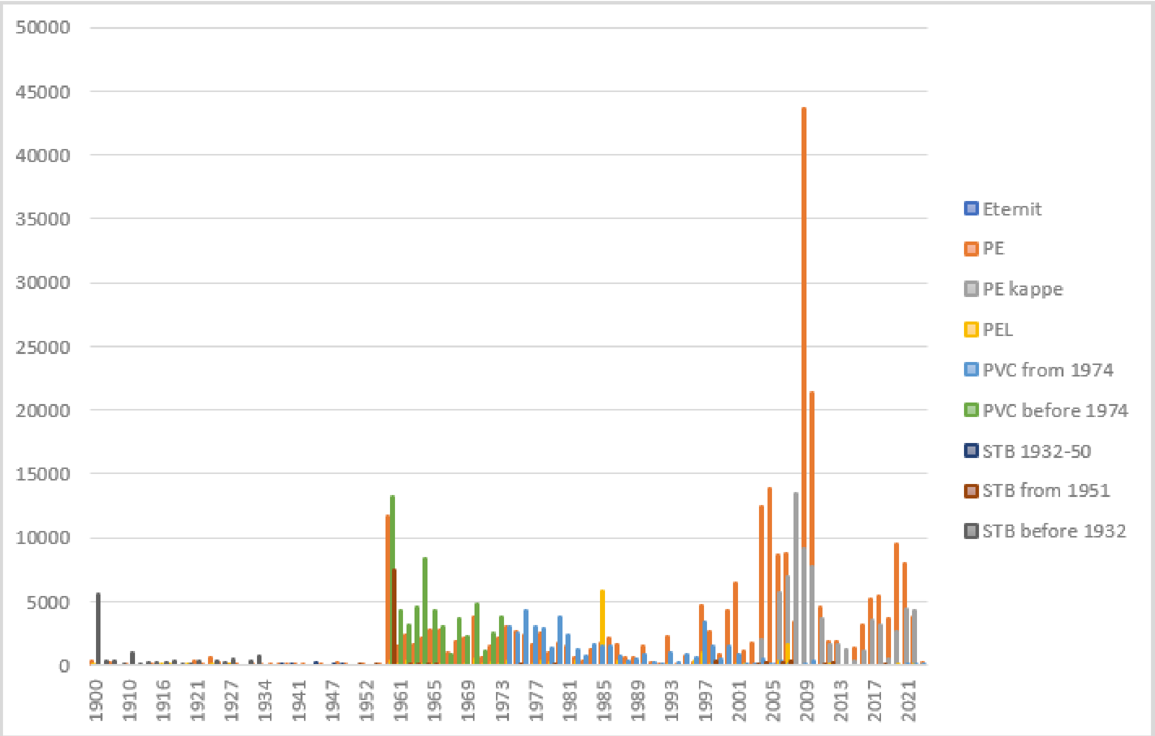

Figure 13, progressive development of water pipelines differentiated on material type and established length [m] put into service between the years 1900-2023 in Middelfart.

In figure 13, the progressive development of water pipelines can be seen, differentiated on material type and established length [m] put into service between the years 1900-2023 in Middelfart.

The total length of the combined water supply system is ~464 km divided into 25,659 segments of pipeline. The data was provided by TREFOR through the Envidan data science department.

Data was processed from the entire pipline database at TREFOR to sort out the pipes which are placed in Middelfart. This was done by geo-coordinates and importing the data into QGIS (A geographic information system), in order to make a selection of the relevant assets in Middelfart. Then once the correct assets where identified, the figure 13 was created. See appendix III for QGIS file and appendix IV for retrieved data.

There are paced two pressure reducing valves in the system between the pressure zones to allow water flow between them. In addition, two booster pumps are placed in the system, which facilitates the pressure change between the pressure zones, having the opposite effect of the mentioned valves.

In the following section the different properties of the pipe materials will be reviewed as shown in figure 13. A short explanation of the mentioned valves and pumps will be given.

Materials and system component types

<u>Water pipes</u>

PE

PE pipes, made from polyethylene (PE) plastic, are commonly used in water supply systems. They are chosen for their durability, flexibility, leak resistance, lightweight nature, and long lifespan. PE pipes can withstand various environmental conditions, resist corrosion, and require seamless fusion welding for leak-free joints. Their flexibility enables easy installation around obstacles, while their lightweight nature simplifies transportation. PE pipes are used in water distribution networks in Denmark, connecting individual properties, irrigation systems, and underground water mains in cities (Dansk Standard, 2011; Kim Brinck, 2014).

PEL

The PEL is made from polyethylene (PE) plastic as well, however mainly used for agriculture and with the only distinction remaining that it is not certified for direct water consumption uses in Denmark (Dansk Standard, 2011).

PE-Kappe

The PE-Kappe pipe, which is a polyethylene (PE) plastic pipe which has a protective coating made of PP. The PP is plastic made from polypropylene, which are resistance to chemicals, have high impact strength.

Hence, making the PE-Kappe composit pipe material highly resistant to damage on its surface and it doesn't easily develop cracks when under pressure. It can handle heavy loads, water pressure changes, and even withstand strong impacts. These properties are essential for situations where the pipe may experience intense pressure, installations in hazardous environments, or pipe replacement using no-dig methods (Dansk Standard, 2011; Kim Brinck, 2014; Uponor, 2023).

PVC
PVC pipes, made from Polyvinyl Chloride, are commonly used in water supply systems. PVC pipes are lightweight, corrosion-resistant, and have a smooth interior surface for efficient water flow. They are cost-effective and resistant to chemicals found in ground or in water (Kim Brinck, 2014).

Cast Iron
Cast iron pipes have been historically used in water supply systems of cities. These pipes are chosen for their strength, durability. They can withstand the high pressures and demands of a city's water distribution network while delivering clean and safe drinking water to consumers. With a long lifespan exceeding 100 years, cast iron pipes provide a reliable and long-term solution for city infrastructure (Kim Brinck, 2014).

Asbestos (Eternit)
Asbestos cement “Eternit” pipes can break easily when there are diggings or movements in the ground. This means that if these pipes are in areas with a lot of traffic, they are more likely to get damaged. They can also fall apart and develop leaks, especially if they are in soil that is acidic and dissolves the cement inside the pipes (Vandcenter syd, 2023).

Pumps
Centrifugal pumps
In a water supply system, a centrifugal pump is a type of pump used to move water from one place to another. It has a rotating part called an impeller with curved blades.

When the impeller spins, it creates a force that pushes water outward. This force draws water into the pump through a suction port. Inside the pump, the impeller speeds up the water and converts its energy into pressure.

The pressurized water is then discharged through another port into the water supply system, where it can be distributed to users (Torben Larsen, 2007). Centrifugal pumps are commonly used because they are efficient, reliable, and can handle large amounts of water.

In Middelfart, centrifugal pumps are used as a booster pump to increase water pressure between the low- and high-pressure zones mentioned earlier. By connecting the booster pump in this way, it ensures that water is delivered at adequate pressure throughout the town, overcoming any pressure deficits and providing consistent water supply to residents, businesses, and other users.

Valves
Pressure reduction valve
A valve type known as a pressure lowering valve aids in regulating the pressure of water flowing through pipes. The pressure lowering valve works by automatically altering the valve opening to restrict the flow and lower the pressure when it senses the incoming water pressure. Only a set maximum pressure may get through due to the adjustable spring-loaded system that counteracts the water pressure in the device. The valve typically consists of an inlet port, an outlet port, a control mechanism (such as a diaphragm or piston), and an adjustable spring.

The incoming water flows into the valve through the inlet port, and the control mechanism responds to changes in pressure to regulate the valve's opening. As the water passes through the valve, the adjustable spring opposes the pressure, ensuring that the downstream pressure remains within the desired range.

Pressure reducing valves have several functions. They shield appliances and water supply systems from extreme pressure, averting harm or leakage. They also aid in extending the life of the system's pipes, fittings, and other parts by bringing the pressure down to a safe level (Envidan, 2023b; Torben Larsen, 2007).

In summary the different types of materials are used in the water supply system, each with their own unique advantages and purposes. The material types and components in a water supply system in Middelfart must be chosen and configured carefully, taking into consideration factors like durability, resistance, pressure handling, and environmental conditions. This leads to the next chapter on hazard identification.

HAZARD IDENTIFICATION

When performing a hazard identification, it is worth considering that different types of hazards pose varying levels of threat. Some require specific strategies to mitigate their impacts. Generally, there are four types of hazards which are worth considering (Nielsen et al., 2019).

Hazards of Type 1: These are events are large-scale events and may be rare. However, they have significant consequences. These types of hazards could be natural catastrophes which are rare and which don’t frequent the same locations necessarily.

Hazards of Type 2: These hazards are known as unknown or emerging hazards, such as new technologies being presented to society such as A.I.. The scale of the consequences associated with this type of hazard and the probability of it from happening are at large unknown in terms of time and space.

Hazards of Type 3: These hazards are comprised of the interdependence between systems or system constituents, which have collateral effects. These hazards often happen in complex systems such as water infrastructure or power grids.

Hazards of Type 4: These hazards encompass the manipulation of information with malevolent intent in the context of information systems. This hazard type can both be related to cyber, spread of falls information with intent to cause harm.

In the context of a water supply system, the Type 3 hazard might involve a failure in the electrical grid that powers the pumps and treatment facilities that supply water Middelfart. If the electrical grid were to fail, and there is no backup power supply, it could cause a cascading failure in the water supply system, leading to widespread water shortages.

The focus in this hazard identification will be related to Type 3 hazards.

To manage this type of hazard, decision-makers might use "what if" scenarios to model the potential impacts of different levels of damage to critical systems. For example, they might ask what would happen if the electrical grid were to fail for several days or weeks, and then model the potential impacts on the water supply system and other critical infrastructure. The occurrence of these scenarios is modelled in the probabilistic resilience model with respect to operational hazards defined by the boundary of the systems reliability (see figure 14 and chapter on model).

Type 3 hazards relate to the overall reliability of a system over time. The bathtub curve is a visual depiction of the failure rate of a system or component can be seen in figure 14. It is called a "bathtub curve" due to its resemblance to the shape of a bathtub (Liu et al., 2022; Torben Larsen, 2007).

The curve is divided into three phases. The first phase is known as the "burn in period". During this phase, the system experiences a relatively high rate of failures at the beginning of its operational life. These failures often occur due to manufacturing defects, design flaws, or other issues associated with the initial stages.

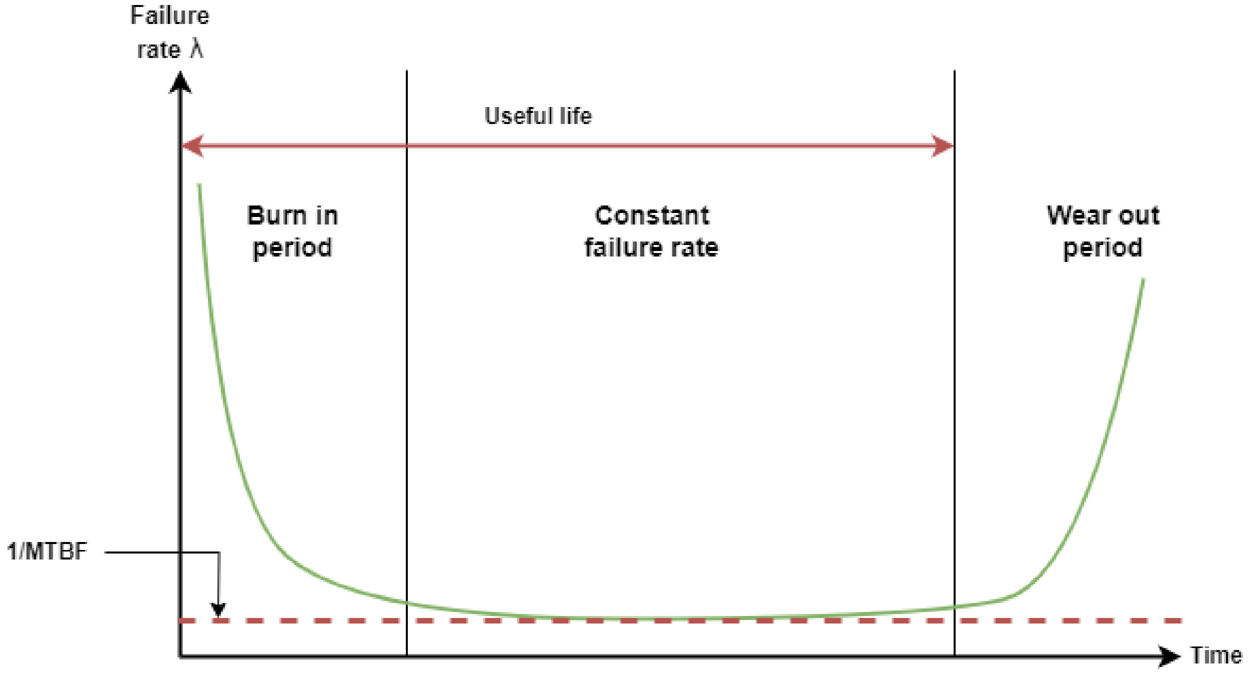

Figure 14, System phases depicted as the bathtub curve (Liu et al., 2022; Torben Larsen, 2007).

The second phase is referred to as the "constant failure rate period". In this phase, the failure rate stabilizes at a relatively low and constant level. The system operates smoothly with a consistent failure rate over an extended period, indicating a relatively stable performance.

The third and final phase is the "wear-out phase.". As the system ages or undergoes long-term usage, its failure rate begins to increase gradually. This increase can be attributed to wear and tear, component degradation, or aging-related factors. The failure rate in this phase rises steadily, indicating a higher likelihood of failures as the system approaches the end of its expected lifespan.

The systematic renewal and replacement of components contribute to maintaining the water supply system in a stable state, where the failure rate is constant and managed to minimized failure events. This is the assumed phase for the existing system in Middelfart.
Parts of this hazard identification has been performed together with Envidan, as well as related literature was consulted (Kim Brinck, 2014; Raspati et al., 2022; Tang et al., 2019b; Torben Larsen, 2007).

To illustrate the hazards posed to the system, the principles of events and their direct and indirect consequences is presented in figure 15 (M. H. Faber, 2008).

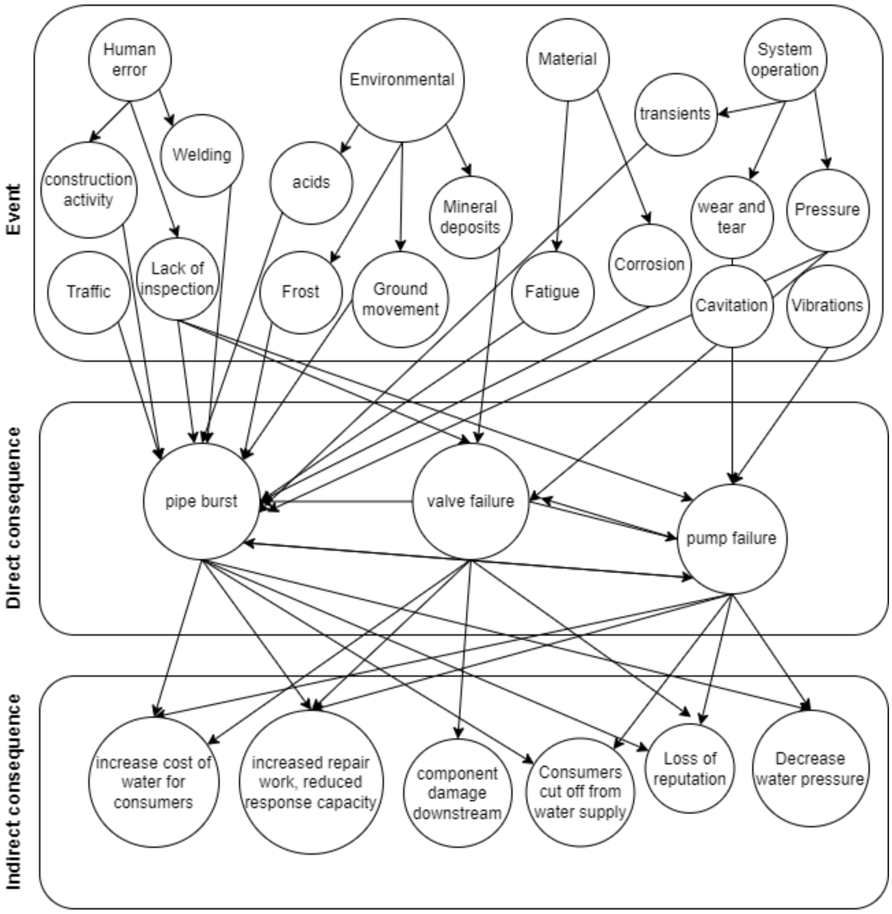

Figure 15, events and their direct and indirect consequences, for enlargement see appendix II.

In this part the different types of hazards are elaborated upon, both in terms of material and component types as well as their direct and indirect consequences.

The interdependencies within the water supply system create a web of cause-and-effect relationships that are essential for the overall system's functionality.

Centrifugal pumps play a crucial role in maintaining a consistent flow and appropriate water pressure throughout the piping network. However, pipe degradation or failure could lead to an increase resistance within the system due to the redirection of the water flow. This heightened resistance could result in leaks or pipe bursts, thereby taxing the pumps as they struggle to maintain water flow and pressure. Conversely, the failure of a centrifugal pump could halt the water flow in the pipes, reducing water pressure or potentially disrupting the water supply entirely.

Pressure reduction valves and pipes are another critical pair in the system. These valves are designed to regulate and maintain a consistent pressure within the pipes. However, the degradation or failure of pipes could unbalance the system's pressure, increasing the load on the pressure reduction valves as they work to mitigate these fluctuations. On the other side of the equation, should a pressure reduction valve malfunction and fail to regulate high pressure, this could increase stress on the pipes, leading to potential damage, leaks, or even bursts.

Finally, centrifugal pumps and pressure reduction valves share a symbiotic relationship. These two components collaborate to control the pressure within the water supply system. A malfunction in a centrifugal pump could reduce the pressure within the system, decreasing the operational load on the pressure reduction valve. In contrast, if a pressure reduction valve malfunctions and fails to curb high pressure, the pumps would face increased resistance, straining to maintain water flow against the high pressure.

Regarding the hazards affecting these interdependencies, internal and external threats can cause direct disturbances. Internally, wear and tear, fatigue, corrosion, joint failures, and malfunction due to mineral deposits can directly impact the pipes, pumps, and valves.

Externally, physical damage from construction activities, ground movements, frost, human errors during operation, installation, or maintenance, and incorrect installation or adjustments can pose significant threats.

These hazards can lead to failures in any of these components, causing a domino effect that disrupts the entire system.

This complex interplay highlights the significance of regular maintenance, inspection, and updating of the water supply system to ensure its efficiency and reliability, thereby avoiding potential direct and indirect consequences. A hydrodynamic model such as one created in EPANET could provision such insights (see chapter on discussion).

The material the specific hazards are elaborated upon in this part:
Pipes: PE and PEL and PE-Kappe PCV, Cast iron:
Operational Hazards:
Over time, these pipes may undergo material fatigue due to continual exposure to variable pressures or temperatures, leading to eventual degradation. Additionally, the pipes' joints, typically connected by fusion welding, may weaken and lead to leaks if not properly installed or maintained. Like PE pipes, the PE-Kappe pipes may experience material fatigue or joint failures over time.

PVC pipes can become brittle over time. Pressure transients can pose internal hazards to these pipes, however this also evident for alle other pipe material types. Pressure transients are sudden changes in pressure within the piping system, typically caused by events such as water hammer, pump start/stop cycles, or valve operations. These transients can subject the PVC pipes to significant stress and strain, potentially leading to pipe failure, cracks, or leaks.

Cast iron can corrode, particularly in the presence of aggressive water conditions that could erode the internal lining. Scaling and rusting can also occur, reducing the effective internal diameter of the pipes and consequently the flow rate. Pinhole failures occur when small holes develop in a pipe due to corrosion or other factors. Joint failures occur when the connections between pipes fail, either due to poor installation or deterioration over time.

Asbestos (Eternit) is having cement in these pipes which can be dissolved by acidic soil, leading to pipe failure.

External Hazards:
Physical damage from construction activities, ground movements due to environmental conditions could compromise the pipes causing circumferential or longitudinal failures. Plastic material pipes if exposure to high temperatures could cause deformation before installation.

Furthermore, improper installation or mishandling during construction can also lead to cracks and fractures. In terms of Eternit pipes are more vulnerable to breakage during ground movement or construction activities. In addition, if the pipe is damaged, there is a risk of asbestos fibers being released, which poses a significant health hazard.

Human errors can happen during wielding, placing pipes, and foundation work in construction, which all contribute to compromised pipeline integrity. These errors may result in misalignment, weak joints, or insufficient support, making the pipes more susceptible to leaks, cracks, or structural failure.

No-dig methods, such as horizontal directional drilling or pipe bursting, can be advantageous for pipeline installation due to minimal excavation. However, during the process of pressing new pipes through the ground, unforeseen obstructions or excessive forces can cause unintended damage to existing pipeline.

Accidental hits on existing water pipelines during excavation activities, such as digging for construction projects or utility installations, can lead to immediate damage. The impact from excavation machinery or tools can cause pipe deformation, cracks.

Heavy vehicular traffic passing over buried pipelines, especially in areas with high volumes of commercial or industrial vehicles, can exert significant pressure on the pipes. Over time, excessive traffic loads can weaken the structural integrity of the pipelines.

In colder climates, frost can penetrate the ground and cause soil expansion. Ground movement due to geological factors, such as soil settling, or slope instability, can pose risks to the stability and functionality of the pipelines.

Centrifugal Pumps:
Operational Hazards: Wear and tear due to constant rotation can degrade the impeller over time, reducing pump efficiency. Moreover, poor maintenance or lubrication can lead to pump failure. High frequency in start and stop intervals also lead to overheating which may damage the pump.

Vibrations can also impact the performance and integrity of centrifugal pumps. Vibrations can arise from factors such as misalignment of pump components, unbalanced impellers, or cavitation.

External Hazards: Human errors during operation, installation, or maintenance can result in pump damage. Improper electrical connections or unstable power supply can also pose a threat.

Pressure Reduction Valve:
Operational Hazards: The valve can malfunction due to wear and tear or a buildup of mineral deposits, which can impede the control mechanism and affect its pressure regulating capacity.

External Hazards: Incorrect installation or adjustments can lead to an improper pressure setting, potentially resulting in high pressure that can damage the downstream system.

Next the potential direct and indirect consequences will be addressed due to component failure which has been mentioned:

Pipe Degradation or Failure:
Direct Consequences: If the pipes degrade or fail, it can lead to leaks or burst pipes. This would not only waste the supplied water but also reduce the water pressure downstream, potentially disrupting the water supply to homes, businesses, and public facilities in Middelfart.

In a ring connection, where multiple sections are interconnected, cutting off one section can cause a redistribution of pressure within the system. The pressure in the remaining sections may increase or decrease, depending on the flow characteristics and the relative resistance to flow in each section.

When a pipe degrades or experiences a failure, the flow of water is redirected through the remaining pipes in the ring, leading to an increase in pressure within those pipes. This increased pressure creates additional resistance for the remaining pipes, which can exacerbate the potential for leaks or burst pipes.

Indirect Consequences: Frequent pipe failures can result in costly repairs and replacements, which could eventually lead to increased water bills for consumers. Also, disruptions in water supply can affect daily activities and operations within the city. Leaks could also cause soil erosion or other environmental damage. Can cause consumers being cut off from water supply for a period.

Centrifugal Pump Failure:
Direct Consequences: If a pump fails at the water works, it could disrupt or reduce the water supply to the entire city. If a booster pump fails, it could affect the water pressure, especially in high-pressure zones that depend on these pumps to elevate water pressure.

Indirect Consequences: Water supply disruptions due to pump failures can significantly impact daily life, businesses, and public facilities. It could also lead to customer dissatisfaction and reputational damage for the water supply company.

Pressure Reduction Valve Failure:
Direct Consequences: A malfunctioning pressure reduction valve can result in excessively high pressure. High pressure can lead to pipe damage, leaks, and even bursts.

Indirect Consequences: High pressure can lead to more frequent pipe failures and increased maintenance costs. When the pressure reduction valve fails and high pressure persists, the overall stress on the pipes increases.

In summary with more frequent pipe failures, the maintenance requirements of the system increase. Repairs, replacements, and troubleshooting become necessary, leading to higher maintenance costs. Additionally, the associated costs of addressing leaks, restoring damaged infrastructure, and potential environmental impacts can further contribute to the increased maintenance expenses.

Pattern recognition of external hazards to the pipelines in Middelfart
The data from TREFOR was sorted however the resulting data was very limited. Despite that a few different ML methods have been applied to the data in an attempt to make predictions. The resulting accuracy scores are shown in table 1.

Model	Accuracy
Logistic Regression	0.4615
Support Vector Classifier	0.5000
Random Forest	0.3462

Table 1, ML model accuracy based on external hazard data (TREFOR).

The utilization of the support vector classifier is employed to assess damage caused by ground movement in all registered dimension sizes exceeding 110mm in diameter across various Material types.

This observation relates to dimensions which fall within the calculated range in the resilience model, implying a higher vulnerability to ground movement hazard, compared to other external hazards such as human errors arising from excavation impacts, frost, or welding inaccuracies. It is possible that conducting thorough geological surveys, could potentially improve or mitigate this issue, which seems predominant in Middelfart in this range of pipe dimensions. For further details on the models and calculations, please refer to appendix V.

MODELS

Modelling the Water Supply System in Middelfart
In this chapter two different modelling approaches will be applied. The first will be the mentioned applied probabilistic resilience model, which can be used for decision analysis mentioned in the methodology. The model solely focusses on the degradation processes of water pipelines and mean time between failure (MTBF) of valves and pumps within the system. Hence the model does not consider any external hazards that could influence its performance or its condition. The second model will investigate different renewal strategies and their associated costs. The intention was to combine the two, however due to time limitations will not be done in this thesis.

Probabilistic resilience model
This scenario-based modelling approach (Faber, 2018), groups different failure events and calculates their expected value which is a statistical concept that represents the average outcome of a random variable over many trials and is applied in Bayesian decision making (Michael H. & Faber, 2012). Hence the outcome with the highest expected value, applied to this model, is the identification of scenarios which has the highest economic impact. Given the probability of the scenario event and the scale of its consequences.

In figure 16, the procedural steps of the model are illustrated.

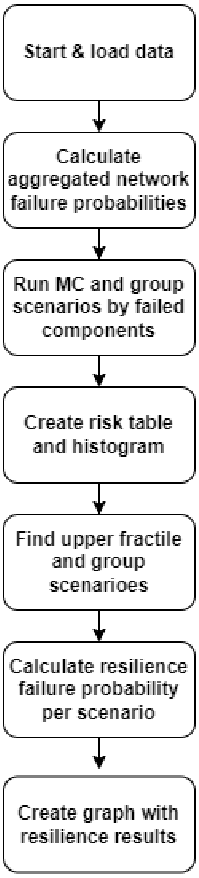

Figure 16, procedural steps of the probabilistic resilience model. For enlargement see appendix II.

Probability of failure

To determine the probability of failure for the different components of the system, including pipe types, valves, and pumps, relevant information has been collected and incorporated into the model.

For the estimation of probability of failure for the pipes in the system, bursts frequency functions have been developed by Envidan and members of DANVA which is an interest organization that represents professionals working in the field of water and wastewater. It operates as a separate nonprofit association, funded by its members (DANVA, 2023; Envidan, 2023b).

The parameters 'a', 'b', 'c', 'd', and 'e' in the 4^{th} degree polynomial function result in different burst frequency function with respect to material type depicted in figure 17, (see Appendix IV for function details in related to material type). The frequency of failure for each pipe material with respect to its age and length, is then used as the shape parameter λ, for the non-homogenous Poisson distribution to account for the probabilistic nature of failure.

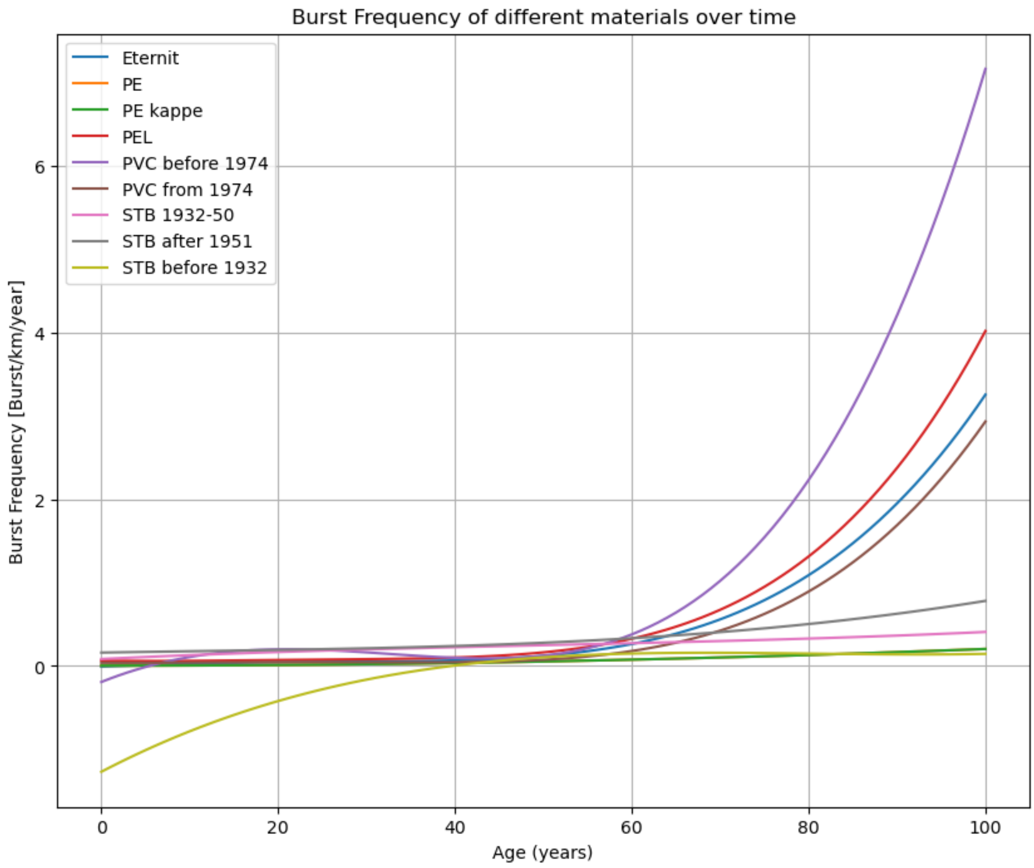

Figure 17, deterioration rates of pipe material types provided by Envidan, which is applied to the model as the shape parameter for Poisson distribution over time. See Appendix IV for details on the provided parameters.

In the context of pumps in the water supply system of Middelfart, the "mean time between failure" (MTBF) refers to the average duration between two consecutive failures of the pumps. It provides an estimate of the reliability and performance of the pumps by quantifying the average time they operate without experiencing a failure (Torben Larsen, 2007) Also see figure 14.

MTBF can also be considered for pressure reducing valves in the water supply system. It represents the average interval between failures of these valves, indicating their reliability and performance in maintaining appropriate water pressure.

MTBF is a critical parameter in evaluating the reliability and maintenance requirements of pumps and pressure reducing valves in the water supply system. It helps guide decisions regarding maintenance schedules, spare parts management, and system design.

In the water supply system of Middelfart, the pumps undergo biannual servicing by Grundfos (Grundfos, 2023). As a result, it is assumed that the probability of failure is limited to occurring between the service periods and is for simplicity of the model assumed reset at the beginning of each service interval.

Data in this regard was requested at TREFOR, however the data was inconclusive and therefore assumed values have been used based on selected components from the OREDA data (DNV - OREDA, 2002). OREDA (Offshore Reliability Data) is a database that provides comprehensive information on the reliability and failure characteristics of various types of equipment used current operations.

This database is widely used in reliability engineering and risk analysis to estimate failure rates and performance parameters.

In this case, the OREDA failure data has been utilized to select the diaphragm valve as suitable for the pressure reduction valve in the water supply system. The diaphragm valve is assumed to have similar operational characteristics and failure patterns to the pressure reduction valve being analyzed.

The mean value of breakdown used for the valves are 38.05 per 10^6 hours. With the assumed time between service being one year (DNV - OREDA, 2002). There is a total of 2 valves placed in Middelfart.

As for the pumps a mean value of breakdown of 5.08 per 10^6 hours is used. The value is derived from the oil export pumps (DNV - OREDA, 2002). In Middelfart the known service interval of pumps are every 6 months as mentioned. There are considered a total of 6 pumps in Middelfart who perform the functioning of distributing the water around the city and between low- and high-pressure zones. For simplicity of modelling no other modes of failure have been applied.

Because they operate in pairs (one for redundancy), it is assumed that one will be in constant operation, and when it fails only then will the other respond and take over.

In conclusion all the mentioned rates of failure are used in the resilience models Monte Carlo simulation. This is done to estimate the probability of different failure events within the system.

Direct consequences

The model focuses on the direct consequences related to repair costs for pipeline bursts, pump failure repair cost, and valve failure replacement cost. When it comes to repairing water pipes, the average cost of 11,210 DKK based on 33 burst events in 2022 is used as a baseline, as detailed information regarding surface types and excavation depth was not stressed. Efforts were made to gather data from the bookkeeping department, but due to a new system implementation in 2020, only records from the past three years were accessible, with the most complete data being from 2022.

Regarding valves, the estimated total cost for replacing pressure reducing valves is set at 10,000 DKK per component. However, for pumps, the information provided only includes the total price of the pump system, making it challenging to differentiate between failure types mentioned in the hazard identification chapter.

Referring to (Torben Larsen, 2007), it is assumed that the repair or replacement cost for pumps can be standardized as a percentage of the gross list price based on pump type and age. Consequently, the cost for repairing or replacing a pump engine is assumed to be 80% of the original price. Since complete data for all pumps was uncertain, a price of 158,267 DKK is used as an approximation for all pumps in the model making the event of failure translate into a total cost of 126,613 DKK.

Indirect consequences & response time
To model the indirect consequences of a failure event, both the response time and the loss of benefit due to the failure event is considered.

TREFOR response time data was analyzed using statistical methods to determine the most appropriate probability distribution that could model the data as shown in figure 18.

A method of moments was used to approximate a truncated normal distribution. The method of moments is a statistical technique used to estimate the parameters of a probability distribution by equating the sample moments with the theoretical moments of the distribution (Michael H. & Faber, 2012). Given that the lower limit for the data is 0 (as indicated by the variable a), a truncated normal distribution seems to be a reasonable choice, particularly since the reasons is that the data cannot assume negative values (since one cannot have negative response times to events).

A histogram of the data along with the PDF of the estimated truncated normal distribution is plotted, providing a clear visual comparison of the data and the fitted distribution. See Appendix V, providing the calculation.

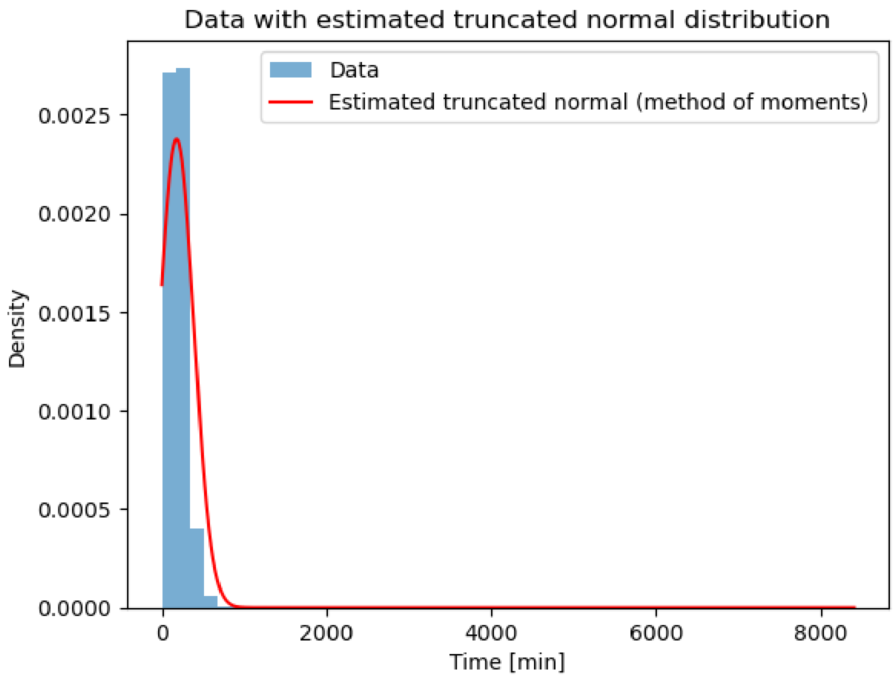

Figure 18, histogram with estimated truncated normal distribution for response times used in the model.

While the response time may vary, so will the consumption of the closed of area under investigation while searching for the water leakage. The average household uses around ~140 m^3 /year in Middelfart.

If the burst happens in the period of consumption while also adding the loss of water from the pipeline the following model assumption used that the usage is spent in 1/3 of the 24-hour day, evenly spread throughout the year. TREFOR has a policy that they do maximum allow for up to 100 households to be close of at any given time.

This results in an assumed combined water loss to consumers of ≈ 0.079 m^3 /minute. The sale price of 1 m^3 of water is 66 DKK. This results in 5,21 DKK per minute, an additional 45 DKK is added to account for any damages, however this value is assumed and should be corrected when data becomes available. Hence, the total cost per minute is 50,21 DKK as the indirect cost due to loss of income and collateral damages.

To get closer to a realistic result would require the feedback from a hydraulic model for the specific area affected. Other considerations could be made in terms of water lost from resulting burst as well as cost incurred by water damage.

The indirect cost due to valve or pumps failure will not be considered in this case. The assumption of reduced benefit generation during a failure state is also not applied to this model as was depicted in figure 10.

Accumulation of benefit
The total water sale in Middelfart is estimated at 2,441,841 m^3, which translates to a total of 161,161,506 DKK in income a year. The profit covers significant services at TREFOR other than the sole production of water and its distribution. Currently there is no budget specifically for the coverage of pipe bursts and the components mentioned so far. The main argument being that it must be fixed no matter what.

After discussing this matter with TREFOR, the accumulation of benefit is analyzed in the range of 0.15-0.25 % of the total income from Middelfart, and then conduct a sensitivity analysis of the budget over time. This means the accumulation of benefit χ will range from (0.15 - 0.25%). The discount rate r_γ will be assumed to be 5%. The initial available capital will equal 1,611,615 DKK or 1% of the total income.

Renewal model
A second modeling approach was attempted to evaluate the rate of renewal of the water supply system. The primary objective was to conduct a sensitivity analysis on a proposed management strategy. The strategy focuses on determining burst frequencies for the system and prioritizing the replacement of pipes based on their age, with the oldest ones being renewed first. Key parameters assessed include burst frequencies, average pipe age, and system value as is considered in (DANVA, 1995).

To illustrate this, the steps involved in the modelling approach are outlined in figure 19.

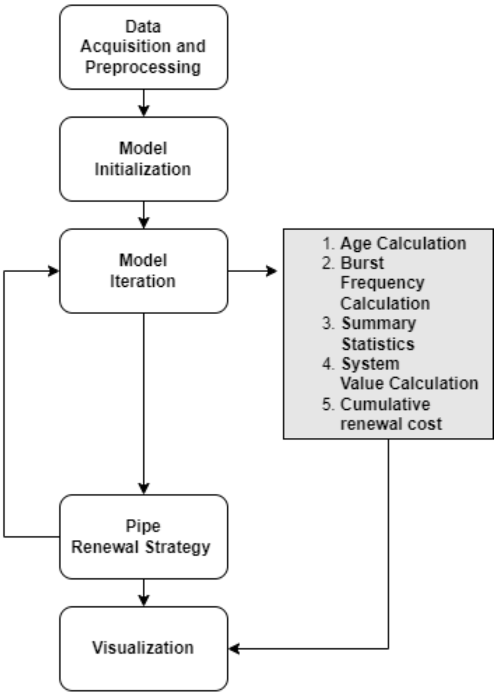

Figure 19, modelling approach for estimate the renewal strategy based on choice of burst frequency.

Data Acquisition and Preprocessing: The first step involves loading the relevant pipe data, which includes details such as the establishment date, length, renewal price, lifespan, and parameters 'a', 'b', 'c', 'd', 'e' related to the burst frequency function as shown in figure 18.

The current year is calculated, and the age of each pipe is determined by subtracting the year of the pipes establishment from the current year.

Model Initialization: The data is loaded and copied into a dataframe which store the burst frequency results, and empty dictionaries are created to store results for total burst frequencies, average ages, and cost over the years.

Model Iteration: The model iterates over a period of 25 years. For each year, the model performs several calculations namely:

- Age Calculation: The age of each pipe for the current year is calculated.
- Burst Frequency Calculation: The burst frequency for each pipe is calculated using a polynomial function of the pipe's age (see figure 18).
- Summary Statistics: The total burst frequency and average age of the network for the current year are calculated and stored for each year over the period of 25 years.
- System Value Calculation: The total value of the pipe network for the current year is calculated. This is done by taking into account the lifespan and current age of the pipes, and the increment for each year is added to reflect the depreciation of the network. The total value of the network is

calculated as the cost of renewal (which is the product of the renewal price per length and the length of the pipe) minus the depreciation. The depreciation is calculated by, the cost of renewal is divided by the life expectancy of the pipe, and this result is multiplied by the current increment in years. This is to account for the decrease in value as the pipe gets older. As time goes on (i.e., as the increment variable increases), the total value decreases.

After this, the renewal cost is added to the total price. This gives the total value of the network for each year. This calculation is done for each strategy and for each year, considering the renewal operations performed according to the strategy's condition.

However, this model uses a simplification, and it does not account for the time value of money or the detailed calculation of depreciation.

It also assumes that the cost of renewing a pipe is constant over time, which might not be the case in real scenarios. However, the pipes that get replaced can be extracted by the time of replacement from the model, hence enabling for later corrections in price.

Finally the pipe renewal strategy and cumulative cost is applied as a proactive pipe renewal strategy is implemented where older pipe segments can be replaced to maintain a set maximum burst frequency.

This involves iterating over the pipes sorted by age and replacing the oldest pipes until the maximum burst frequency is no longer exceeded. The renewal cost is calculated based on the renewal price and length of the pipes renewed. The prices for renewal are provided by POLKA index (see Appendix IV). POLKA stands for Price and Lifetime Catalog (Pris og levetidskatalog in Danish), which is used to determine the tax value of water companies' assets (Konkurrance of forbrugsstyrelsen, 2023).

Visualization: Finally, the calculated total burst frequencies, average ages, and total values of the pipe network are plotted over time along with cumulative costs. These plots provide a visual representation of how the parameters of the water supply system evolve over the years under the implemented management strategy.

Through this modelling approach, the aim is to gain insights into the future states of the water supply system in Middelfart, understand the cost implications of different management strategies.

The assessment relating to the replacement of pipes can be employed and transferred to the probabilistic model mentioned earlier. Functioning as a selection function, for scenarios in which pipes are renewed, and the change in frequency is made in the resilience model (see figure 20).

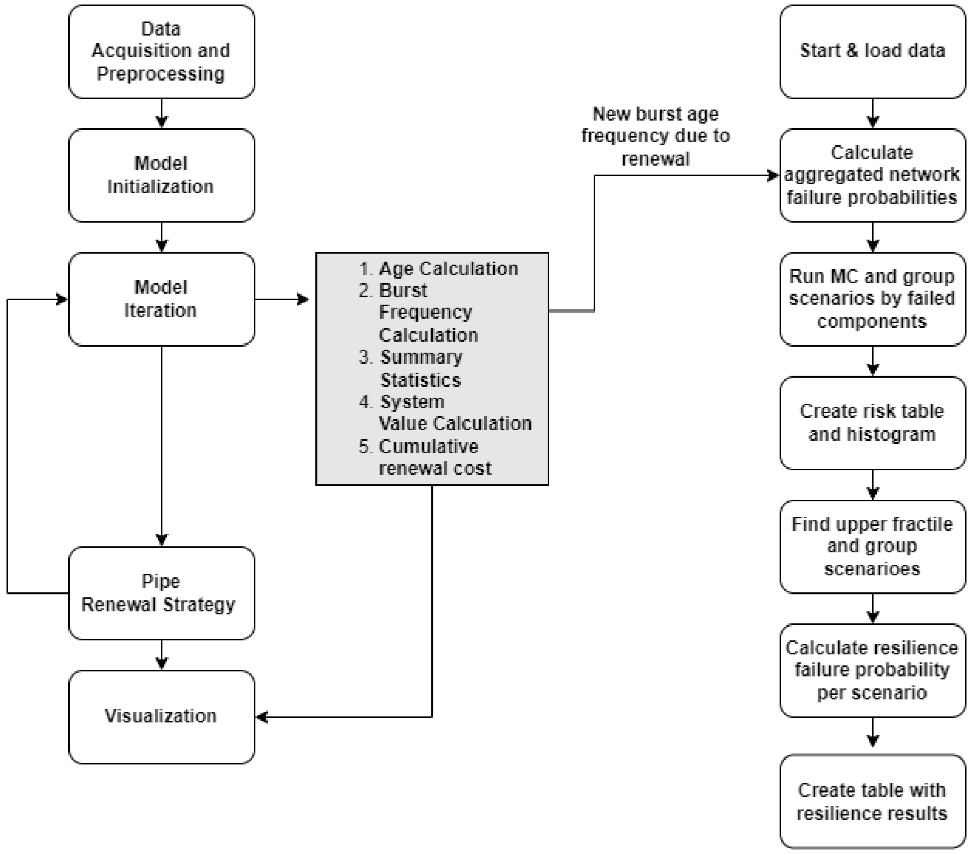

Figure 20, Use case for model connection of renewal strategy and probabilistic resilience model.

RISK ANALYSIS

MODEL ANALYSIS - RESILIENCE & RENEWAL MODEL

In this chapter a risk analysis and model results will be shown and expanded upon.

Resilience model

The resilience model constitutes a 3-part analysis, (i) the model investigates the total risk and expected values of all simulation results. (ii) the model identifies the scenarios and associated components with the highest expected value. (iii) a sensitivity analysis is performed by variation in benefit savings, and a fixed starting capital of 1% of total income from water sale.

The Monte Carlo simulation was executed with 100,000 iterations spanning a timeframe of 10 years. Considering the substantial computational requirements, only pipelines with a diameter exceeding 110mm were considered, encompassing a total of 1,574 components instead of the entire 25,659 pipeline segments which constitute the entirety of the system. Additionally, the pumps and valves were incorporated into the model. The computation time was 7+ hours per simulation (see appendix V).

Then the scenarios are grouped, and probability of the event is calculated along with direct-, indirect cost, response time, number of pipe bursts, and failed valve and pumps. Also, total cost, net present value and expected value is calculated for every scenario, which constitute collectively constitute the failure scenario within one year.

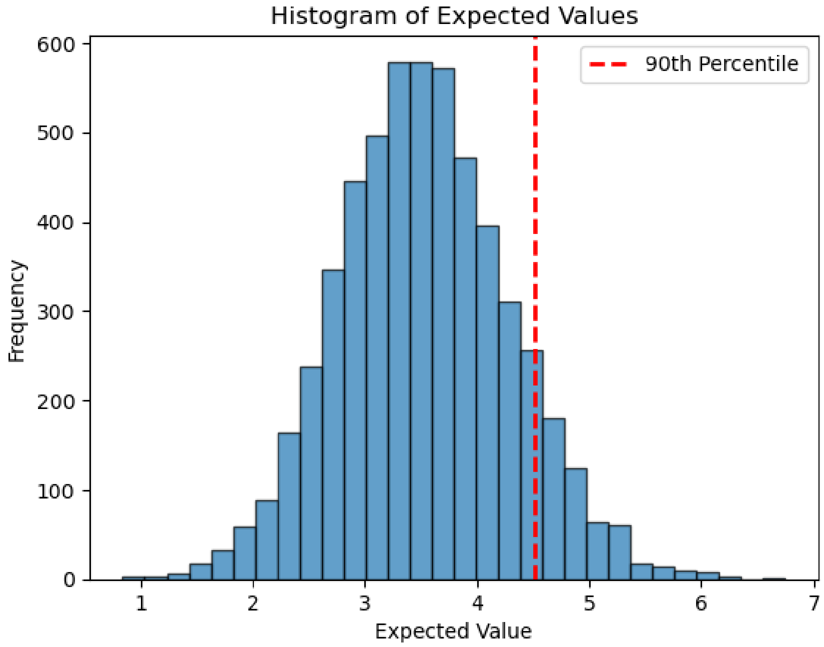

Figure 21, Histogram of total risk with upper 90th percentile marked by the red dotted line.

Figure 21 represents the total risk and upper 90th percentile of expected values. This upper range would be interesting to analyze since the scenarios here have the greatest impact on the system.

The identification of which components contribute to these modes of failure in this area can this way be identified, and decisions can be made regarding how to reduce the probability of failure for those components. Such as reducing the MTBF of selected pumps, valves or change of pipeline material.

Scenario with highest expected value
Scenario: PIPELINE ID: [18017, 18031, 18032, 19891, 20819, 20862, 20944, 21002, 21023, 21534, 21564, 104737, 107596, 108117, 108134, 168707, 172607, 198885, 213393, 240956, 349631, 1013695, 1013697], **PUMP ID:** P3
Expected Value: 6.74
Net present total value of event: 674,515 DKK
Number Of Bursts: 30
Probability of Failure: 1e-05

Table 2, Scenario with highest expected value from simulation shown in figure 21.

Table 2 displays the scenario with the highest expected value. The pipeline id's which contributed to this failure event are listed along with which pump failed. As mentioned, before it would be useful to investigate these components further and consider how changes to their vulnerability might change the outcome of new calculations by reducing their probability of failure.

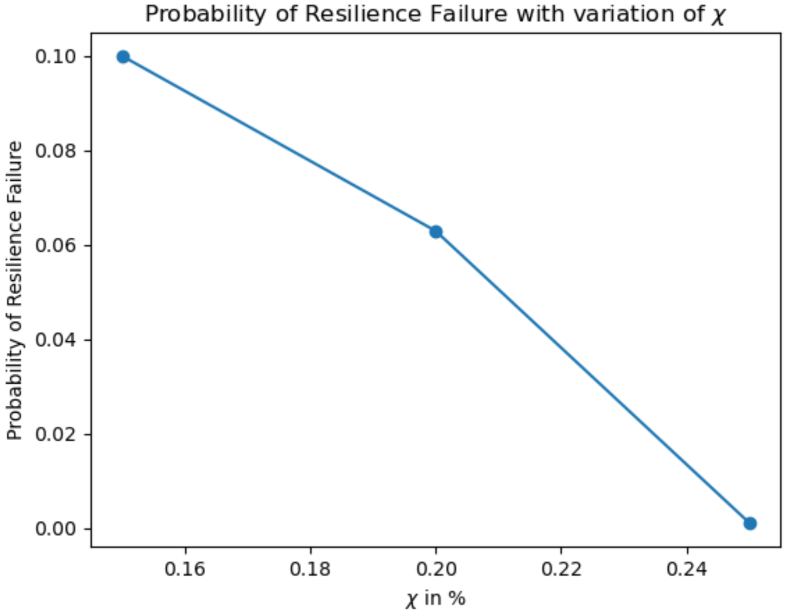

Figure 22, probability of resilience failure sensitivity analysis with variation in benefit savings, and a fixed starting capital of 0.1% of total income from water sale.

In figure 22, the probability of resilience failure is representing the range of variation in benefit savings between 0.15% - 0.25% and a fixed starting capital of 0.1% of total income from water sale. At a benefit savings rate of 0.15%, the probability of risk amounts to 10%. When benefit savings increase to 0.2%, the risk of resilience failure decreases to 6.5%. Furthermore, with a benefit savings rate of 0.25%, the risk diminishes further to 1%.

These are the cost associated with risk reduction over the evaluated time horizon with respect to the specific configuration of system components chosen for analysis. Consequently, decision-makers at TREFOR can assess and determine their desired level of risk acceptance based on the availability of budgetary resource (see appendix V for model).

Renewal model

The model analyzes the present and future conditions of the system for all pipe segments which constitute a total of 25,659 components. The model evaluates three decision options that the utility company TREFOR, regarding the maximum permissible burst frequency for their water supply system in Middelfart.

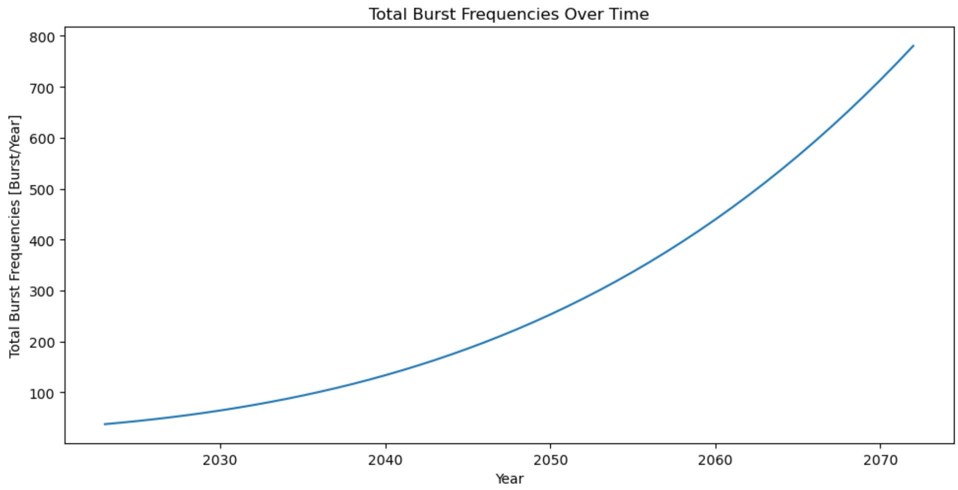

Figure 23, total burst frequency over a 50 year time-period of the water supply system.

The renewal model seemed to fit well since there in 2022 was registered 33 burst due to material factors, and the model which was calculating from 2023 had a start rate of 36 bursts.

As depicted in figure 23, the cumulative burst frequency of the integrated water supply system is projected to experience a substantial failure rate due to the escalating incidents of pipe bursts. This assessment encompasses a time span of 50 years, assuming no renewals are carried out.

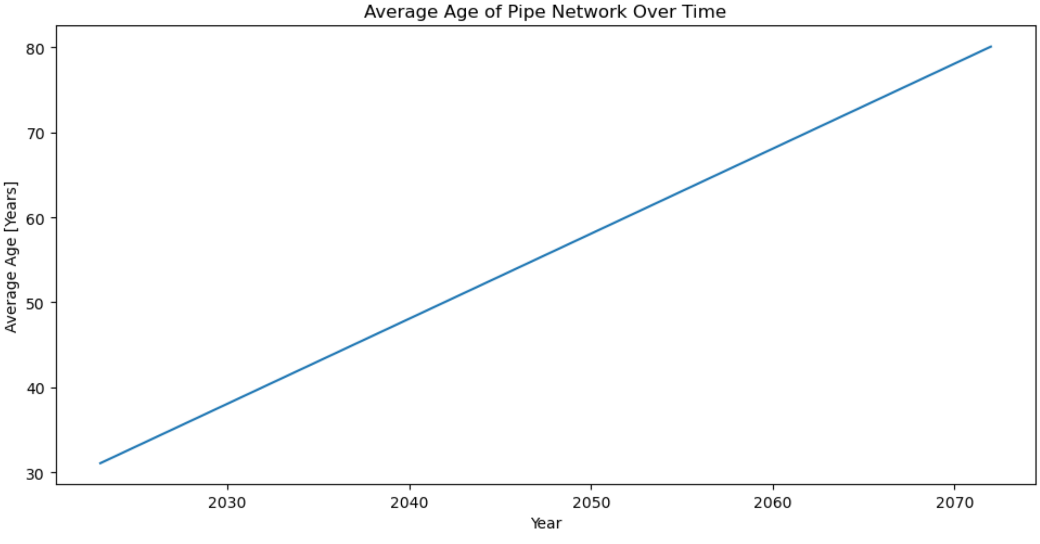

Figure 24, the average age of the water supply system over a 50-year time-period.

The average age of the water supply system shows a consistent upward trend as shown in figure 24. The projected lifespan for all pipes is 75 years, while specifically for steel pipes, their operational life expectancy extends to 100 years.

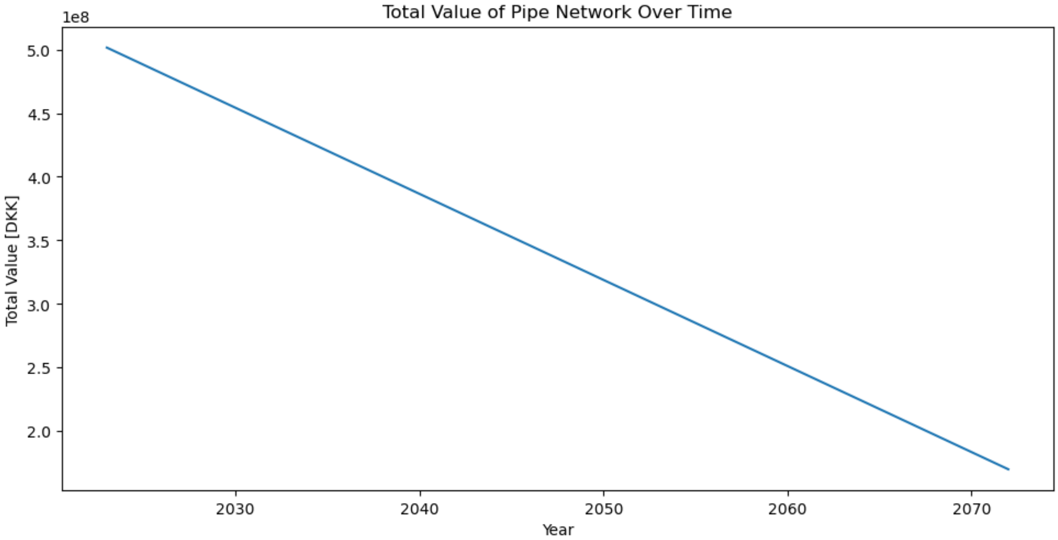

Figure 25, the total value of the pipe network over a 50-year time period.

In figure 25, is showing the total value of the pipe network over a 50-year time. The depreciation function calculates the total value of the pipe network by subtracting the accumulated depreciation from the initial cost. This provides an estimate of the remaining value at each year for the combined system.

The function considers the length of each pipe and applies a depreciation rate based on its lifespan. The utility company was involved in the discussion and decision-making process regarding this approach.

In following part, a set target for maximum burst frequencies in the system is selected. Three options are considered here. Namely a maximum of 50, 75 and 100 burst per year for the system, which are calculated over the period of 25 years.

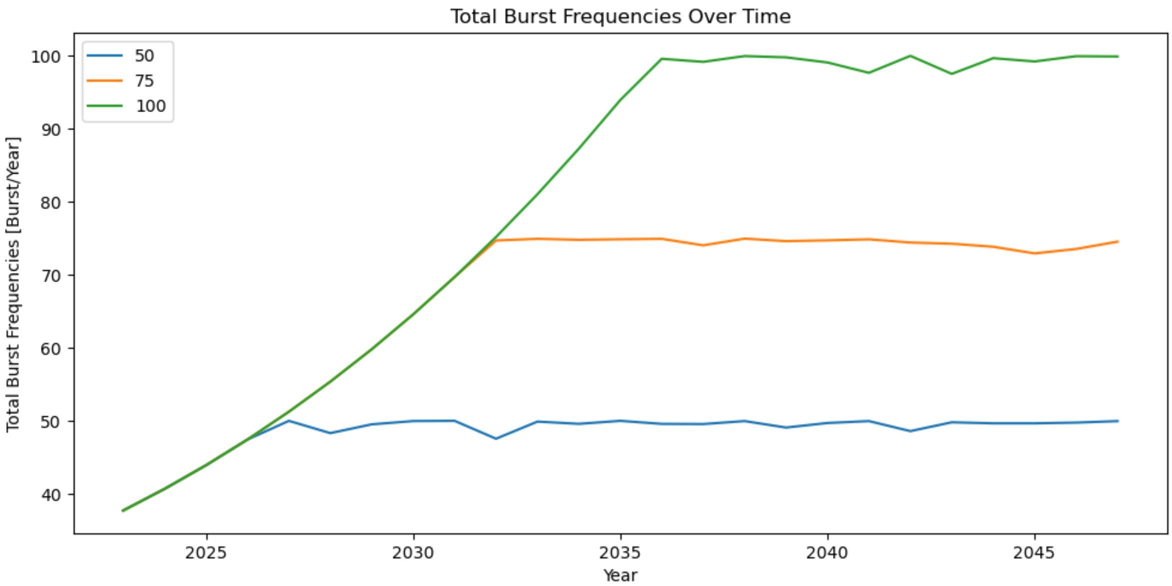

Figure 26, the system burst frequency over a 25-year time period of the water supply system.

Figure 26 illustrates the three distinct burst frequencies observed as the system approaches its target limits. As previously stated, the pipes chosen for replacement to reduce the system's burst frequency are determined by their highest age.

This process continues until the frequency reaches or falls below the desired threshold. Occasionally, there may be variations around the threshold because certain pipe segments selected for renewal could be longer in length.

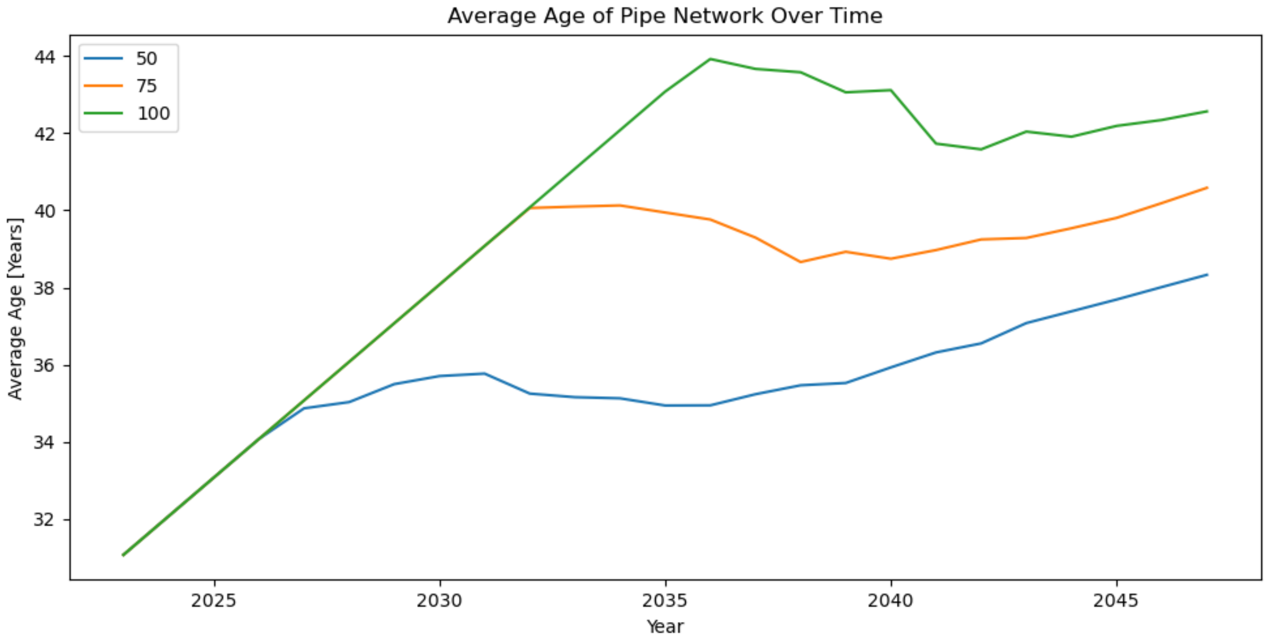

Figure 27, the average age of the water supply system over a 25 year time-period.

When the pipes in the system are renewed, the average age, depicted in figure 27, is adjusted, and becoming younger. However, over time, the average tends to shift back towards an upward trend as the newly replaced components age and the components that haven't been renewed contribute more to the overall age.

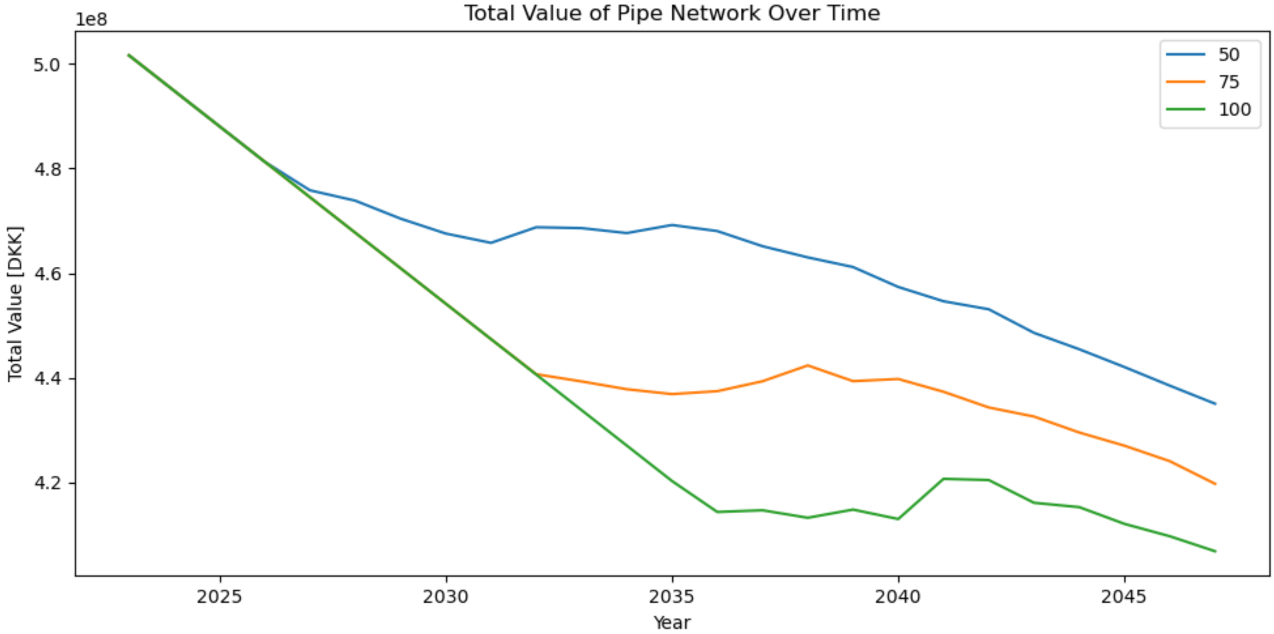

Figure 28, the total value of the water supply system over a 25-year time-period.

As depicted in figure 28, it is anticipated that the overall value of the system will rise or move counter to its rate of depreciation during periods of new investments.

However, as time progresses, the significance of older pipe components begins to exert a downward pressure on the remaining value of the system, alongside the previously depreciated pipes.

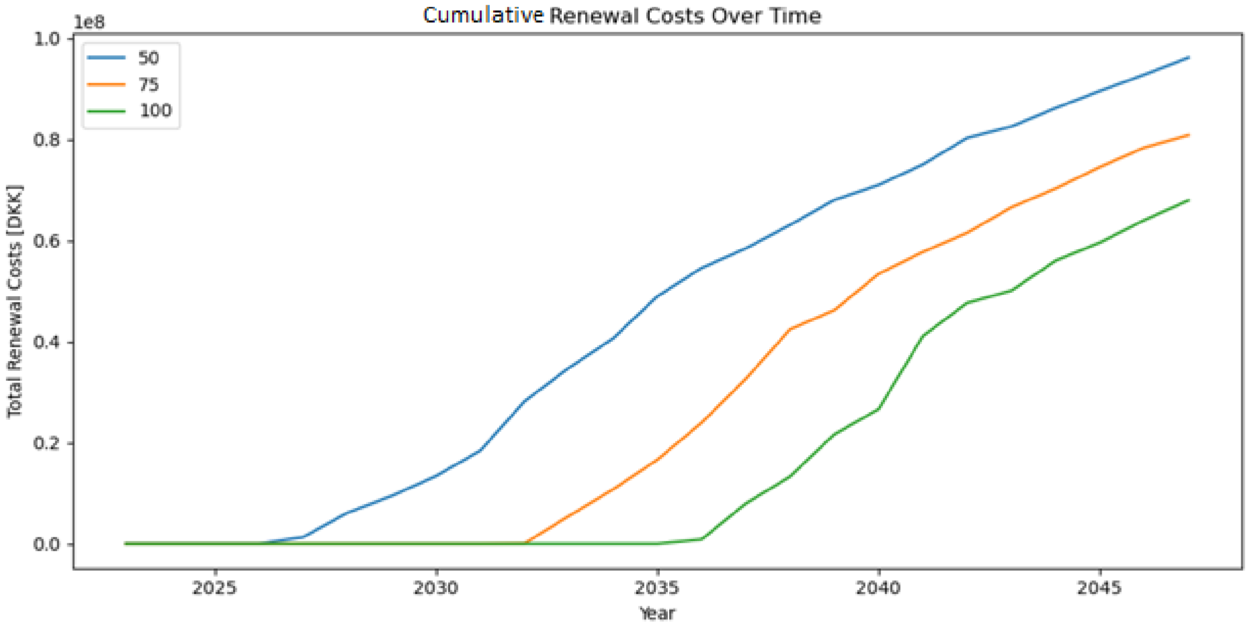

Figure 29, the cumulative renewal cost over a 25-year time-period of the water supply system.

Over time, it is expected that the cumulative cost of renewal will steadily increase as shown in figure 29.

This outcome arises naturally due to the requirement for the replacement of additional or larger pipe sections. By the year 2048, the accumulated renewal costs are projected to reach 96,076,052 DKK when adopting a burst frequency of 50 bursts per year starting from the year 2027. Alternatively, a burst frequency of 75 bursts per year leads to costs amounting to 80,777,423 DKK starting from year 2032. Furthermore, an alternative burst frequency of 100 bursts per year corresponds to costs totaling 67,893,812 DKK starting in year 2036 (see appendix V for model).

EVALUATION

The modeling of the Water Supply System in Middelfart as mentioned utilizes two distinct yet interconnected approaches, the probabilistic resilience model and a renewal model.

The probabilistic resilience model is scenario-based and focuses on internal degradation processes of water pipelines, and the mean time between failure (MTBF) of valves and pumps. It considers the statistical concept of expected value, allowing it to identify scenarios with the highest economic impact based on the scale of their consequences and their probability of occurrence.

The model is efficient in identifying scenarios and associated components that could be the root cause of failure, which serve as a starting point in optimizing the overall system resilience. For instance, by reducing the MTBF of pumps or valves, or by altering the pipeline material.

However, one drawback is that this model does not consider external hazards that could affect the system. Additionally, it is computationally intensive and time-consuming, with simulations running for over seven hours each, limiting the scope of its application for this thesis to pipelines with a diameter of over 110mm.

To reduce the risk level of the system in terms of resilience failure to 1%, an initial investment of 1,611,615 DKK will be made in year 0, followed by annual investments of 402,903 DKK over a 10-year period. Alternatively, a 6.5% risk of resilience failure requires an annual investment of 322,323 DKK. Finally, accepting a 10% risk of resilience failure would require annual investments of 241,742 DKK over the same 10-year period.

The renewal model, on the other hand, focuses on evaluating different strategies for renewing the water supply system and their associated costs. It offers insights into the system's present and future conditions and provides decision options to the utility company TREFOR concerning the maximum permissible burst frequency for their system.

The model presents a predictive analysis of the cumulative burst frequency, the average age of the water supply system, and the total value of the pipe network over a 25-year period, considering the alternative of not conducting any maintenance. It provides a view of the escalating incidents of pipe bursts, the consistent upward trend in the system's average age, and the depreciation of the pipe network's total value.

In terms of cost-benefit analysis, the model projects the cumulative cost of renewal. This will assist the utility company in deciding the acceptable burst frequency based on the availability of financial resources.

Despite the model's contributions, it should be noted that variations around the chosen burst frequency threshold could occur, owing to the variable lengths of the pipe segments selected for renewal.

The annual cost of renewal varies between the optional strategies, however on average the strategies sum up to the following:

- **Strategy with 50 bursts per year: 4,574,574 DKK* per year**
- **Strategy with 75 bursts per year: 5,048,589 DKK* per year**
- **Strategy with 100 bursts per year: 5,657,817 DKK* per year**

*) Need to be adjusted to NPV.

In conclusion, the combination of these two models provides an attempted evaluation of the water supply system in Middelfart. While the probabilistic resilience model focuses on risk management based on internal degradation processes, the renewal model offers options for system renewal.

Both models could provide even more insights if, model assumptions were investigated further, as well as if external hazards were considered. Future studies could focus on overcoming these limitations.

DISCUSSION

The resilience model has made several assumptions regarding the operational features of the water supply system and the financial implications of system failures. To enhance these assumptions and advance future research, several key strategies should be considered.

By incorporating a hydraulic model, it would provide more realistic results by better estimating the impact of a burst on the system. This model would simulate the flow and pressure changes within the system due to a burst, thus improving the accuracy of the assumed water loss. Or coupled with other operating interdependent system as mentioned in (Santamaria-Ariza et al., 2023).

An EPANET model (Center for Environmental Solutions and Emergency Response, 2023), was made to investigate this option at the beginning of the project shown in figure 30. (See Appendix V for model file).

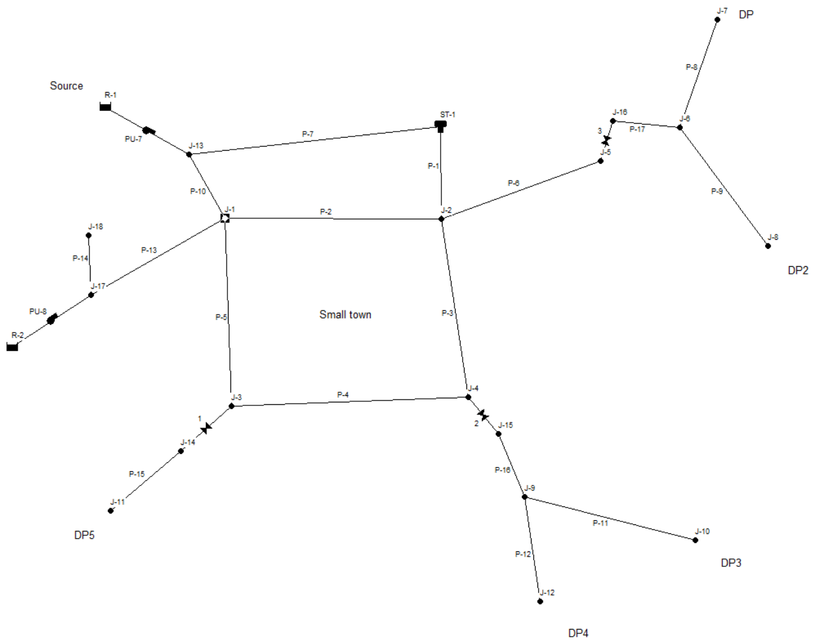

Figure 30, EPANET model for testing software and Python extension WNTR.

The Python extension WNTR (WNTR, 2023) is designed to be a flexible platform for modeling and analyzing water distribution system resilience, and it is compatible with widely used scientific computing packages for Python.

WNTR allows for the simulation of various hydraulic metrics that are based on variable flows and/or pressure. These metrics can then be used to evaluate the resilience of water distribution networks under normal or abnormal conditions.

The types of metrics constitute:

- Topographic metrics
- Hydraulic metrics
- Water quality metrics
- Water security metrics
- Economic metrics

The topographic metrics they describe the physical characteristics of a water network, such as the number of nodes and links, the length of pipes, and the elevation of nodes.

Complementing these, the hydraulic metrics, can simulate pressure and water flow and different demands as well as energy usage by pumps.

The water quality metrics which monitor the quality of the water flowing in the network. Its measures aspects like temperature and chlorine concentration. In addition to these, the metric on water security assesses how secure the network is from any form of contamination, be it intentional or unintentional. One such metric is the vulnerability index, which is important in ascertaining the vulnerability of different segments of the network to contamination.

Finally, the economic metrics come providing valuable insights into the cost of operating and maintaining the network. This metric was one of the intended use cases explored for this thesis. It allows for the simulation of leaks in pipes and size of the leak can be specified. It also measures the effect on the hydraulic performance of the network. In this way it can be evaluated using various hydraulic metrics, such as pressure and flowrate due to leaks.

Another economic metric is the energy cost, which helps estimate the monetary requirement for pumping water through the network.

While future work could involve a more principal example with a simpler model. It would still necessitate to conduct a more detailed cost analysis which would hopefully lead to more precise cost estimates. Perhaps with a cross reference to other utility companies.

Gathering more specific data on the cost of water damage, cleanup, and loss of service would enhance the understanding of indirect costs. A closer examination of the different costs associated with various types of failures and their subsequent repair or replacement would also be beneficial. It was attempted through the database operated by Envidan named EnviPortal (Envidan, 2023a).

Another aspect worth to consider is the actual failures of valves and pumps in Middelfart, which are not currently accounted for in the analysis, but assumed values by the (DNV - OREDA, 2002). Future research should investigate the effects of these failures, including the associated costs and impacts on system reliability.

Improving the failure data used in the model would enhance its accuracy. This could be achieved by collecting long-term data from the Middelfart water system and potentially collaborating with other water utilities to gather a larger dataset.

Rather than assuming a distribution for the response time, future models could simulate varying response times related to specific locations, and scenarios accounting for traffic and temporality of the events. This approach would provide more realistic estimates of the consequences of system failure.

To address the unpredictability of component failures, it might be advantageous to establish a specific budget for pipe bursts and other component failures at TREFOR. This dedicated fund could be adjusted based on historical data and predicted failure rates as assessed in this thesis.

Conducting a thorough analysis of the profitability of the system and how the income generated can be reinvested into maintenance and improvements would provide more robust financial assumptions. The current analysis considers the accumulation of benefits in a range of 0.15-0.25% of the total income.

Considering seasonal variations in water usage could also be of interest. The model currently assumes an even distribution of water usage throughout the year, but incorporating variations based on weather and other factors would lead to more accurate estimates of water loss during system failures. Especially considering the nature of more extreme summers, which might lead to future restrictions on consumption.

Lastly, a comprehensive study of redundancy mechanisms, including standby pumps, their effectiveness, and associated costs should be conducted. This would provide a better understanding of the backup systems and their role in maintaining system reliability.

By implementing these strategies and continually refining the model with new data and insights, the assumptions used in the analysis can become more accurate and relevant. This would ultimately result in better outcomes and more informed decision-making regarding the maintenance and operation of the water supply system.

CONCLUSION

To answer the main problem formulation on "What economic measures can be undertaken to enhance the resilience of TREFOR utility company's water supply system in the city of Middelfart, specifically focusing on selected critical components". The research has stressed the viability of both the probabilistic resilience model and the renewal model in advancing TREFOR utility company's economic measures towards enhanced resilience of their water supply system in Middelfart.

The probabilistic resilience model, provides a platform for identifying failure scenarios, enabling effective optimization of system resilience. By concentrating on internal degradation processes, this model allows to experiment with different Mean Time Between Failure (MTBF) for system components like pumps and valves.

It is important to acknowledge that this model's utility could be significantly extended through future research that integrates external hazards considerations. This will be crucial in creating a more holistic and robust strategy for system resilience. In terms of the renewal model, its strength lies in its ability to explore and evaluate different renewal strategies and their associated economic implications. Its predictive capabilities present a depiction of the future condition of the water supply system and the financial requirements needed for sustained resilience.

Notably, the study has revealed that despite the annual cost variations between different renewal strategies, there are practical economic thresholds that can guide TREFOR in their decision-making processes. For instance, adjusting the burst frequency in relation to available financial resources. Nonetheless, it should be recognized that the model has potential inaccuracies due to the variable lengths of pipe segments selected for renewal.

Considering these findings, it is recommended that TREFOR combine both models to optimally improve their system's resilience. However, further exploration and refinement of these models, such as the inclusion of external hazards and a thorough investigation of model assumptions, are vital for better predictive accuracy and more comprehensive strategic decisions.

Overall, the research illuminates a pathway towards more resilient utility infrastructures, underpinned by a sound economic rationale.

A system identification was conducted to assess which components constitute TREFOR's water supply system in Middelfart. In terms of defining the potential economic consequences in case of their failure, the data was unfortunately lacking due to updating at TREFOR administrative systems. However assumptions where made based on discussions with TREFOR.

The current rate of degradation of pipes within the water supply system, was determined by calculating the received degradation curves provided by Envidan. This insight provided useful in assessing the rate of failure within the system.

In relation to determining what the types of risk are imposed on system, burst data was provided by TREFOR. Here the registry provided into what burst occurred in relation to material factors as well as external. The ML models seemed vague at best. The renewal model seemed to fit well since there in 2022 was registered 33 burst due to material factors, and the model which was calculating from 2023 had a start rate of 36 bursts.

The response time to failure events was also calculated based on assessed data from TREFOR, this knowledge was used in the probabilistic resilience model to help determine the indirect consequences of loss of profit in terms of water sale due to a pipe burst event.

The study underscores the need for further refinement of these models, to incorporate considerations like external hazards and improve predictive accuracy.

Despite data limitations, valuable insights about system degradation, risks, and response times were assembled. Ultimately, the research charts a course towards economically-sound, resilient utility infrastructures, and highlights the importance of ongoing research and model refinement.

APPENDIXES

APPENDIX I - BIBLIOMETRIC & STATE-OF-THE-ART

APPENDIX II - FIGURES

APPENDIX III - QGIS AND EPANET

APPENDIX IV - DATA

APPENDIX V - MODELS

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