Navigating the Future of Ageing Bridges:

Addressing Deep Uncertainty through Adaptive Pathways for the Renewal and Renovation Program in the Netherlands

M.Sc Construction Management And Engineering

Tia Nurfitriani

Delft University of Technology

TU Delft

Rijkswaterstaat
Ministerie van Verkeer en Waterstaat

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Addressing Deep Uncertainty through Adaptive Pathways for the Renewal and Renovation Program in the Netherlands

by

Tia Nurfitriani

to obtain the degree of Master of Science

at the Delft University of Technology,

to be defended publicly on Monday August 25, 2025 at 11:45 AM.

Student number:	5927641	
Project duration:	February 1, 2025 – August 25, 2025	
Thesis committee:	Prof. Dr. Ir. M.J.C.M. (Marcel) Hertogh,	TU Delft, Chair
	Dr. Ir. E.J. (Erik-Jan) Houwing,	TU Delft, Supervisor
	Ir. D.J. (Dirk-Jan) Molenaar,	Rijkswaterstaat, Mentor
	Ir. J.(Jaap) Bakker,	Rijkswaterstaat, Advisor

Cover:	The Van Brienenoord Bridge motorway surface opens to the public on January 30, 1965 (https://wederopbouwrotterdam.nl/actueel/van-brienenoordbrug-55-jaar-oud)
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Rijkswaterstaat
Ministerie van Infrastructuur en Waterstaat

Preface

This master's thesis marks the completion of my studies in the Construction Management and Engineering program at TU Delft. Returning to academic life abroad after nine years since my undergraduate studies was a significant challenge for me. However, the past two years at TU Delft have contributed immensely to my personal and academic growth, far beyond what I initially thought possible. I would like to express my sincere gratitude to everyone who has supported me throughout this remarkable journey.

My interest in ageing infrastructure began during my experience working on renovation projects, where I was drawn to how construction could restore the value of an ageing structure while preserving its historical significance. This thesis has deepened my understanding of how ageing, while inevitable, can be met with thoughtful and purposeful responses. Throughout the course of this thesis, I have had the opportunity to engage with both academics and professionals whose insights have significantly enriched my perspective and contributed to the development of this work.

I would like to express my deepest gratitude to my thesis committee for their valuable guidance and encouragement throughout the process. When I was not really sure about my capacity to do this thesis, the support and trust from all of the committee members have helped me go this far with my thesis.

My sincere thanks to Mr. Marcel Hertogh for his support since the beginning of my thesis. When I struggled to find a committee for my thesis, he welcomed my thesis idea and even helped me connect with my supportive supervisor, Mr. Erik-Jan Houwing, and Rijkswaterstaat. A heartfelt thanks also to Dr. Erik-Jan Houwing for his guidance and warm words, which gave me the confidence to finish this master's thesis.

I would like to thank Rijkswaterstaat for the graduation internship experience. I am really grateful to Mr. Jaap Bakker for trusting me with my topic and offering me the opportunity to have a graduation internship in Rijkswaterstaat. I am sincerely thankful to have Mr. Dirk-Jan Molenaar as my daily mentor in Rijkswaterstaat, who helped me navigate the process of my thesis in Rijkswaterstaat and provided valuable insights and feedback. I would also like to thank all the interview participants for sharing their valuable time and perspectives. Your insights have greatly enriched the content of this thesis and deepened my understanding of the topic.

A special thanks to LPDP RI (Indonesian Endowment Fund) as the sponsor of my journey in TU Delft. LPDP has financially supported me to experience a wonderful journey at TU Delft and has taken care of me in my two years living abroad in the Netherlands.

A sincere thanks also goes to my employer, the Public Works and Spatial Planning Office of Cilegon City Municipality, for allowing me to take a long break to pursue my studies in the Netherlands.

Furthermore, I would like to thank my family, who have been my strongest source of strength and motivation throughout this journey. I am also deeply grateful to be surrounded by supportive Indonesian communities in Delft — PPI (Indonesian Students Association), especially the 2023 cohort, my ind-CME friends, my RH1243 housemates, and the members of RVDH. I feel like I never really leave home when I'm all around you.

Finally, I hope this thesis provides valuable insights and inspires further research on this topic.

Tia Nurfitriani
Rijswijk, August 2025

Executive Summary

Introduction

Most of the bridges in the Netherlands were constructed in the 1960s to coincide with the rise of traffic care, making them approach the end of their technical life in the next decades. As a result, many of these structures are now approaching the end of their technical lifespan, creating an urgent need for renewal and renovation. However, planning for ageing bridges presents significant challenges due to limited knowledge about their state and historical conditions, uncertainty about future requirements, and competing considerations in infrastructure decisions. This situation reflects a condition of deep uncertainty, where experts cannot agree upon the system boundary, external context and the relative importance of the outcomes.

To address this condition, a shift is needed from prediction-based planning toward a more adaptive approach that monitors how the future evolves and allows for adjustments as new insights emerge. The implementation of adaptive pathways through the Dynamic Adaptive Pathways Planning (DAPP) approach enables the mapping of alternative sequences of actions across multiple plausible future scenarios, making it adaptive.

This study investigates the applicability of adaptive pathways as a planning approach to manage deep uncertainty in the renewal and renovation of ageing infrastructure in the Netherlands. The main research question guiding this study is formulated as follows:

How can adaptive pathways be applied to address deep uncertainty in the renewal and renovation of ageing bridges in the Netherlands?

Literature Review

The literature review identifies various sources of uncertainty, including structural, scenario, social, and stakeholder uncertainty. It also introduces a spectrum of knowledge that ranges from deterministic understanding to total ignorance. Deep uncertainty lies within this spectrum, where knowledge is incomplete and reliable probabilities cannot be assigned. This challenges the effectiveness of traditional "predict-and-control" approaches and highlights the need for more adaptive strategies. An adaptive approach, such as DAPP, offers a way to plan under uncertainty by allowing dynamic adjustments over time in response to changing conditions.

The literature review explores indicators of ageing in infrastructure, which may arise from technical, functional, and economic factors. Technical ageing can be addressed through preservation or downgrading measures, while functional ageing is managed through mitigating or upgrading interventions, such as renovation and renewal. The review also emphasises the importance of life cycle management, which involves managing cost, risk, and performance indicators throughout the asset's life cycle.

Research Design

This study employs a Design Science Research (DSR) methodology, which aims to generate design knowledge by purposefully applying the Dynamic Adaptive Policy Pathways (DAPP) concept to develop adaptive pathways for addressing uncertainty in managing ageing bridges. The DSR approach in this study follows five iterative steps: problem identification, definition of the solution objective, design development, demonstration, and evaluation. To support this process, an empirical and holistic case study was conducted using semi-structured interviews and document analysis as primary data collection methods. In addition, a semi-quantitative expert interview was carried out to provide further insights during the design development phase.

Case Study

The Renewal and Renovation (R&R) program is the case for this study, with a focus on ageing bridges. The program is Rijkswaterstaat's large initiative aimed at renewing and upgrading critical infrastructure that is now approaching end-of-life. Rijkswaterstaat is the asset manager of the infrastructure owned by the Ministry of Infrastructure and Water Management of the Netherlands. Based on interviews and document analysis, several key factors are identified. The drivers that trigger the R&R program include structural deterioration, increased traffic, and potential changes in future demand. The R&R program is supported by enablers involving asset management, political priority, and innovation. However, the program also faces barriers that can hinder the process, such as budget constraints, contracting issues, limited resource availability, and changes in regulations.

Problem Identification and Solution

The problems in the R&R program are identified by examining the gap between the existing approaches used by Rijkswaterstaat and the challenges posed by uncertainty. Current planning methods are largely deterministic and expert-driven, relying heavily on forecasting and modelling. However, structural uncertainty introduces the risk of inaccurate assumptions, which can undermine the reliability of these forecasts. Although Rijkswaterstaat acknowledges uncertainty by including cost surcharges as a financial reserve, these surcharges are based on statistical variation. As a result, they are not well-suited to capturing non-linear developments or addressing extreme, unforeseen scenarios.

In addition to the need for a more adaptive approach, the current planning strategy shows a shift in priority from a demand-driven approach, which relies on future demand projections, to a capacity-driven approach, which is based on the system's ability to accommodate those demands. The existing approach struggles to meet growing demands due to limited capacity, requiring the prioritisation of bridges that are most in need of renewal or renovation. This prioritisation necessitates establishing the sequence or order in which bridges are addressed. However, stakeholder and social uncertainty introduce differing perceptions regarding the urgency of individual bridges and varying preferences for the types of measures that should be implemented.

The objectives of the solutions are developed to address the identified gaps. The first objective involves introducing adaptive approaches, with flexibility, the availability of options, and budget reserves serving as key indicators. The second objective focuses on capacity-driven planning to manage the limitations in system capacity. This includes prioritisation and sequencing as indicators. The third objective promotes a portfolio approach by grouping ageing bridges into portfolios. This objective is reflected through indicators such as project bundling, cross-project learning, and capacity building.

Design Development

The design development approach in this study consists of five sequential steps as follows:

1. **Decision Context:** In the renewal and renovation of ageing bridges, factors such as end-of-lifespan, uncertainty, long planning lead times, and limited capacity are key aspects that frame the context for the design development.
2. **Adaptation Tipping Points:** Adaptation tipping points (ATP) in the context of ageing bridges are associated with end-of-life indicators that signal the need for new measures, involving a combination of technical, functional, and economic aspects.
3. **Actions:** The actions in response to the ATP include increased maintenance through preservation, restricting usage through mitigating and downgrading, and upgrading through renovation and renewal measures.
4. **Adaptation Pathways Map:** The Adaptation Pathways Map visualises the possible and logical sequences of actions or pathways over time. Figure 1 presents the proposed adaptation pathways map.

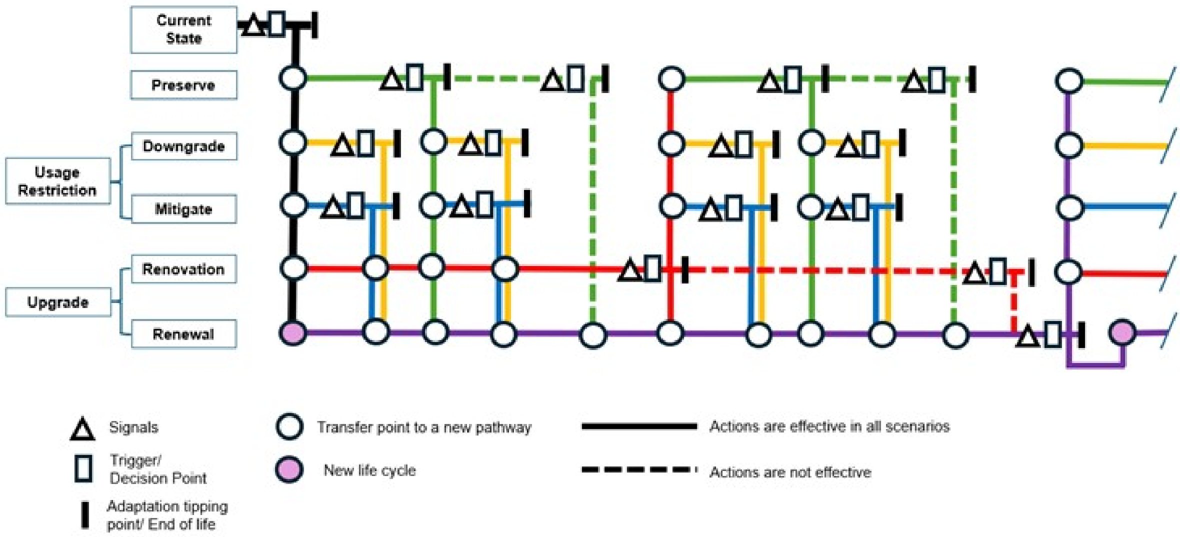

Figure 1: Adaptation Pathways Map

5. **Adaptive Plan:** The adaptive plan consists of signal detection and monitoring of cost, risk, and performance indicators. It also includes preparatory actions as proactive measures and contingency actions as reactive responses to changing conditions.

Adaptive pathways outline possible sequences of actions for renewing and renovating ageing bridges over time. When multiple pathways exist, they can be evaluated based on regret potential, timing, switching costs, and path dependency. This helps narrow the options and improves the efficiency of budget planning, reducing lead times. Adaptive pathways also support prioritisation by aligning actions with urgency and available capacity. Within a portfolio approach, they help sequence projects to enable cross-project learning and build capacity.

Demonstration

The demonstration involves a fictional portfolio of ageing bridges and incorporates a hypothetical scenario related to organisational capacity and project lead time, which necessitates prioritisation. Adaptive pathways are used to map out possible options for each bridge, support the identification of alternative sequences, and enable anticipation of changes in the planning process. The demonstration also illustrates how uncertainty may lead to potential changes and shows that uncertainty can be treated not only as a challenge but also as an opportunity to improve the sequencing of actions. Furthermore, it underscores the importance of assessing adaptive pathway options to guide the arrangement of sequences within the portfolio.

Design Evaluation

The design evaluation assesses the extent to which the demonstrated process design aligns with the objectives of the proposed solutions. The demonstrated process design supports the implementation of adaptive approaches by enabling the portfolio to adjust the sequence of actions, as long as it is within its capacity constraints. It also facilitates capacity-driven planning through the use of guiding questions that help evaluate urgency and determine suitable execution timeframes. These questions form the basis for prioritising and sequencing actions under limited capacity. However, the implementation of the portfolio approach is not explicitly demonstrated. Instead, the portfolio functions as a contextual framework within the scenario, influencing sequence arrangements through elements such as learning effects, which can reduce lead times and enhance capacity over time.

Discussion

The discussion highlights several key insights in the implementation of adaptive pathways for the renewal and renovation of ageing bridges.

- Under deep uncertainty, outcomes of bridge renewal and renovation are only partially known. Limited historical data and unquantifiable non-technical factors hinder reliable probability estimates, while complex interrelations make it difficult to model the system comprehensively.
- Rijkswaterstaat has shifted from infrastructure provision to asset management, placing system capacity at the core of the R&R program. This shift highlights the need for a bottom-up approach that assesses adaptive capacity and identifies measures to enhance resilience under changing conditions.
- Adaptive pathways implementation enables planning across a spectrum of uncertainty, from deterministic knowledge to total ignorance. It facilitates the development of multiple future options while allowing deterministic analysis to assess their feasibility under varying conditions.
- Adaptive pathways complement Life Cycle Management by treating asset measures as part of an integrated sequence. The pathways map offers a roadmap of possible routes over the asset's life cycle, enabling long-term planning and flexible transitions as conditions change.

Recommendation

In addition to research directions, this study advances four practical recommendations. First, the implementation of the adaptive pathways should start with categorising the bridges based on shared challenges rather than the technical life to develop portfolio combinations that support shared capacity and cross-project learning. Second, Rijkswaterstaat's acceptance of cost, risk, and performance as integrated indicators should be assessed, including conditions in which one may take precedence. Third, flexible budget reserves should be developed through analysis of cost impacts related to path dependency, timing, switching costs, and regret potential, thereby moving beyond reliance on single-point statistical estimates. Fourth, forecasting should be regarded not as a mechanism of control but as a means of estimating thresholds that trigger further action. Such thresholds can inform scenario-based planning by delineating actions for circumstances in which they are met, not met, or evolve over time.

Considering this study's limitations, several directions for future research are proposed to build upon its findings. Since the demonstration used fictional cases, future studies could apply adaptive pathways to real-world ageing bridge projects to evaluate their practical applicability under real conditions. Expanding the scope beyond Rijkswaterstaat to include bridges managed by municipalities or private entities could provide a more comprehensive understanding of infrastructure renewal across governance levels. Research could also investigate how to organise bridges into portfolios to optimise capacity use and enable cross-project learning. Further studies are needed to develop integrated approaches for identifying thresholds across multiple indicators, determining when measures are no longer acceptable. Additionally, the value of options in adaptation pathways could be explored using real options theory to quantify the options derived from the adaptive pathways. Finally, future research could examine the potential new long-term collaboration model to manage the sequence of actions in the pathways.

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Nomenclature

Abbreviations

Abbreviation	Definition
ATP	Adaptation Tipping Point
COO	Chief Operational Officer
DAP	Dynamic Adaptive Planning
DAPP	Dynamic Adaptive Pathways Planning
DM1	Decision Moment 1
DM1	Decision Moment 2
DR	Discount Rate
DSR	Design Science Research
EELI	End of Economic Life Indicator
IFD	Industrial, Flexible, and Demountable
LCC	Life Cycle Cost
LCM	Life Cycle Management
LCP	Life Cycle Performance
LCR	Life Cycle Risk
NPV	Net Present Value
OiV	Object in View
PV	Present Value
RA	Regional Analysis and Advice
R&R	Renewal and Renovation

1 Introduction

1.1. Introduction

1.1.1. Background Information

Most of the civil infrastructures in the Netherlands were constructed in the 1960s to coincide with the rise of car traffic (TNO, 2021) and now require major upgrades (Rijkswaterstaat, 2023c). According to Rijkswaterstaat (2023c), the Dutch agency under the Ministry of Infrastructure and Water Management, much of the Dutch infrastructure is approaching the end of its technical lifespan, with less than 33% of its expected service life remaining. Some structures have even already surpassed it. With the expected service life of 60 to 120 years, the infrastructure will reach the end of its lifetime in the coming decades.

The physical ageing process impacts the ability of the infrastructure to perform effectively. Ageing deteriorates the condition of the infrastructure, by causing material degradation, corrosion, and structural weakness (Wang et al., 2021), which get worsen over time. This affects the infrastructure's capacity to serve its functionality. The ageing process makes the infrastructure more prone to defects, making it more challenging to maintain its ideal state. Moreover, it also increases the risk of failure, raising safety concerns in the ageing infrastructure (Rijkswaterstaat, 2023c). Additionally, ageing infrastructure struggles with interoperability, as it was not designed to accommodate modern technologies (Wang et al., 2021). Integrating newer systems often requires extensive modifications.

Infrastructure reaches the end of its life not only due to physical ageing but also when it no longer meets evolving functional demands (Hertogh et al., 2018). Many existing structures were designed decades ago under outdated requirements that may no longer suit present or future needs. The ageing infrastructures are also currently subjected to greater stress than initially anticipated (Rijkswaterstaat, 2023c). Global trends such as population growth, urbanisation, shifts in transportation modes, and increased freight movement have led to heavier loads, higher traffic volumes, and more frequent use (CEDR, 2023; Aljoufie et al., 2001). These changes call for ageing infrastructure planning measures that are adaptable to dynamic external conditions.

As many Dutch infrastructures approach the end of their service life, there is an urgent need for maintenance, renovation, or renewal (Rijkswaterstaat, 2023c). This highlights the importance of addressing both physical ageing and changing external demands. However, these factors alone do not justify major interventions. Decisions must also weigh the economic viability of continued maintenance versus replacement or renovation (Hastings, 2010; Hertogh et al., 2018; Bakker et al., 2025).

1.1.2. Problem Statement

Planning measures for ageing infrastructure are hindered by limited knowledge about both its current condition and the historical loads it has endured. The information about the state of ageing infrastructures in the Netherlands is difficult to find because the infrastructures were built decades ago. Some technical documentation, such as drawings and calculations, is no longer available, and the quality is also unknown (TNO, 2021). Additionally, data on the cumulative loads experienced over the years is insufficient, further complicating assessment and planning for ageing infrastructures (TNO, 2021).

Planning for ageing infrastructure must also account for uncertainty in future external conditions. Given the high capital costs and long lifespans of infrastructure, plans must be resilient to changing condition (Haasnoot et al., 2019). This is challenging, especially for large infrastructure projects, which often have long lead times and sometimes span decades from conception to completion. This makes the plans more vulnerable to becoming outdated or misaligned with future needs due to unforeseen situations arising in the future (Bosch-Rekvelt et al., 2024).

Planning interventions for ageing infrastructure involves different stakeholders with different criteria preferences. Some may emphasise large-scale measures that offer long-term solutions. However, this is not always preferable due to their high initial costs, and they tend to be delayed. Consequently, these interventions lead to a growing maintenance burden, which continues to rise annually and causes more unplanned disruptions and prolonged inconvenience (Rijkswaterstaat, 2023c).

These challenges in the planning for ageing infrastructure reflect what Lempert et al. (2003) describe as “deep uncertainty”. In these situations, experts do not know, or decision-makers cannot agree upon:

1. how the system works and its boundaries, as seen in the limited knowledge of the current state and historical conditions of ageing infrastructure,
2. the external context of the system, reflected in uncertainty about future changes that could alter functional requirements, and
3. the outcomes of interest from the system and their relative importance, illustrated by competing considerations in infrastructure decisions, such as cost, performance, and risk.

Decision-making under deep uncertainty requires a shift from prediction-based planning to a more flexible, adaptive approach that monitors how the future unfolds and allows for adjustments as new knowledge emerges (Marchau et al., 2019). This challenges the traditional planning paradigm, which assumes a predictable future (Capra, 1982). Addressing the ageing infrastructure problem calls for adaptive strategies that can respond to unforeseen developments and learn to adapt towards change (Haasnoot et al., 2013). Unlike conventional approaches that rely on a fixed optimal plan based on a single ‘most likely future’ (Dessai and Hulme, 2007; Dessai and Van der Sluijs, 2007), adaptive planning keeps options open and builds flexibility into long-term strategies. As such, exploring adaptive methods is essential for managing deep uncertainties in ageing infrastructure projects.

Dynamic Adaptive Pathways Planning (DAPP), formerly known as Dynamic Adaptive Policy Pathways, is a decision-making approach designed for deep uncertainty that explicitly incorporates decision-making over time (Haasnoot et al., 2019). Its core principle is to plan proactively and adapt dynamically in response to how the future actually unfolds. DAPP maps out alternative sequences of actions through adaptive pathways, across multiple potential futures. It highlights path dependencies or how decisions are influenced by earlier choices. The method responds to the condition that actions have an uncertain design life and might fail sooner or later to continue achieving objectives as the operating conditions change. This is particularly relevant to ageing infrastructure, where there is uncertainty around how long maintenance is viable or when upgrades are necessary due to deterioration and changing demands. The use of adaptive pathways in the DAPP approach is initially applied for the water management sector in the Netherlands to deal with the impact of climate change on the sea level rise (Haasnoot et al., 2012). With a different context to deal with, the suitability of adaptive pathways implementation for ageing infrastructure needs to be further investigated.

1.2. Research Objectives

The main objective of this study is to explore the applicability of adaptive pathways as a planning approach to manage deep uncertainty in the renewal and renovation of ageing infrastructure in the Netherlands. It seeks to identify key uncertainties, assess the limitations of current approaches, and investigate how adaptive pathways can offer more flexible and future-oriented strategies for infrastructure planning. The findings will serve as the basis for evaluating the applicability of adaptive pathways, particularly in terms of supporting flexibility in adjusting the actions on when change occurs. Ultimately, the study seeks to determine the extent to which adaptive pathways can guide the timing and programming of actions for infrastructure approaching the end of its service life.

1.3. Scope of the Research

This study is limited to the perspective of Rijkswaterstaat as the asset manager responsible for ageing infrastructure in the Netherlands. According to ISO 55000 2014, three key roles in asset management are categorised into asset owner, asset manager, and service provider. For the infrastructure assets managed by Rijkswaterstaat, the Ministry of Infrastructure and the Water Management acts as the asset owner, while market parties serve as service providers.

Given the wide range of civil infrastructure types, this study focuses specifically on ageing bridges in the Netherlands. Bridges are highlighted due to their urgency, as many are nearing the end of their service life and require major overhauls (Rijkswaterstaat, 2023c). Compared to other infrastructure types, bridges are more vulnerable to wear, ageing, and environmental stress (Figueiredo et al., 2023). They are also more affected by changing socio-economic conditions, such as increased traffic loads. As critical links in the Dutch transportation network, disruptions to bridges can cause substantial economic and social consequences.

This study focuses on the applicability of adaptive pathways as a planning approach to manage deep uncertainty in the renewal and renovation of ageing infrastructure in the Netherlands. The scope is limited to five key areas:

1. **Literature Review:** This part involves a comprehensive review of academic literature. The study explores theories related to uncertainty, various approaches for addressing uncertainty, and the concept of the Dynamic Adaptive Policy Pathways (DAPP) approach. The literature review also examines key indicators of ageing infrastructure, strategies for managing ageing assets, and the life cycle management concept in infrastructure.
2. **Case Study:** This part describes the context of ageing bridges in the Netherlands and the Renewal and Renovation (R&R) Program in the Netherlands. It also examines key factors influencing the renewal and renovation process, including the main drivers, enablers, and barriers. The analysis draws on relevant documents and expert interviews to gain insight into how ageing bridges in the Netherlands adapt to uncertainty and how decisions are made regarding their renovation and renewal.
3. **Problem Identification and Solution:** This part investigates the types of uncertainty present in the renewal and renovation of ageing bridges in the Netherlands and examines the extent to which adaptive approaches can be applied by Rijkswaterstaat. The aim is to identify the gap between the uncertainty and the limitations of the existing approach. In addition, this part explores the objective of the solution to address this gap in the renewal and renovation of ageing bridges in the Netherlands.
4. **Design Development:** This part focuses on designing a process for implementing adaptive pathways for the renewal and renovation of ageing bridges, using the DAPP approach. It includes the development of an adaptation pathways map and an assessment of Rijkswaterstaat's organisational readiness to implement an adaptive plan that can support the application of adaptive pathways.
5. **Design Demonstration:** This part demonstrates the developed process design using fictional cases to illustrate how adaptive pathways can be applied in practice. It also includes an assessment of the identified pathways within the demonstration.

1.4. Research Questions

1.4.1. Main Research Question

How can adaptive pathways be applied to address deep uncertainty in the renewal and renovation of ageing bridges in the Netherlands?

1.4.2. Research Questions

1. **What types of uncertainty influence the renewal and renovation of ageing bridges in the Netherlands?**

   This research question investigates the types and sources of uncertainty involved in the renewal and renovation of ageing bridges in the Netherlands.

2. **What is the gap between the identified uncertainties and the existing approaches in Rijkswaterstaat to manage them in the renewal and renovation of ageing bridges?**

   This research question examines the gap between the uncertainty and the limitations of the existing approach of Rijkswaterstaat in addressing uncertainty.

3. **How do adaptive pathways support planning under uncertainty in the context of renewal and renovation of ageing bridges?**

   This research question explores the potential of implementing adaptive pathways under uncertainty to support the renewal and renovation of ageing bridges.

4. **To what extent can adaptive pathways be implemented in the renewal and renovation of ageing bridges to address deep uncertainty?**

   This research question investigates the feasibility and applicability of implementing adaptive pathways to support the renewal and renovation of ageing bridges.

1.5. Research Methodology

This study adopts the Design Science Research (DSR) paradigm as its methodological framework. DSR focuses on generating design knowledge or insights into how artefacts, systems, or processes can be purposefully designed by human agency to achieve specific goals (Hevner et al., 2004). It involves analysing the existing academic knowledge base to assess the availability of relevant design knowledge, which may take the form of theories, frameworks, instruments, or artefacts (Vom Brocke et al., 2020). DSR is particularly relevant to the objective of this study as it enables the generation of new knowledge on how the adaptive pathways concept introduced in the Dynamic Adaptive Pathways Planning (DAPP) approach can be systematically applied through practical tools and theoretical insights to support the organisation in coping with the uncertainty of ageing infrastructure measures.

This DSR process includes six steps: problem identification and motivation, definition of the objectives for a solution, design and development, demonstration, evaluation, and communication; and four possible entry points as illustrated in Figure 1.1. However, this study focuses specifically on the first five steps of the DSR methodology, ranging from problem identification to evaluation, and does not include the communication step. The emphasis of this study is placed on developing and assessing the applicability of the proposed approach, rather than on formally disseminating the final artefact or findings.

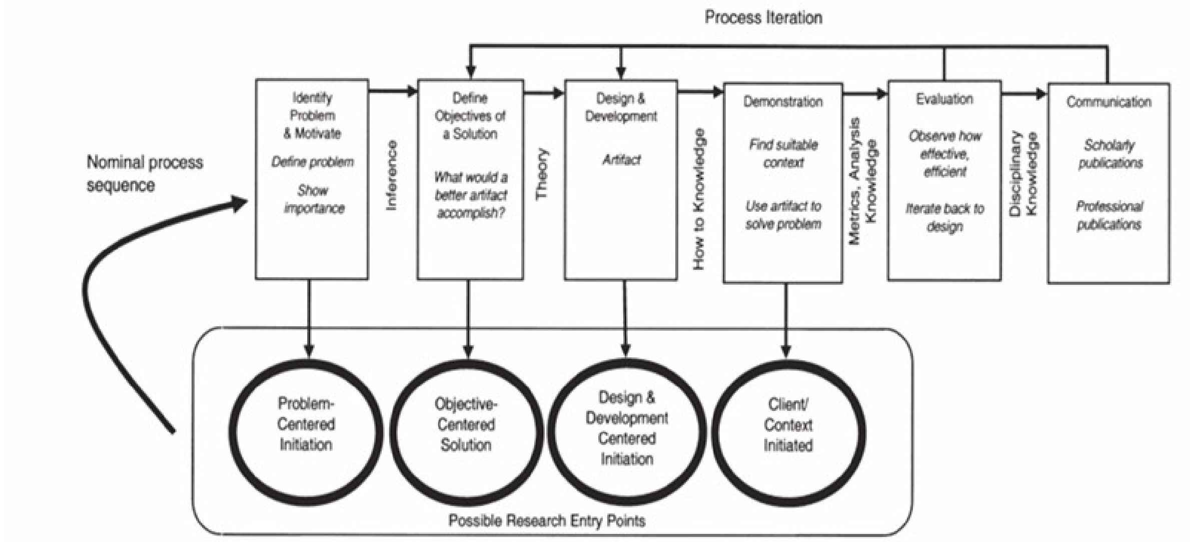

Figure 1.1: DSR Methodology Process Model (Vom Brocke et al., 2020)

1.6. Thesis Outline

This study is structured into eight chapters:

- **Chapter 1** introduces the research by outlining the problem statement, objectives, research questions, and scope.
- **Chapter 2** reviews relevant literature, such as the adaptive approaches towards uncertainty, focusing on the Dynamic Adaptive Policy Pathways (DAPP) approach, and strategies for ageing infrastructure.
- **Chapter 3** presents the research methodology, detailing the Design Science Research (DSR) approach along with data collection, processing, and analysis methods.
- **Chapter 4** delivers the case study overview and findings.
- **Chapter 5** investigates uncertainties and examines the existing approach in addressing uncertainties to identify the problem and develop a solution.
- **Chapter 6** focuses on the design and development of processes for implementing adaptive pathways for the renewal and renovation of ageing bridges.
- **Chapter 7** demonstrates the application of the proposed process design for implementing adaptive pathways in the renewal and renovation of ageing bridges.
- **Chapter 8** evaluates the findings.
- **Chapter 9** discusses the findings of the research, highlights its contributions to the field, and outlines the limitations of the study.
- **Chapter 10** concludes the thesis by summarising key research findings, addressing the main research question, and offering recommendations for future work.

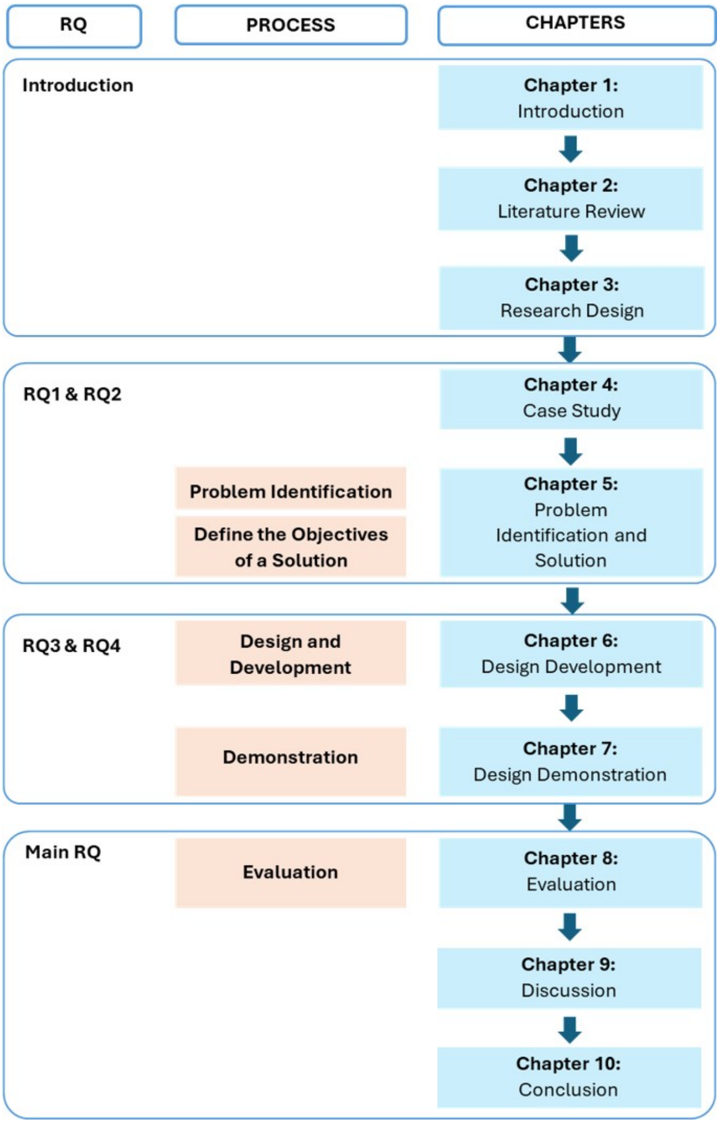

Figure 1.2: Thesis Outline (Own Figure)

2
Literature Review

This chapter presents a literature review that examines key theories and approaches related to ageing infrastructure. The first section reviews strategies for addressing uncertainty in long-term infrastructure planning through adaptive approaches. The second section focuses on the phenomenon of ageing in infrastructure and the measures developed to manage its impacts.

2.1. Approaches in Response to Uncertainty

2.1.1. Uncertainty

Uncertainty can be described as a lack of complete knowledge about past, present, or future events (W. Walker et al., 2013). In the context of decision-making, it reflects the gap between the knowledge currently available and the information that would be required to make the most optimal policy decision. This concept inherently carries a degree of subjectivity, as it depends on satisfaction with existing knowledge. It is influenced by the individual values, assumptions, and perspectives of the actors involved in the decision-making process (Marchau et al., 2019). In general, uncertainties can be categorised into the following types:

- **Structural Uncertainty:** This uncertainty stems from an incomplete or imperfect understanding of the system being analysed. It occurs when there is insufficient knowledge about the correct model structure to represent the system accurately (W. Walker et al., 2003; Refsgaard et al., 2007). Since this type of uncertainty is tied to how the system is framed and conceptualised, it is often difficult or even impossible to quantify. Structural uncertainty encompasses model uncertainty regarding the model's specification or structure (Kennedy & O'Hagan, 2001), parameter uncertainty about the values of model parameters (W. Walker et al., 2003), and relationship uncertainty concerning the connections between variables or components (Pearl, 2009).
- **Scenario uncertainty:** This arises when there is uncertainty about future changes in external factors beyond the control of decision-makers (W. Walker et al., 2003). These often involve broader, macro-level drivers that planners cannot directly influence. Scenario uncertainty is typically managed using scenario planning, robust decision-making, or exploratory modelling. These approaches allow planners to explore multiple plausible futures rather than rely on a single forecast, aiming to identify decisions that perform well across a variety of potential future states (J. H. Kwakkel et al., 2016).
- **Social and Stakeholder Uncertainty:** This refers to the unpredictability surrounding the behaviours, preferences, reactions, and interactions of people and institutions involved in or affected by decision-making (Reed, 2008). It arises from ambiguity in the values, norms, and preferences of individuals or stakeholder groups and their potential for change or conflict over time (Brugnach et al., 2008). Social uncertainty includes what stakeholders value, how they may respond to projects, and how social dynamics like trust, power, and participation may shape outcomes. Incompatible ways of the stakeholders in framing problems constitute a significant source of social

uncertainty (Brugnach et al., 2011).

Identifying sources of uncertainty can improve the quality of planning decisions (W. Walker et al., 2003). Recognising the varying degrees of uncertainty is essential for distinguishing between different planning challenges. Identifying the types of uncertainty during the planning process allows planners to choose instruments suited to the specific issue at hand (De Neufville & Scholtes, 2011).

To effectively manage uncertainty, it is essential to recognise that knowledge exists along a spectrum from the unachievable ideal of complete deterministic understanding to total ignorance (Marchau et al., 2019). Deterministic understanding represents a state where all relevant information is known with precision, enabling clear predictions and decisions. In contrast, total ignorance describes a condition where no reliable model, data, or expectations are available to anticipate future events or system behaviour. The position on this spectrum shapes the strategy in navigating the response towards uncertainty. Between these two extremes lie several distinct categories of uncertainty.

- **Probabilistic uncertainty** arises when outcomes are not predetermined but can be quantified using known probabilities (W. Walker et al., 2013).
- **Ambiguity** when there is a lack of agreement on how to define or interpret a phenomenon, despite some knowledge being available (Brugnach et al., 2008). This means the outcomes are known, but there is vagueness in how to understand them.
- **Deep uncertainty** emerges when there is disagreement or unavailable knowledge to describe the system, assign probability to represent uncertainty, and value the desirability of the alternative outcomes (Lempert et al., 2003). In deep uncertainty, the condition is not totally unknown, but a reliable probability cannot be assigned.

Type	Outcomes	Probabilities	Models
Deterministic	Known	Known	Known
Probabilistic	Known but Not fixed	Known and Agreed	Known and Agreed
Ambiguity	Known	Unknown or Disputed	Mostly Known
Deep Uncertainty	Partially Known	Unknown or Disputed	No Consensus or Multiple Competing Models
Total Ignorance	Unknown	Unknown	Unknown

Table 2.1: The Spectrum of Uncertainty

2.1.2. Traditional Approach Towards Uncertainty

In response to the uncertainty, the traditional policy approach emphasises on the deterministic understanding that assumes a predictable future. This approach is rooted in technical-instrumental and neo-positivist thinking, which claims certainty is easily attainable (Dessai and Hulme, 2007; Dessai and Van der Sluijs, 2007; Capra, 1982). It views environments as static, and the process of change is presumed to unfold linearly (de Roo et al., 2021).

This traditional approach is based on the ”Predict-and-Control” paradigm. It assumes that once predictions are made, systems or behaviours are expected to enable optimal control strategies. This “Predict-and-Control” paradigm resembles the top-down method commonly used in some regional and local climate adaptation policies, which heavily depend on future projections to define policy scenarios (Kwadijk et al., 2010).

The traditional approach remains popular in policy-making for its technical reliability and effectiveness in controlled settings. It supports consistent regulation through standardized practices and quantifiable metrics based on future projections (Pahl-Wostl, 2006; Kwadijk et al., 2010). However, this approach has notable limitations in addressing uncertainties, including:

- The assumption of a predictable future often leads to static, optimal plans based on a single scenario (Dessai and Hulme, 2007; Dessai and Van der Sluijs, 2007). If reality deviates from the projection, the plan is likely to fail (Haasnoot et al., 2013). It also has limited flexibility for adjustment, especially once the infrastructure is already built (Pahl-Wostl, 2006).
- The traditional approach relies heavily on technical solutions and expert-driven projections (Pahl-Wostl, 2006; Kwadijk et al., 2010). High uncertainty often makes modelling and prediction difficult, leading to frustration (Walter, 1997). Additionally, inaccuracies in historical data further undermine the reliability of these forecasts.
- In the traditional approach, the strong reliance on technical-instrumental solutions and projection tends to limit stakeholder engagement (Pahl-Wostl, 2006). This narrows the applicability across different problem scales or decision-making contexts (Kwadijk et al., 2010).

2.1.3. Adaptive Approach Towards Uncertainty

Dynamic external conditions and evolving societal demands make the traditional approach inadequate for developing flexible, adaptive infrastructure (Hertogh et al., 2018). Uncertainty about how, when, and at what pace changes will occur creates major challenges (de Roo et al., 2021), especially for large-scale, long-term, and capital-intensive projects, where rigid planning can cause costly inefficiencies and fewer opportunities for adjustment (Haasnoot et al., 2019). The traditional "Predict-and-control' approach is no longer suitable for these conditions. A different approach that recognizes uncertainty becomes necessary. It should aim to prepare for uncertain events by monitoring how the future evolves and allowing adaptations over time as knowledge is gained (Marchau et al., 2019). The approach should also incorporate stakeholders' perspectives and subjective views to guide outcomes in a direction that reflects societal preferences (Healey, 1997; Innes, 1996).

Bottom-up Approach

In contrast to the top-down traditional approach, a bottom-up approach focuses on assessing a system's adaptive capacity and identifying measures to enhance resilience under changing conditions (Carter et al., 2007). Rather than relying on future projections, it operates more independently and can proceed without them (Kwadijk et al., 2010).

In the bottom-up approach, adaptive capacity is a key trigger for action. Reaching the capacity's threshold becomes the signals for further intervention (Kwadijk et al., 2010). Adaptive capacity refers to the system's ability to adjust to changing conditions and cope with existing and future stress without losing options for the future (Folke et al., 2002). It reflects learning and flexibility to experiment, adopt novel solutions, and develop generalised responses to broad classes of challenges (W. Walker et al., 2001). The adaptive capacity of infrastructure can be achieved by implementing adaptive planning and adaptive management.

Adaptive Planning

Adaptive planning acknowledges that daily environments evolve autonomously (de Roo et al., 2021). Generally, planning behaviour can be "leading", which focuses on control and certainty, or "following," which adapts to changes. Adaptive planning combines both approaches flexibly, adjusting to specific contexts and needs. de Roo et al. (2021) developed a planning rationality framework that integrates additional rationalities to support adaptive responses to uncertainty and dynamic change, as shown in Figure 2.1. The framework consists of the following spectrums:

- **Spectrum A: Contemporary planning**
  This spectrum illustrates shifting from top-down, expert-led planning to more participatory, negotiated forms. Spectrum A covers traditional expert-driven (technical) and participatory (communicative) approaches. Both approaches assume a relatively stable world where goals are clear and plans can be executed. However, this spectrum does not address deep uncertainty or dynamic change, making it inherently non-adaptive.
- **Spectrum B: Conditioning the possibility of change**
  This spectrum highlights the tension between control and autonomy in adaptation. In Spectrum B, planning plays a "leading" role by proactively creating conditions for change before pressures

arise. This approach supports adaptive planning by enabling systems to evolve rather than trying to control them.

- **Spectrum C: Acting in response to change**
  In Spectrum C, planning responds to change by adjusting actions as new developments arise. This allows decisions to evolve based on actual events rather than relying solely on initial assumptions, which is the core of adaptive planning. It emphasises reflexive practice and iterative improvement, which are the key components of adaptive management.
- **Spectrum D: The need for a capacity to change**
  This spectrum shows the depth of adaptive capacity, ranging from incremental adjustments to profound systemic change. In Spectrum D, planning evolves in response to emerging changes and facilitates more profound transformation. It goes beyond adjusting behaviour and instead focuses on building the capacity to reshape the underlying structures that govern systems.

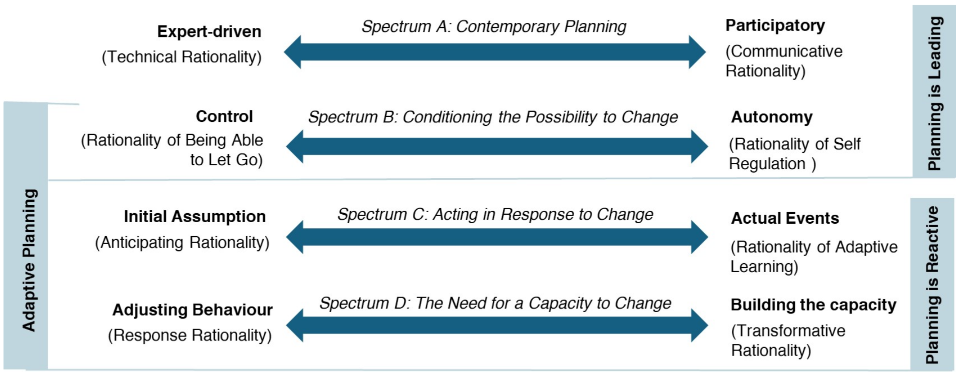

Figure 2.1: Spectrum of Adaptive Planning (Adapted from de Roo et al. (2021)

Adaptive Management

Adaptive management initially emerged in natural resource management to reduce uncertainty (Holling, 1978; Walter, 1997. It helps recognise and confront uncertainty, especially for complex systems where the future cannot be predicted (Allen and Garmestani, 2018; Pahl-Wostl, 2006). Adaptive management involves iterative decision making, the propagation of uncertainty, and using management to reduce uncertainty while pursuing other management objectives (Williams & Brown, 2018). The core philosophy of adaptive management is "learning to manage by managing to learn", which involves learning cycles, continuously revising plans based on feedback and new insights (Pahl-Wostl, 2006; Zevenbergen et al., 2015).

Adaptive management's structures and strategies are designed to be flexible and responsive, enabling systems to cope with novel and changing conditions (Pahl-Wostl, 2002). It reflects the "following" behaviour described by De Roo et al.2021, where policies and interventions adapt in response to change. Unlike the "leading" characteristic in the adaptive planning, which focuses on setting the stage for flexibility, adaptive management applies flexibility during implementation by adjusting actions and enhancing outcomes. The flexibility helps to develop safe-to-fail management approaches to acknowledge inevitable changes and surprises (Allen & Garmestani, 2018).

Adaptive management also promotes broader stakeholder involvement by engaging local communities, institutions, and various levels of governance (Pahl-Wostl, 2006; Holling and Meffe, 1996; Zevenbergen et al., 2015). It represents a shift away from the centralised, top-down decision-making, system control, and expert-only planning characteristics, as found commonly in the traditional approach. Instead, it highlights the importance of shared learning within networks of actors, fostering collective understanding and building trust among stakeholders (Pahl-Wostl, 2006).

2.1.4. Dynamic Adaptive Pathways Planning

Dynamic Adaptive Pathways Planning (DAPP), or previously named Dynamic Adaptive Policy Pathways, is an adaptive planning approach that enables decision-making under uncertainty by allowing dynamic adaptation over time in response to changing circumstances (Haasnoot et al., 2013). The approach is based on the recognition that policies and decisions have a limited design life and may become ineffective as conditions evolve (Kwadijk et al., 2010).

DAPP is structured as pathways with sequences of actions over time. These include initial actions and contingent long-term options that can be implemented if certain conditions arise (Haasnoot et al., 2013). DAPP breaks adaptation into manageable steps, starting with flexible short-term actions to avoid early overinvestment or locking in investments (Haasnoot et al., 2024). It allows flexibility in changing paths and avoiding maladaptation. DAPP enables adaptation to start, rather than waiting for certainty.

DAPP combines two partially overlapping and complementary adaptive planning approaches, adaptation pathways (Haasnoot et al., 2012) and Dynamic Adaptive Planning (DAP) (W. Walker et al., 2001)to help decision-makers navigate long-term uncertainty. Both approaches stress the need for adaptivity in plans to cope with deep uncertainty through near-term actions, while keeping open the possibility to modify, extend, or otherwise alter the plans depending on how the future develops (Haasnoot et al., 2013). Adaptation pathways and DAP rely on the Adaptation Tipping Point (ATP) as a foundational concept, making the ATP central to the DAPP approach.

Adaptation Tipping Point

The adaptation tipping point (ATP) refers to the magnitude of change at which the existing management strategy no longer achieves its intended objectives (Kwadijk et al., 2010;Haasnoot et al., 2013). It was initially introduced by Kwadijk et al. for water management adaptation in the Netherlands in response to the national government's desire for a planning approach to be less dependent on any particular set of scenarios (Haasnoot et al., 2013). The ATP was developed to address the limitations of the bottom-up approach's applicability, which requires extensive time for assessment and tends to rely heavily on expert judgment and qualitative data (Fussel, 2007). The ATP concept was designed to enhance the transparency and reproducibility of the bottom-up approach, making it more applicable for decision-making. The method has demonstrated clarity and practicality, which offers valuable support to decision-makers in navigating future uncertainties (Kwadijk et al., 2010).

An ATP analysis starts with the perspective that a system requires certain conditions to support its objectives. Reaching an adaptation tipping point does not imply the system's obsolescence or catastrophic consequences, but signals the need for an alternative management strategy. Figure 2.2 compares the sequence of actions in ATP approach with the classical approach. The classical approach begins with certain scenario and focuses on the development of the changes in the external pressures and the scenario to respond to the changes. On the other hand, the ATP approach focuses on the limit of system capacity and adaptation timing.

In the ATP approach, the analysis starts with exploring the capacity of the system, not the projection of the changing condition as found in the classical approach. It then examines how changes in external conditions affect objectives in different sectors. Measures to achieve these objectives are identified and analysed to determine the existing system's optimal and critical boundary conditions linked to external pressures. Following this, the approach evaluates the durability of current measures by identifying the conditions and timing under which they will no longer meet objectives. This assessment helps in selecting future adaptation measures.

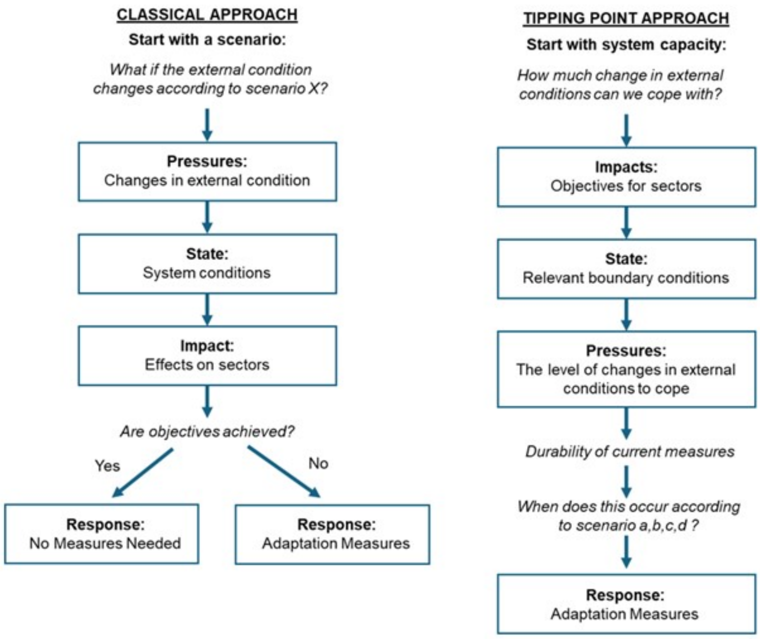

Figure 2.2: Adaptation Tipping Point Approach (Own Figure, adapted from Kwadijk et al. (2010))

Adaptation Pathways

The adaptation pathways approach presents a sequence of possible actions after a tipping point reached. It is illustrated in the form of adaptation trees, such as a decision tree or a roadmap (Haasnoot et al., 2013). The concept of adaptation tipping points (ATP) is the core of adaptation pathways. Adaptation pathways approach refers to the moment when the ATP is reached as the sell-by-date of a policy (Haasnoot et al., 2013). An adaptation pathways map depicts these potential future routes that helps planners flexibly navigate long-term uncertainties (Haasnoot et al., 2012).

The adaptation pathways map illustrates alternative routes to get to the same desired point in the future, with each route meeting a predefined minimum performance threshold that determines acceptable outcomes (Haasnoot et al., 2013). It provides a road map-like visualisation of the solution space over time (Haasnoot et al., 2024). The map visually represents adaptation with steps over time to link short-term actions with long-term and overcome barriers and decision paralysis (Bloemen et al., 2019; Haasnoot et al., 2019; Kingsborough et al., 2016). It also identifies when a current policy may no longer be effective and indicates the appropriate next step to take (Haasnoot et al., 2013).

The Adaptation Pathways map, typically created manually using model outputs or expert judgment, offers a comprehensive overview of possible adaptation routes. The most common visualisation style is the Metro-map, inspired by subway systems (Haasnoot et al., 2024). It illustrates various adaptation options, their endpoints, and transfer points between pathways that highlight aspects such as flexibility, potential lock-ins, and risks of maladaptation.

Figure 2.3 displays a basic example of this Metro-map style. This mapping approach allows decision-makers to explore and select preferred pathways that align with their goals. In a Metro map:

- **Terminal stations** mark the occurrence of an Adaptation Tipping Point (ATP),
- **Transfer stations** indicate decision points where alternative actions become available,
- **Dashed lines** represent routes unavailable in some scenarios due to unacceptable performance.

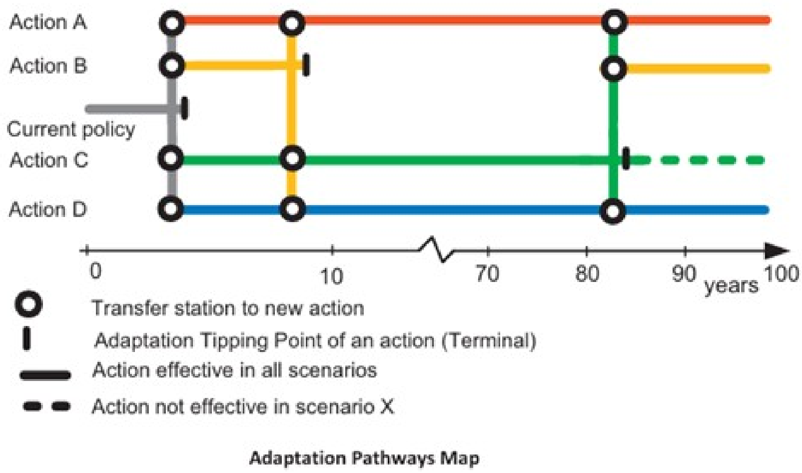

Figure 2.3: Metro-map Style Adaptation Pathways (Haasnoot et al., 2013)

The visualisation of the solution space over time through the map has appealed to decision-makers in addressing uncertainty and the complexity of the changing conditions with societal activities and values (Haasnoot et al., 2024).

Dynamic Adaptive Planning

Dynamic Adaptive Planning (DAP), also known as adaptive policymaking, is a structured method for developing dynamic and robust strategies (J. Kwakkel et al., 2010; Marchau et al., 2019; Ranger et al., 2010). It is grounded in the recognition that uncertainty is inevitable and that static plans are prone to failure in a rapidly changing world (Kwadijk et al., 2010). As new information becomes known, the plan should incorporate the ability to adapt dynamically through learning mechanisms (J. H. Kwakkel et al., 2016; W. Walker et al., 2001).

DAP offers step-by-step method for formulating basic and contingency plans, allowing the initial plan to be adjusted as new information arises (Haasnoot et al., 2013). As shown in Figure 2.4, DAP begins by defining goals and objectives and then designing an initial plan to achieve them (W. Walker et al., 2019). It assesses the vulnerabilities and opportunities of proposed actions and identifies which measures should be implemented immediately and which can be reserved for future use. This process helps account for a broad range of uncertainties. Signposts are established to track unresolved vulnerabilities. When these signposts reach predefined thresholds, corresponding contingent actions are triggered to keep the plan aligned with its objectives. The plan, monitoring system, and adaptation options remain in place unless monitoring reveals that goals are no longer attainable or if those goals change, in which case the plan is re-evaluated and redesigned.

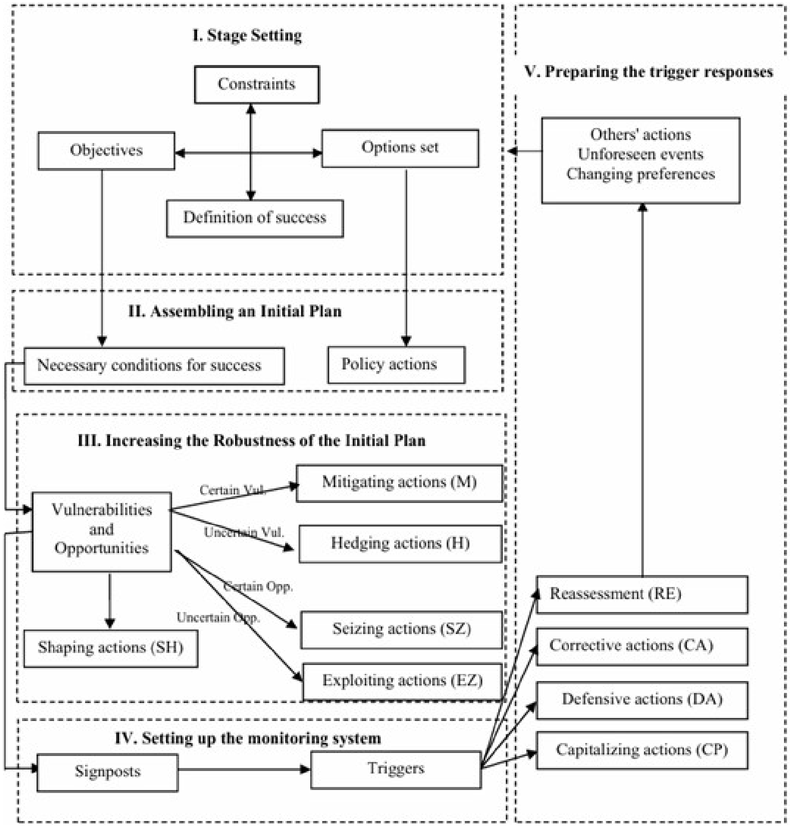

Figure 2.4: Dynamic Adaptive Planning (W. Walker et al., 2019)

DAPP Approach

Dynamic Adaptive Policy Planning (DAPP) integrates the strength of adaptation pathways and Dynamic Adaptive Planning (DAP) approaches. It also reflects the implementation of adaptive planning and adaptive management in response to the change of external conditions. In the DAPP approach, the adaptation pathways map outlines both immediate actions and preparatory steps for potential future actions, in case the conditions change (Haasnoot et al., 2013). The adaptation pathway map provides adaptive planning through the sequences of actions that help determine the durability of a strategy. It indicates under what conditions the strategy may fail to meet the objectives and at what point this may happen under each scenario (Haasnoot et al., 2012). On the other hand, DAPP contributes through adaptive management by incorporating learning mechanisms that anticipate potential failures and keep the plan on track (B. Walker et al., 2002; Pahl-Wostl, 2006). It also involves contingency actions that might be triggered later and implements a monitoring system to determine when they should be triggered.

Figure 2.5 shows the stepwise approach to adaptive pathway planning (Haasnoot et al., 2024), as follows:

- DAPP starts by identifying the current context, objectives, and key uncertainties and assessing the existing conditions to understand the scope and timing for adaptation.
- In the next phase, potential solutions are mapped, including preparing the available options and their thresholds, limits, and opportunities. These options are then assessed based on their vulnerabilities and opportunities.
- The process continues with exploring and evaluating pathways to align with long-term maintenance and societal goals. In this step, the adaptation pathways map is developed.
- Next, a dynamic adaptive plan (DAP) is formulated by outlining initial actions to preserve flexibility and a monitoring strategy with defined signposts and trigger values.

- Finally, the immediate actions are implemented, and the monitoring system is established. The plan is then continuously reassessed and revised if indicated by a signal from unexpected or newly available actions.

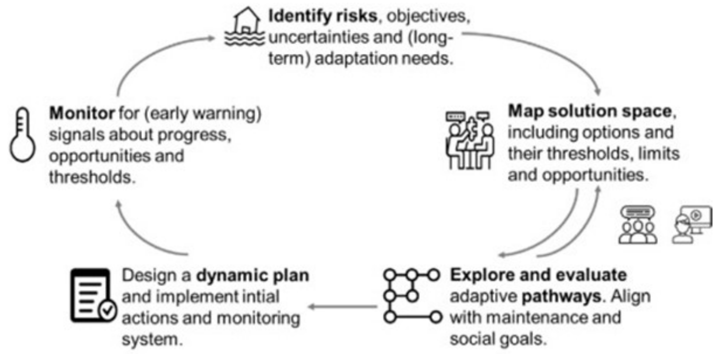

Figure 2.5: Dynamic Adaptive Planning Pathways Framework (Haasnoot et al., 2024)

2.2. Ageing Infrastructure

2.2.1. Ageing Infrastructure Indicators

Technical Ageing Indicator

Technical ageing mainly refers to gradual processes like material wear or fatigue that affect a structure's usability (Bakker et al., 2025). It also refers to the reduced ability to resist ageing caused by abrupt events or calamities. However, Rijkswaterstaat does not classify such events as part of technical ageing in its infrastructure. Technical ageing leads to declining technical properties below the minimum standards needed for intended use (Bakker et al., 2025). It reduces the functional performance, resulting in lower user comfort, decreased structural reliability, and increased maintenance costs (Pan et al., 2009).

Technical ageing affects the technical lifespan of the infrastructure. The span of its technical life is determined on several factors, such as material properties, design, environmental conditions, maintenance quality, and load variations (Bijen, 2004; Hastings, 2010). The end of technical lifespan is reached when regular maintenance no longer achieves the required or acceptable performance standards or safety level (Bijen, 2004; Rijkswaterstaat, 2022b). The condition when the structure can no longer be repaired or upgraded to meet the required technical standards also signals the end of technical lifespan in the infrastructure (Bakker et al., 2016). According to Rijkswaterstaat (2022b), the technical lifespan of an infrastructure ends when the following conditions apply:

- Natural ageing, which leads to significant technical deterioration.
- Changed use, which causes accelerated technical defects.
- Applied techniques are no longer supported, which means that the object can no longer be maintained or can only be maintained at very high costs.
- Changes in standards that change the assessment of the extent to which an object is suitable for use.

Technical ageing is not always a definitive or objective indicator for determining when an asset should be retired (Bakker et al., 2016) because the assessments of the infrastructure's technical condition often offer limited evidence that signals its end-of-life. Even when a significant impact of ageing is present, renewal due to technical ageing may not be necessary if viable repair options still exist.

Functional Ageing Indicator

Functional ageing occurs when a network or its components become less suitable for their intended use due to changes in usage or the environment. It arises from external factors such as increased usage, heavier loads, climate change, and new regulations Hertogh et al., 2018. Functional ageing is recognised when performance of infrastructure falls below an acceptable threshold or the gap between desired and actual performance becomes too large (Bakker et al., 2025). In this condition, the object still meets the technical requirements, but it no longer meets the current functional requirements (Rijkswaterstaat, 2022b).

One factor contributing to the infrastructure's functional ageing is its limited functionality. Many infrastructures are not designed for the way they are used today (Rijkswaterstaat, 2023c). The long lifespan of the infrastructure built back also contributes to many structures in the Netherlands having limited functionality already. In the post-war reconstruction period, the decision-makers focused on a single purpose (Hertogh et al., 2018) and took a mono-disciplinary approach with little regard for negative externalities (Hobma & Schutte-Postma, 2010). The infrastructure networks often focused on one dominant function that reduced their flexibility to adapt to future changing demands (Hertogh et al., 2018; Bakker et al., 2025), leading to their functional obsolescence in the future.

The functional ageing signals the end of the infrastructure's functional life. The functional lifespan refers to the period during which a structure still serves its purpose without altering its properties (ISO15686, 2011). The end of the functional's lifespan arises is reached in these following situations (Rijkswaterstaat, 2022b):

- An adjustment of the network;
- The fact that an object no longer meets social requirements;
- A change in the function of the network of which the object is a part.

In many cases, functional ageing becomes the main cause for the assets to reach the end of their service life earlier than their originally estimated technical lifespan. In the Netherlands, 88% of the infrastructure demolitions in the national road network were due to functional ageing, compared to 12% from technical ageing reasons (Nicolai, 2019).

Economic Indicator

While the technical and functional end of life can be the basis for the infrastructure to be renewed or demolished, they do not necessarily become the only rationale for the renewal or demolition. The information about the technical condition is often limited to provide sufficient grounds that indicate the end of life for the infrastructure (Bakker et al., 2016). The functional end of life is also hard to define, as the infrastructure may still meet its design requirements even though not sufficient anymore for the changing conditions (Bakker et al., 2016).

Economic life is an indicator to provide an objective ground for decisions, either to maintain or renew. it refers to the expected period of time during which an asset is useful to the average owner (Bakker et al., 2016). Hastings (2010) describes the economic life of an asset as the age beyond which it is no longer cost-effective to keep it. Economic life spans the period of time during which no excessive expenditure is required on the operation, maintenance or repair of a component or construction (European Union, 1994; ISO15686, 2011). Athough the asset's lifespan may be determined through technical judgment, the renovation and replacement decision should ideally be based on its economic life (Hastings, 2010). Economic life is an average forecasted replacement interval. It is not a judgment for the end-of-life of an asset, as the reality usually does not last exactly as the average forecasted (Bakker et al., 2016).

Economic life can be used to indicate the end of the life of the infrastructure. It ends when maintaining or renovating the asset becomes too expensive, making replacement the more financially viable option (Hertogh et al., 2018; Hastings, 2010; Bakker et al., 2016). From a financial perspective, the end of economic life is reached when the marginal annual maintenance cost equals the average annual cost over the structure's entire life cycle (Hastings, 2010).

Rijkswaterstaat developed the End of Economic Life Indicator (EELI) to assess, from an economic standpoint, whether maintaining an ageing structure is still financially justified compared to a one-to-one replacement (Bakker et al., 2016). Based on Life Cycle Cost (LCC) analysis, EELI calculates the ratio between the cost of maintaining a structure until its expected renewal year, versus replacing it earlier and maintaining the new asset. A ratio above 1 indicates that continued maintenance is no longer cost-effective compared to early replacement. It becomes more cost-effective to renew the object entirely rather than merely maintaining its components (Bakker et al., 2016). While Rijkswaterstaat uses EELI to identify structures that may need renewal, it is only one of several factors considered in the final decision.

2.2.2. Strategies for Ageing Infrastructure

Response to Ageing in Infrastructure

The ageing process and its impacts can be managed by adjusting usage or improving infrastructure in response to changes in asset condition and external factors. Measures should be tailored to the specific type of ageing being addressed (Bakker et al., 2025). The measures of ageing infrastructure are categorised based on the type of ageing that occurs:

Technical Ageing

The technical ageing is managed through two main approaches, as follows:

- **Preservation** focuses on slowing or counteracting the ageing process (Bakker et al., 2025). In preservation, technical objects are maintained above the minimum quality level necessary to ensure required performance. The preservation is distinguished into the maintenance and renewal of assets. Maintenance involves measures that slow or partially counteract technical ageing, while renewal (Klanker et al., 2016) means fully restoring the asset to its original ”as good as new” condition. In the context of preservation, renewal means replacement of the components. On the other hand, in the context of infrastructure, the renewal means replacing the entire infrastructure, while replacement of the component is seen as a maintenance measure (Bakker et al., 2025).
- **Downgrading** involves accepting the effects of ageing and adjusting the asset's usage to a lower agreed-upon performance level to prevent failure (Bakker et al., 2025). Technical obsolescence is not fully restored to an ”as good as new” condition. This measure allows the asset to deliver at a performance level below the agreed-upon before.

Functional Ageing

The functional ageing is addressed through the following measures:

- **Mitigating** measures involve modifying functional requirements by making interventions elsewhere in the system, without altering the asset (Bakker et al., 2025). This measure fulfils the functional needs differently from its initial functional requirement.
- **Upgrading** measures aim to enhance an asset's functional performance by upgrading or adding existing structures, often accompanied by partial or complete demolition of existing assets (Bakker et al., 2016). The improvement measure includes increasing the utility value of the infrastructure, adjusting to the changing demand of its functional requirements.

Managing the measures for the technical and functional ageing involves continuously deciding between preservation, upgrading, mitigating, and downgrading (Bakker et al., 2025). As infrastructure ages, the cost of preservation will reach a point where full renewal becomes more cost-effective than repeatedly performing maintenance measures (Bakker et al., 2025). Due to significant costs involved, the decision to renew should not be based solely on technical considerations. Renewal of the asset also needs to address the functional ageing, as functional upgrades are often not feasible without demolishing and replacing existing infrastructure. Therefore, renewal triggered by technical ageing should also be seen as an opportunity for functional upgrade to avoid other near-future replacements as requirements evolve.

Measures for Ageing Infrastructure

Rijkswaterstaat (2022b) distinguishes measures to improve the lifespan of its assets based on the complexity of the objects:

Simple Objects

The 'simple objects' are defined as the permanent structures with a clear distinction between regular maintenance and measures when the object reaches the end of its technical lifespan. These measures are categorised as follows:

- **Renewal** involves one-to-one replacement, where a new object replaces the ageing one. It marks the start of a new lifespan in the system.
- **Renovation** aims to extend an object's lifespan while maintaining its functions. It typically adds about 30 years of service before full replacement is needed.
- **Usage restriction** extends an object's lifespan by limiting its functionality until replacement, even though not as effectively as renovation. With this option, the renewal option is postponed, but the lifespan is extended. Usage restriction often results in additional costs for monitoring the condition to guarantee safe functioning.

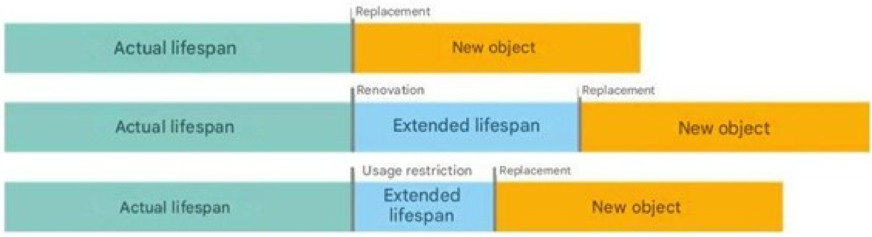

Figure 2.6: Measures for Simple Objects (Rijkswaterstaat, 2022b)

Complex Objects

Unlike simple objects, complex objects do not have a linear approach to the end of their technical lifespan. Complex objects consist of civil engineering structure and control and operation systems. The renovations of complex objects are carried out every 15 years, as shown in Figure 2.7. After a lifespan of 105 years, the entire object is replaced. The renovation in a complex project is divided into three types:

- **Operation and control:** Replacement of the complete operation, control, and monitoring system (3B system).
- **Minor renovation:** Replacement or complete renovation of electrical installations and mechanical components (Logical Function Fulfillers, or LFVs).
- **Major renovation:** Includes minor renovation and the renovation or replacement of civil engineering components, such as concrete and steel structures, that have reached the end of their technical lifespan.

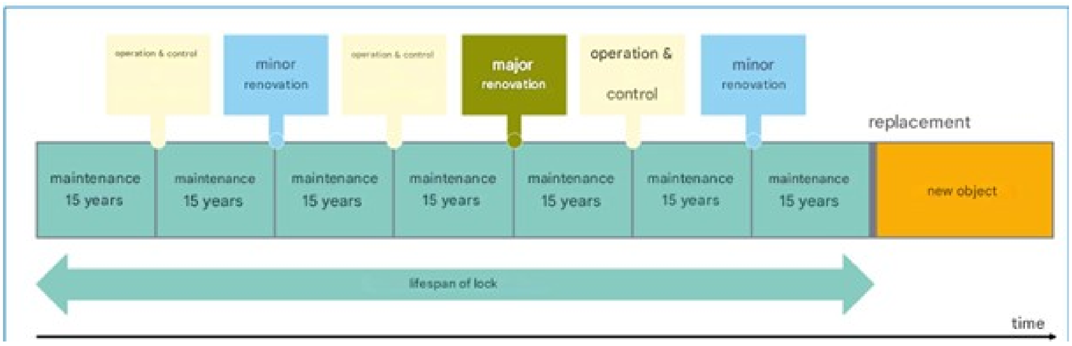

Figure 2.7: Renovation in Complex Object (Rijkswaterstaat, 2022b)

2.2.3. Life Cycle Management

While many asset managers do not have life cycle strategies for their assets (Hertogh et al., 2018), life cycle thinking has been an important topic of interest for Rijkswaterstaat. This approach is operationalized through Life Cycle Management (LCM). LCM oversees an asset or asset system throughout the whole life cycle by aiming for an optimal balance among performances, costs, and risks (Fuchs et al., 2014). LCM employs key indicators, which consist of Life Cycle Cost (LCC), Life Cycle Risk (LCR), and Life Cycle Performance (LCM), to guide an asset or asset system management from the initiation phase up to the operation and demolition phase. While traditional service agreements often focus on the short-term aspects, such as cost, schedule, and quality, incorporating LCM indicators is expected to provide insight into the long-term implications for assets and systems and avoid short-term decisions.

LCM manages the interface between life cycle stages. It works in different contexts, from construction to the maintenance and operation stage. The outcome of LCM in terms of LCC, LCR, and LCP of each process in the life cycle become the input for the next phase (Fuchs et al., 2014). LCM helps to make the right choice in relation to performance and risks by avoiding double work across the different phases. By looking at the whole life cycle, the positive impacts of high initial investment that lead to a reduction of the future operational cost can be anticipated.

LCM addresses the challenges of a dynamic environment, as illustrated in Figure 2.8. Constant changes drive evolving performance requirements, new risks, and shifting cost impacts for infrastructure (Hertogh et al., 2018). The changing environment presented by the outer ring triggers the cycle, leading to decisions on upgrading or replacing assets. LCM emphasises the importance of flexibility in assets for functional changes over time, early in the project definition phase, to accommodate future changes better and save costs over time (Fuchs et al., 2014).

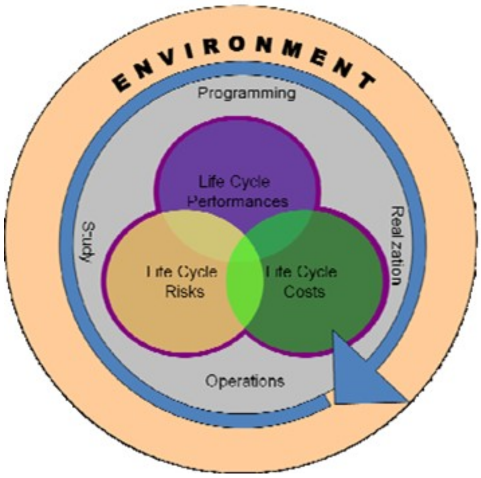

Figure 2.8: Relationships in Life Cycle Management (Fuchs et al., 2014)

Life Cycle Management Aspects

LCM is the trade-off between Life Cycle Performance (LCP), Life Cycle Costs (LCC), and Life Cycle Risks (LCR) that must be explicitly managed throughout the asset's life cycle.

Life Cycle Performance (LCP)

Life Cycle Performance (LCP) measures how well the infrastructure performs to meet the expected performance criteria. Performance is assessed based on the following requirements (Hertogh et al., 2018):

- Performance requirements linked to the core functions that the object must deliver within the broader network.
- Object-specific performance requirements, shaped by the particular characteristics of the object and its surrounding environment.
- General performance requirements established by organizational policies, as well as national and international regulations.

LCP needs to be monitored to ensure the object delivers the expected performance level. A 'performance life indicator' for the object, which is derived from multiple performance aspects, such as load-bearing capacity, traffic capacity, noise pollution, aesthetics, etc, (Hertogh et al., 2018). Several studies have been conducted to establish performance indicators specifically for infrastructure managed by Rijkswaterstaat.

- Xie (2017) introduced the concept ”Performance Age” as the long-term parameter to support replacement decisions for highway bridges. This concept estimates the age of a bridge based on its performance, incorporating multiple criteria and indicators from different perspectives and various interests of stakeholders on a timescale.
- Recognising the limitation of Xie’s approach that is applicable only when the system remains intact, González (2018) further refined the concept of Performance Age in a more sound, standard, and objective way. In his study, González (2018) addressed the limitation of Xie’s approach by acknowledging the non-linear ageing patterns of the object and also examined the integration of the concept in the decision-making process for the asset.
- The monitoring for the performance development of the bridge is explored by Mooren (2022). The study developed a model design to simulate the development of functional performance of bridges and viaducts as part of a network over time. The model visualises critical infrastructure geographically, using dynamic performance indicators over time. This visualisation aims to enhance asset managers’ ability to monitor infrastructure conditions and inform appropriate intervention strategies.

These studies offer valuable tools for managing the Life Cycle Performance of assets by enabling the identification of underperforming components within the network and tracking their performance development over time.

Life Cycle Cost (LCC)

Life Cycle Cost (LCC) refers to “cradle to grave” analysis that estimates the cost of acquiring, commissioning, operating, maintaining, and disposing of the asset. It ensures costs are reasonable and helps evaluate different options for achieving the objectives of the asset (Hastings, 2010; Davis Langdon management consulting, 2007).

The structure of LCC consists of direct costs and indirect costs, as illustrated in Figure 2.9. Direct costs cover initial construction, operation and maintenance, repairs, rehabilitation, and end-of-life activities. In infrastructure renovation projects, for example, bridge renovation projects, indirect costs may include user delay costs from disruptions (e.g., passenger and freight delay) and environmental costs (e.g., CO_2 emissions from construction activities and traffic congestion) (Stipanovic et al., 2020).

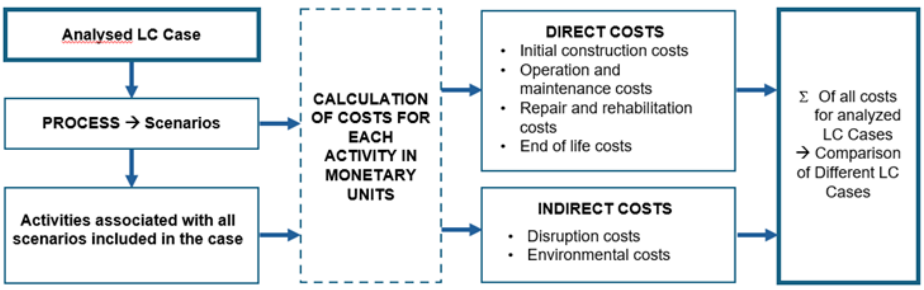

Figure 2.9: Life Cycle Cost Structure, adapted from (Stipanovic et al., 2020)

LCC can be expressed in terms of a Net Present Value (NPV). In an LCC calculation, the present value (PV) of the cash flow is calculated. PV is the current worth of a future sum of money or stream of cash flows, given a specific discount rate. A Discount Rate (DR) is used to accurately account for the time value of money when comparing costs and benefits that occur at different times over an asset’s life.

The PV is derived using the following equation:

$$PV = \sum_{t=t_1}^{t_n} \frac{I_t}{(1+DR)^t} \tag{2.1}$$

where:

- PV: Present Value
- I_t: Investment/Cash Flow at time t, (with a price level of time t = 0)
- DR: Discount Rate
- t_1, t_n: Start and end time periods

Rijkswaterstaat develops 'Economical End of Life Indicator' or EELI as the practical indicator for LCC Management. This indicator is defined as the ratio of the present value of all future costs needed to keep the structure and replace it in a theoretically determined end of life, divided by the cost of an early replacement (Bakker et al., 2016). A ratio greater than 1 indicates that continuing to maintain the structure is no longer cost-efficient than opting for early replacement. The EELI can support the justification of renewal decisions by providing efficient LCC insights. However, it should not be regarded as a strict economic rejection threshold for the available measures (Bakker et al., 2025).

Life Cycle Risk (LCR)

Life Cycle Risk (LCR) accounts for both potential threats and opportunities (Hertogh et al., 2018). Threats stem from the risk of undesirable events and their consequences, as risk inherently involves the likelihood of certain situations occurring and is closely tied to variable uncertainties. At the same time, these occurrences can also present opportunities for improved performance. Together, these risks and opportunities influence the costs and benefits throughout the asset's entire life cycle that are managed through the LCR. LCR can be managed with the Risman method to provide a structured framework to identify, classify, and manage risks throughout the different phases of an asset's or system's life (Well-Stam, 2004). This method emphasises the importance of managing the risk and uncertainty. According to the Risman method, LCR management involves the following measures:

- **Risk Inventory:** Risk inventory involves identifying and quantifying potential risks over time. The Risman method supports this by mapping uncertainty across three dimensions: Location (where the uncertainty arises); Level (the degree of knowledge); and Nature (the source of that knowledge). Tools such as the Risk Breakdown Structure (RBS), risk matrices, scenario analysis, and Monte Carlo simulations can be used for identifying and analyzing risks probabilistically.
- **Risk Agreement:** Risk agreement contains accepted risks between partners over the life cycle. The risk agreement is conducted as a structured, collaborative process between project stakeholders to define, allocate, and formalize how risks will be handled. This includes assigning risks to the parties best equipped to manage and bear them effectively.
- **Risk Monitoring:** In risk monitoring, the risks are continuously observed and assessed throughout the life cycle. This includes tracking known risks, identifying emerging ones, and evaluating the effectiveness of mitigation efforts. Methods may include regularly updating the risk register, re-running Monte Carlo analyses, and using visual tools like a traffic light system to signal risk status.
- **Risk Management:** Risk management implements timely measures to keep risks at agreed levels. This involves the risk mitigation strategy, such as accepting, avoiding, reducing, or transferring risks. The also includes contingency plans and buffers to mitigate the development of the risks.
- **Opportunity Management:** Opportunity management timely recognises chances to improve performance, reduce costs or reduce risks. Unlike risk management, this measure is oriented toward a positive orientation. Opportunities are linked to changes in market conditions, technological innovation, early task completions, and resource availability. Opportunity management creates a strategic advantage and builds the resilience of the assets.

Life Cycle Management for Renewal Decision Making

LCM provides critical information to support decisions on further measures and the moment for the existing asset to be upgraded or renewed. It provides a broader view by incorporating the whole life cycle of the infrastructure as the key factor for the decision to maintain or upgrade. The inventory of LCM aspects should be the basis for renewal decision-making. LCM gives a reliable basis for the renewal procedure by making a reliable forecast for the end of the lifetime of the assets (Hertogh et al., 2018).

The end-of-life of an asset is ultimately a decision, not a technical fact (Hertogh et al., 2018). Technical end-of-life does not necessarily imply the end-of-life of an object, unless it has completely collapsed and cannot be repaired. Similarly, reaching the functional end of life does not always indicate the need for renewal, as the infrastructure may still fulfil its initial design requirements even though it no longer aligns with the changing conditions (Bakker et al., 2016). In practice, renewal decisions are typically made when repair costs become disproportionately high compared to replacement, or when performance levels fall below acceptable thresholds (Hertogh et al., 2018). With multiple end-of-life criteria of an object, the decision to renew needs to be made by taking into account the LCM aspects. Since an asset can have multiple end-of-life criteria, renewal decisions should be guided by broader LCM considerations.

To support the decision-making process, a decision tree flow may help to determine the appropriate measures to take based on certain conditions of the object. Hastings (2010) introduced a decision flowchart that integrates operational, financial, and risk-based considerations to guide asset renewal decisions. Although originally developed for equipment assets, the framework may also be applicable to civil engineering infrastructure. Figure 2.10 presents the decision flowchart adapted from Hastings' original flowchart, with terminology adjusted to suit the context of civil engineering infrastructure.

- The decision-making process begins by assessing whether the asset can still support its intended performance. This can be affected by technical ageing, resulting from physical deterioration that reduces the asset's capacity, and functional ageing, where the asset fails to meet increasing performance demands.
- If the asset continues to perform adequately, the next consideration is its economic life. Renovation or renewal becomes a viable option when maintaining the asset is no longer cost-effective.
- If the asset has not yet reached its economic end-of-life, the next step is to assess the need for repairs. Repairs should not be pursued if their cost exceeds the asset's projected value after restoration.
- If the repair cost does not exceed the estimated after-repair value of the asset, the next aspect to consider is whether the repaired asset still carries a risk of sudden major failure that could result in significant unexpected costs.
- If none of these conditions are met, then the adaptation through renovation or renewal of the asset becomes unnecessary.
- If any of the conditions are met, renovation or renewal can be avoided by redeploying the asset through repurposing it for a different function or use. The redeployment may involve preservation, downgrading, or mitigating measures.

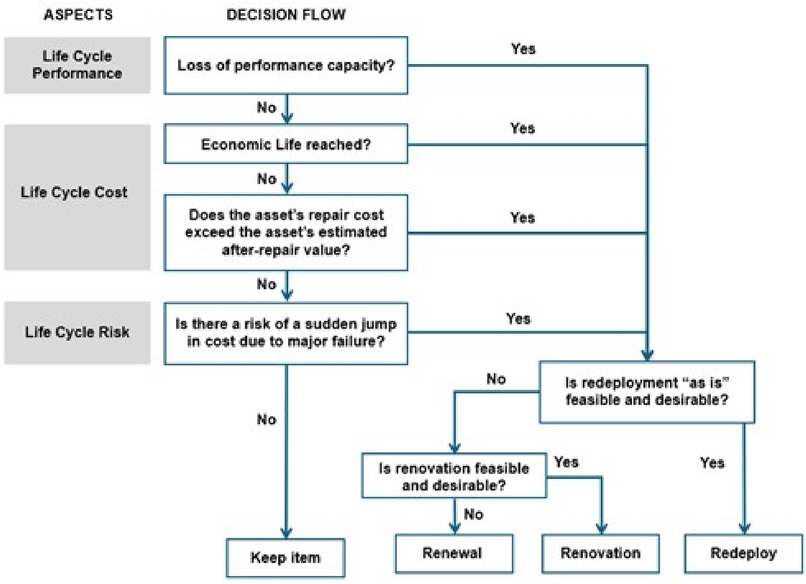

Figure 2.10: End-of-life Decision Flowchart (Own Figure Adapted from Hastings (2010)

2.3. Closing Remarks: Literature Review

The first section of the literature study provides a theoretical foundation for understanding uncertainty and the appropriate approaches to respond to it. Recognising the diverse sources of uncertainty allows for distinguishing between different types of challenges and selecting suitable instruments tailored to each specific context. Furthermore, understanding the spectrum of knowledge, ranging from deterministic to total ignorance, creates the need to move beyond traditional "predict-and-control" approaches and encourages the need for more adaptive approaches that account for uncertainty. These theoretical insights assist in investigating the source of uncertainty and analysing the gap in existing approaches for addressing them. The insights serve as the basis for problem identification and developing the objective of the solution.

Various perspectives on adaptive approaches also offer valuable insights into the key elements that need to be addressed when managing uncertainty. Among these, the concept of Dynamic Adaptive Policy Pathways (DAPP) provides a practical method for structuring possible responses by using adaptive pathways. This concept serves as a guiding framework in the design and development step of this study, supporting the formulation of anticipated measures towards the uncertainty encountered in the Renewal and Renovation Program.

The second section explores the indicators of ageing infrastructure and the strategies used to respond to ageing and manage the infrastructure's life cycle. In the context of infrastructure, ageing can be identified through various indicators, including technical, functional, and economic factors. Understanding the state of ageing is essential for recognising when further measures are needed and for determining the most appropriate actions to address the ageing process effectively.

The theory about life cycle management highlights the importance of life cycle strategies for infrastructure assets, emphasising the long-term implications of measures rather than short-term solutions. This includes managing the interfaces between different measures throughout the asset's life cycle and addressing the challenges posed by a dynamic and changing environment. Life cycle management, which incorporates cost, risk, and performance indicators, serves as a basis for decision-making in determining the end-of-life of infrastructure assets. It also provides a foundation for evaluating the impact of measures in relation to how these measures influence the development of key indicators throughout the asset's life cycle.

3
Research Design

This chapter outlines the research methodology employed in this study. The following sections provide a comprehensive overview of the methodological approach, including the research design, data collection, and data analysis.

3.1. Design Science Research Methodology

This research adopts a Design Science Research (DSR) methodology. This methodology focuses on generating design knowledge or insights into how artefacts, systems, or processes can be purposefully developed by human agency to achieve specific goals (Hevner et al., 2004). DSR is employed in this research to investigate the applicability and implementation of the Dynamic Adaptive Policy Pathways (DAPP) approach as a means to address uncertainty and develop strategies in managing ageing infrastructure.

Figure 3.1 presents the research design of this study, showing the integration of the DSR stepwise approach along with the specific methods employed in each stage. The design process is inherently iterative, incorporating feedback loops that support the continuous refinement and enhancement of outcomes. The DSR methodology applied in this study consists of five iterative steps:

1. **Problem Identification:** This process begins by defining the specific research problem, identified through both literature and the real-world case, to justify the relevance and value of developing a solution.
2. **Define the Objectives for a Solution:** The objectives of a solution are formulated based on the defined problem and informed by existing knowledge of what is technically possible and practically feasible.
3. **Design and development:** This activity involves determining the desired features of the solution and its structure, and then creating the actual design.
4. **Demonstration:** This activity involves demonstrating how the designed artefact can be applied to address the identified problem and fulfil the defined objectives.
5. **Evaluation:** The evaluation assesses how effectively the design addresses the identified problem. This involves comparing the intended objectives of the solution with the actual results observed during its application in the relevant context.

This study employs the theories from the literature review as the knowledge base in the process. The knowledge base is analysed to determine which extent to which existing design knowledge can address the problem of interest (Vom Brocke et al., 2020). Empirical studies are conducted to define the problem space where the phenomena of interest occur, encompassing the existing infrastructure, organisational context, and available measures. The empirical study includes a case study for the problem identification and objective definition steps.

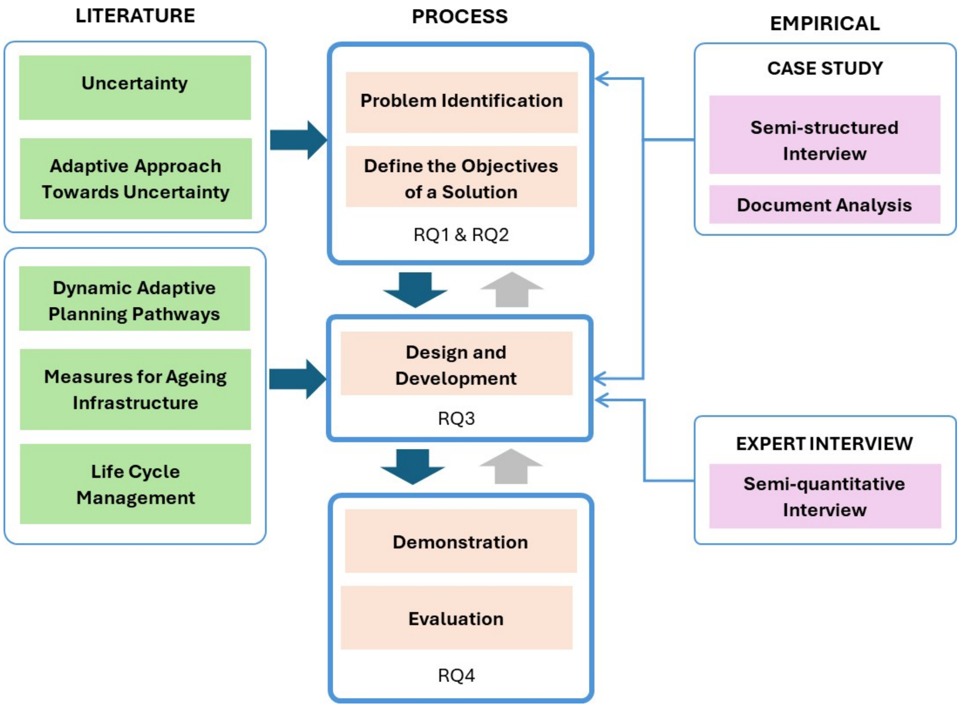

Figure 3.1: Research Design (Own Figure)

3.2. Holistic Case Study

The case examined in this study focuses on the ageing bridges in the Netherlands managed by Rijkswaterstaat. Rijkswaterstaat is a government agency under the Dutch Ministry of Infrastructure and Water Management, responsible for the practical execution of public works and water management. Its tasks include the construction and maintenance of roads and waterways, as well as flood protection and prevention. However, this study specifically concentrates on Rijkswaterstaat's role as the asset manager of ageing bridge infrastructure. The phenomenon of the ageing bridges managed by Rijkswaterstaat is analysed as a holistic case study. The case study involves document analysis gathered from internal documents and publicly available information found online, and semi-structured interviews.

3.2.1. Document Analysis

The document analysis involves collecting data from both internal organisational documents, accessed through the organisation's information system, and publicly available sources, such as government websites and news platforms. These documents are related to key themes including ageing bridges, renovation and renewal, decision-making processes, and infrastructure planning programs. They provide a solid contextual foundation for the study, helping to ensure that the research is firmly grounded in real-world practices. Table 3.1 presents examples of documents selected for analysis in this study.

No.	Source	Data or Information
1.	Rijkswaterstaat's Report	• Forecast Report 2022: Renewal and Renovation • State of Infrastructure 2023 • Innovation Agenda 2030
2.	Rijkswaterstaat's Research Documents	Papers and Master's Thesis
3.	Rijkswaterstaat's Website	• Roadmap and Mission • Information about decision making process in the Renewal and Renovation (R&R) Program • Information and news about maintenance or construction activities by Rijkswaterstaat
4.	External Report	• Renewal of Civil Infrastructure: Dutch National Forecast for Replacement and Renovation by TNO 2021 • Innovation Challenge Infrastructure: National Forecast Report 2023 by TNO
5.	News	Related information or statements about the renewal or renovation of bridges in the Netherlands

Table 3.1: Document Examples for Analysis

Insights from the document analysis are used to develop more informed and targeted questions for the subsequent semi-structured interviews. Following the interviews, the document data is also utilised for data triangulation, enabling cross-verification of interview findings from different perspectives and thereby enhancing the credibility and validity of the research outcomes.

3.2.2. Semi-structured Interview

Semi-structured interviews were conducted to gather insights into the renewal and renovation of ageing bridges, the associated decision-making processes, and the organisational monitoring measures. The information obtained will be analysed to identify uncertainty and to assess the organisation's capacity to address that uncertainty. Semi-structured interview provides questions to guide the flow of the interview, but offer the possibility to explore deeper insights that might occur during the interview, beyond the questions prepared.

Interview Topics and Respondents

In this case study, the interviews are divided into three main topics: 1) Bridge Adaptability in the Netherlands; 2) Renovation and Renewal Decision-Making in Rijkswaterstaat; 3) Monitoring Measures Conducted by Rijkswaterstaat. Each topic has a different list of questions and respondent criteria. The topics are divided due to the specific knowledge and experience required to answer the question, recognising that individual respondents may not have the capacity to address all areas comprehensively.

The details of the topics and respondent criteria for the interviews are as follows:

- **Topic 1: Bridge Adaptability in the Netherlands**

  This topic investigates the adaptability of ageing bridges in the Netherlands in response to changing conditions, as well as the necessary measures to maintain their functionality. The interview targets bridge experts with experience in infrastructure planning, design, or construction.

- **Topic 2: Renovation and Renewal Decision-Making in Rijkswaterstaat**

  This topic examines the decision-making process for renovation and renewal within Rijkswaterstaat, including associated challenges and expected outcomes. The interview is intended for Rijkswaterstaat personnel or affiliated stakeholders directly involved in decision-making, particularly those with insights into prioritisation strategies and policy implementation.

- **Topic 3: Monitoring Measures Conducted by Rijkswaterstaat**

  This topic focuses on the monitoring protocols used to assess asset conditions and identify when intervention is required. The interview is aimed at technical staff, engineers, or monitoring specialists within Rijkswaterstaat who are responsible for performance evaluation, inspections, and data collection related to infrastructure condition monitoring.

The respondents for the interviews are recruited through the network of Rijkswaterstaat supervisors and recommendations from the respondents who are interviewed.

No	Topic	Actor Code	Background	Role	Date of Interview
1	Topic 1	A1	Rijkswaterstaat	Advisor	01/05/2025
2	Topic 2	B1	Rijkswaterstaat	Advisor	09/05/2025
3	Topic 2	B2	External Party	Consultant	12/05/2025
4	Topic 2	B3	Rijkswaterstaat	Advisor	06/06/2025
5	Topic 3	C1	Rijkswaterstaat	Consultant	24/06/2025
6	Topic 3	C2	Rijkswaterstaat	Program Manager	24/06/2025

Table 3.2: Interview Respondents

Interview Protocol

The interviews were conducted either in person or online using Microsoft Teams. Before the interview, participants received an informed consent form outlining the general terms of participation and any potential risks involved. Each interview lasted approximately 60 minutes and was conducted in English. The interviews were audio-recorded to facilitate accurate transcription and analysis. To ensure participant confidentiality, all interviews were anonymised during transcription. After the interviews, the transcripts were prepared and made available to respondents upon request for comments or corrections.

Data Analysis

- For the interviews conducted in person, transcripts were generated from the recordings using Microsoft Word. For online interviews, Microsoft Teams' automatic transcription feature was used. All transcripts were reviewed and manually corrected to ensure accuracy prior to analysis.
- The refined transcripts were then analysed using Atlas.ti, a qualitative data analysis software that facilitates locating, coding, tagging, and annotating elements within unstructured data. The analysis focused on identifying key factors, uncertainties, current approaches, and the adaptive concepts found in the renewal and renovation of ageing bridges.
- Coding and theming were applied to the transcripts through hybrid coding, which combines deductive and inductive coding. The analysis starts with deductive coding based on predefined categories or theoretical concepts, but opens up to inductive codes as new codes and themes emerge from the data. These codes and themes were continuously reviewed and refined to ensure they accurately reflected the content and intent of the interviews.
- The codes are visually mapped using networks in Atlas.ti to illustrate relationships and communicate the insights gained from the data. These networks are used to construct meaning by analysing how the codes are interconnected, helping to reveal underlying patterns and themes and draw conclusions relevant to the research objectives.

3.3. Semi-quantitative Interviews

In this study, a semi-quantitative interview approach is used to evaluate and compare the effectiveness of actions within the adaptive pathways. A semi-quantitative interview combines structured or scaled questions with open-ended ones, allowing for the quantification of certain data while also capturing in-depth insights from participants (Neuman, 2013). This method offers a structured yet flexible approach to understanding complex issues, particularly when scoring or ranking is needed for prioritisation (Guest et al., 2013). It is particularly useful in comparing the perceived effectiveness of the actions considered in this study, which include preservation, mitigation, downgrading, and upgrading.

In a semi-quantitative interview, the actions are assessed using a questionnaire based on life cycle indicators such as cost, risk, and performance. Ideally, these values would be derived from historical data. However, due to time constraints, the scores in this study are based on expert perceptions. The scorecard values are collected through a questionnaire in which experts assign perceived scores informed by their domain knowledge. This is followed by open-ended questions to explore the reasoning behind their responses, allowing for deeper insight and contextual understanding. This also helps validate the interpretation and clarity of the questionnaire items.

3.3.1. Topics and Respondents

The interview explores the perceived impacts of various measures for ageing bridges on key life cycle management aspects, such as cost, performance, and risk. These parameters are used to assess the relevance and effectiveness of measures applied to ageing bridges. The study targets experts with bridge-related expertise, including professionals from contractors, consultants, and other construction backgrounds. The purpose of the quantitative data collection is not to achieve statistical generalisation, but rather to gather informed expert judgments that support qualitative insights and comparative analysis.

This semi-quantitative interview was conducted with an expert who has over 20 years of experience in the field of bridges on 13 June 2025. The expert has a professional background as an engineer in a construction company based in the Netherlands. In this study, the expert is referred to using the code D.1.

3.3.2. Questionnaire

The questionnaire in this study is administered online using Microsoft Forms. It employs a Likert scale ranging from 0 to 10 to measure the perceived impact of each measure related to ageing bridges. To support consistency and clarity in responses, each question is accompanied by a score guide, which helps respondents interpret the scale and navigate their answers effectively.

The questionnaire in this study was divided into four main topics based on the type of information asked, as follows:

- **Informed Consent:** requests the respondent's consent to participate in the questionnaire, outlining the purpose and conditions of the study.
- **Respondent Profile:** collects general background information about the respondent, such as their professional role, experience, and familiarity with bridge projects.
- **Measures:** includes questions regarding the perceived impact and effectiveness of the measures, such as preservation, mitigating, downgrading, renovation, and renewal, measures in ageing bridges.

3.3.3. Follow-Up Open Question

A follow-up explanatory interview is conducted to clarify or explain the quantitative results by directly engaging with the respondent. The score derived from the questionnaire becomes the guidance for the interview. The follow-up question investigates the following aspects:

- Reasons and assumptions for the scores in the questionnaire.
- Perceived ranks of the measures when they are compared.
- Other possible answers that are not covered in the questionnaire.
- The limitations of the questionnaire in exploring the topics, and recommendations to improve the validity of the questionnaire.

Interview Protocol

In general, the interview protocol for this explanatory interview follows a similar structure to the semi-structured interviews conducted in the case study. Prior to the interview, participants were provided with informed consent. Each interview was conducted in English, lasted approximately 60 minutes, and was audio-recorded. An anonymous transcript was then developed based on the recording to ensure confidentiality.

A distinct aspect of this semi-quantitative interview, compared to the case study interviews, is that the respondent was presented with a questionnaire to guide the discussion. During the interview, the respondent was allowed to revise their initial scores based on new insights that emerged, particularly after comparing the responses using the scorecard. The final scores recorded in the scorecard, as adjusted during the interview, are used to compare the perceived effectiveness and impacts of different actions in addressing the challenges of ageing bridges.

Data Analysis

The data analysis is conducted by integrating the findings from the questionnaire and the follow-up question. Integrating findings from the questionnaire (quantitative) and the follow-up question (qualitative) aims to create a coherent narrative where the qualitative findings explain or add meaning to the quantitative results. Each finding from the questionnaire and interview is analysed separately. The findings from both approaches are then integrated by connecting, building, or merging data, particularly during interpretation (Creswell & Plano Clark, 2011).

In integrating the findings, this study uses side-by-side comparison to interpret and present quantitative and qualitative findings together. Side-by-side comparison allows researchers to narratively link questionnaire results with participant explanations (Creswell & Plano Clark, 2011). In a side-by-side comparison, the quantitative and qualitative findings, as well as the interpretation, are put in side-by-side in a tabular format. This format visually shows how the two data sets relate and allows a clear connection between the quantitative and qualitative findings in a structured, transparent, and interpretable way. The result interpretation is used to justify the score for assessing the actions.

4
Case Study

This chapter describes the overview of the case study and the identification of influencing factors in the case based on the empirical study through document analysis and interviews. The chapter focuses on the ageing bridges in the Netherlands as a holistic case study. The first section describes the overview of the case study about the state of the ageing bridges and the Renewal and Renovation (R&R) program in the Netherlands. The second section investigates the influencing factors, including drivers, enablers, and barriers, in the renewal and renovation of the ageing bridges.

4.1. Case Study Overview

4.1.1. The State of Ageing Bridges in the Netherlands

The national road network in the Netherlands was mainly built in the 1960s and 1970s, with expansions continuing into the early 2000s (Rijkswaterstaat, 2023c). Transport network development had evolved significantly during this time, as shown by the increasing number of bridges constructed. With a typical expected lifespan of about 80 years (Bakker et al., 2025), there are many bridges in the Netherlands that are approaching the end of their lifespan and are now due for renewal and renovation. Figure 4.1 illustrates the proportion of bridges within the main road network based on their remaining expected lifespan. It reveals that 84% of fixed steel bridges, more than 56% of movable bridges, and over 20% of fixed concrete bridges have less than 33% of their expected service life remaining. Notably, some movable and fixed concrete bridges have already exceeded their expected lifespan.

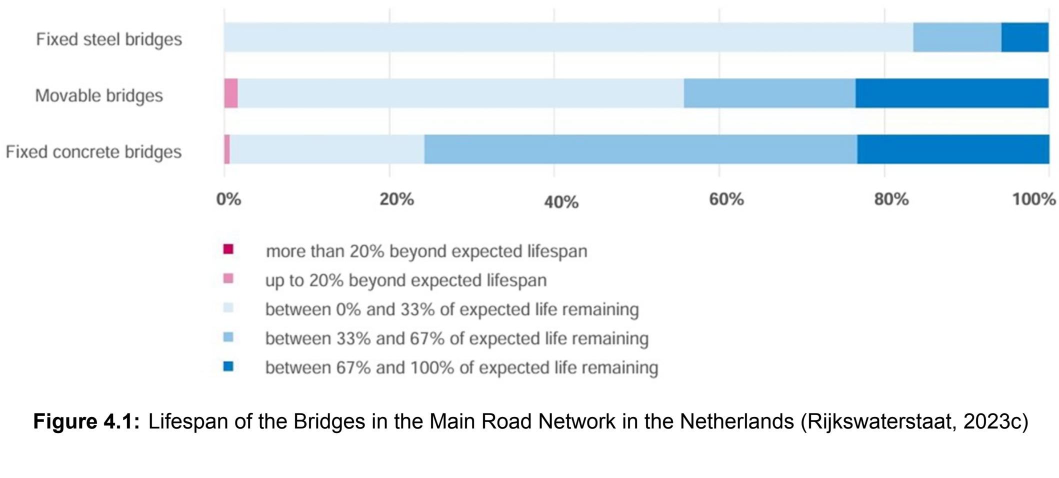

Figure 4.1: Lifespan of the Bridges in the Main Road Network in the Netherlands (Rijkswaterstaat, 2023c)

Even though many of the bridges are due for renovation or renewal, these measures are often postponed for all sorts of reasons (Rijkswaterstaat, 2023c). The postponement leads to unplanned disruptions during which the maintenance is still carried out. This impacts the performance of all networks, which leads to higher costs and lower availability.

4.1.2. Renewal and Renovation (R&R) Program

Rijkswaterstaat is a government agency within the Ministry of Infrastructure and Water Management. It serves as the asset manager for bridges within the main road network in the Netherlands, which are owned by the Ministry. In this role, Rijkswaterstaat is responsible for the maintenance and operation of these assets, as well as for overseeing new construction, major infrastructure projects, and large-scale renovation and renewal initiatives (Fuchs et al., 2014).

The Renewal and Renovation (R&R) program is Rijkswaterstaat's large initiative aimed at renewing and upgrading critical infrastructure that is now approaching end-of-life. The R&R program covers national maintenance, renewal, and renovation of infrastructure across the main road network, water network, and water system. This R&R program follows structured phases (Rijkswaterstaat, 2023b):

- **Object in View (OiV)**

  This phase outlines the national renovation and renewal (R&R) agenda by forecasting assets approaching their technical end-of-life within the next 15 years. The forecasts are categorised into three time horizons, as illustrated in Figure 4.2: short-term, medium-term, and long-term. The short-term forecast relies on object-specific assessments (Klanker et al., 2016). For the medium term, an "issue-based approach" is applied, focusing on known problems affecting specific groups of structures to estimate their replacement timelines. In the long term, projections are derived using a purely statistical method. This phase concludes with an agenda-setting moment, where decisions are made regarding which assets should proceed to a more detailed investigation for potential renovation or renewal.

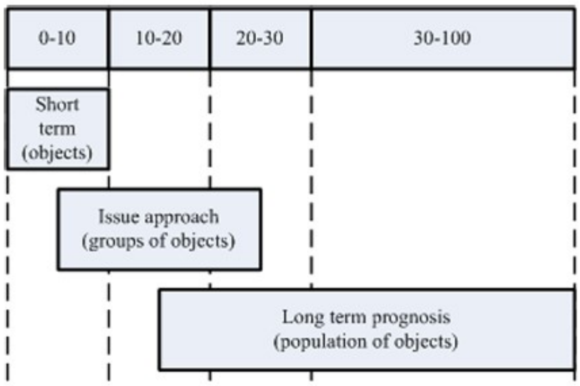

Figure 4.2: Time Horizon Forecast (Klanker et al., 2016)

- **Regional Analysis and Advice (RA)**

  This phase begins with a regional analysis that considers both the infrastructure network and its environmental context. It aims to explore potential solution strategies for addressing ageing assets. The outcome of this phase is the first key decision moment (DM1), where selections are made regarding which assets within the R&R scope should proceed to more detailed investigation in the next phase. The duration of this phase typically ranges from 3 to 6 months.

- **Planning Phase (PA)**

  This phase focuses on exploring solution variants and selecting a preferred option for the asset. It involves assessing the scope, technical feasibility, and implications of each variant. The phase concludes with the second decision moment (DM2), where it is determined whether and in which variant the asset will proceed to the realisation phase. The duration of this phase ranges from 3 to 25 months.

- **Realisation Phase (RF)**

In this phase, the selected variant is executed. This phase consists of assignment execution, preparation for execution, contracting, and the actual execution of the selected variant. This phase can take over a year to complete. Depending on the complexity of the project, this phase may take more than a year to complete.

Figure 4.3 provides an overview of the entire R&R process chain. As the process progresses through its phases, the solution space is expected to converge, while the level of detail in the outputs increases.

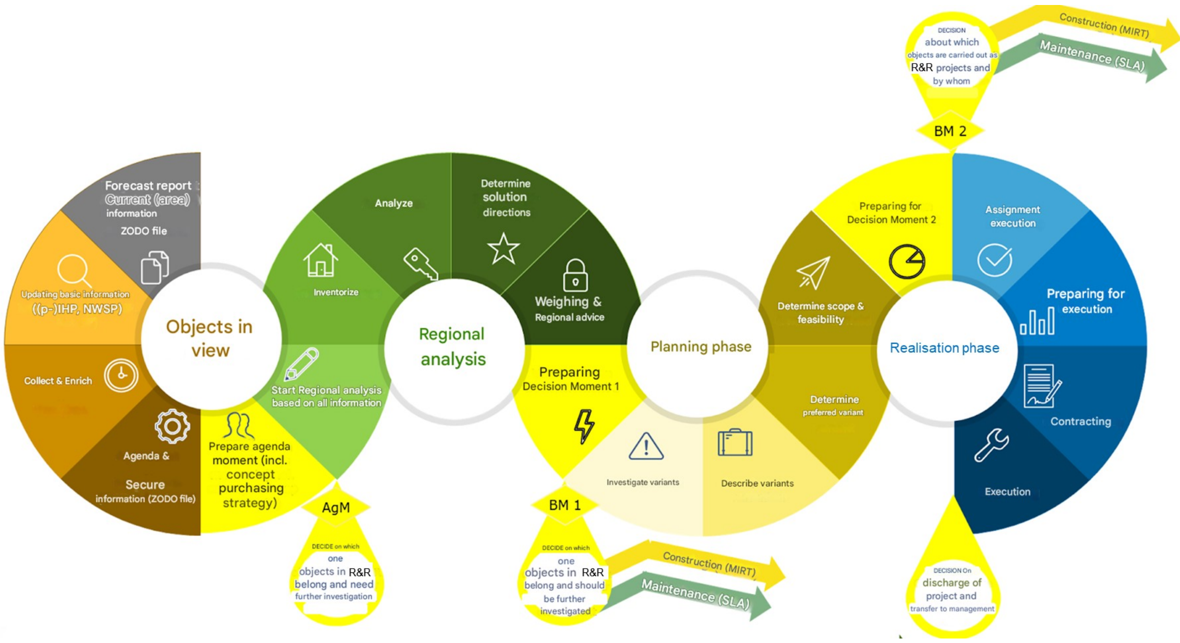

Figure 4.3: Process Chain of Renewal and Renovation Program (Rijkswaterstaat, 2023b)

4.2. Key Factors on Renewal and Renovation

4.2.1. Drivers for Ageing Bridges Renewal and Renovation

Drivers refer to the underlying factors or forces that trigger the need for the renewal or renovation of ageing bridges. Figure B.1 in Appendix B illustrates the interrelated factors that influence both the structural and functional capacity of the bridges. These conditions underline the importance of renewal and renovation for ageing bridges.

Structural Deterioration

Structural deterioration on the bridges can result from internal factors, such as natural ageing and external factors like changes in use that increase loads and accelerate ageing. Common signs of deterioration include corrosion and cracks. This ongoing deterioration presents a significant safety risk due to the potential for structural failure that needs to be monitored over time.

Rijkswaterstaat monitors bridge conditions through proactive inspection programs. The findings from the inspection results guide decisions on further measures. For example, the inspections of bridges in the Netherlands with a tooth-ridge connection or a construction to connect the bridge parts with each other revealed that 90 bridges and viaducts were incorrectly designed, allowing water from de-icing road salts to infiltrate the concrete and reach the reinforcement (Rijkswaterstaat, 2025a). This caused chloride-induced corrosion, leading to cracks that compromise the structural load paths (Bijen, 2004). Bridges identified as having an elevated risk from the inspections are now scheduled for renewal.

Initiatives to address bridge deterioration risks may be prompted once major failures occur. Some deterioration signs are not easily detected during inspections, potentially leading to sudden bridge failures without any signs. This risk has also been highlighted as a concern by the advisor from Rijkswaterstaat (A.1).

> *"We are afraid of that (sudden failure), because, of course, we do inspections every six years. The only reason we do that is because we can see that there are problems with cracks, and everything that has to do with the moment of failure. We see bending moment failure as it always does with cracks. But if the cracks are beneath the asphalt or if it's shear in a brittle failure mode, then it's not likely that you will see any degradation increasing over the years. Shear cracks can happen in one to four months." (A.1)*

A notable example is the unexpected collapse of a bridge in Dresden, Germany, caused by hydrogen embrittlement. This incident led the Netherlands to evaluate bridges with similar conditions for potential risk mitigation (Rijkswaterstaat, 2025a). Hydrogen embrittlement led to cracking in certain types of steel used for concrete reinforcement in the 1950s and 1960s, gradually reducing structural integrity and placing bridges with similar specifications from that era at high risk. Consequently, 13 bridges in the Netherlands with the risks have been placed on a priority list for renewal by Rijkswaterstaat.

Increased Traffic

In the Netherlands, many existing bridges are experiencing more intensive usage than originally anticipated, as they were not designed for current traffic demands (Rijkswaterstaat, 2023c). The growth of e-commerce and load traffic has made road transport the leading mode for freight, which accounts for 38% of total freight volume across all transport modes in the Netherlands (Statistics Netherlands, 2024). The advisor from Rijkswaterstaat (A.1) explained that the dominant reliance on road transportation is linked to economic uncertainties.

> *" We hardly see any increase in transport on roads and on water. We see all the increase in loads transported on the roads. That has to do with insecurities. It's much easier to do an investment in trucks because in five years you can already earn your investment back. For a train. It will take 5 to 25 years, and for a ship, also about 25 years. And in 25 years, so many things can happen because of the political instability or economic instability. You're not sure if you can earn your money back, and in five years that you can really see what is going to happen in the next five years, so it's much easier to, well, at this moment it is a good time to invest in a new truck." (A.1)*

The growth of traffic volumes, especially the increased presence of heavy trucks, places additional stress on bridge infrastructure by increasing traffic loads (European Commission, 2018; Fisher, 1984; AASHTO, 2011). It is estimated that truck overloading contributes to approximately 10% of the excessive load on the road traffic (Rijkswaterstaat, 2023c), accelerating the deterioration process and causing many bridges to approach the end of their service life sooner than initially projected. Beyond freight-related pressures, increasing traffic intensity is also driven by both population and economic growth (Aljoufie et al., 2001).

The increasing traffic beyond the structural and design capacity of the bridge led to the need for major renovation. The notable cases can be found in the Van Brienenoord bridge in Rotterdam (Acosta et al., 2023) and the Gallecopper bridge in Utrecht (EW Magazine, 2025). Both bridges experienced traffic volumes far beyond their original design assumptions decades ago. The inspections on the Van Brienenoord bridge have identified fatigue-sensitive joints and steel expansion elements, a form of deterioration commonly found in welded bridges subjected to high dynamic loads. Repeated stress cycles in such environments lead to the formation of microcracks in welds and joints, potentially resulting in brittle fractures in the bridge (Maljaars et al., 2012). The increases in load demand on the bridges have driven major renovation efforts, highlighting similar needs in other ageing bridges with comparable conditions (NOS, 2025).

The increasing traffic also leads to functional bottlenecks, where bridges, although still structurally sound, are no longer adequate to meet recent mobility needs (Bakker et al., 2025). Consequently, the design of the bridges needs to be modified and upgraded to accommodate the increasing traffic. The advisor from Rijkswaterstaat (B.1) also noted this.

> *" (Functional reasons like the width of the bridge, that are no longer wide enough for the capacity of the traffic, are) not a condition for renovation. It's the time for an upscaling, so we have to make it another bridge, or an extra lane or an excess if there's more traffic than the bridge is designed for. The bridge itself is technically in good state, but we can't handle more traffic on it." (B.1)*

A prominent example of this case is the A9 Schiphol Bridge. As part of the A9 Badhoevedorp–Holendrecht highway expansion, the A9 Schiphol Bridge underwent a major upgrade to address projected future traffic needs on this corridor (Rijkswaterstaat, 2025b). The upgrade was driven by the insufficient width of the original concrete deck and bascule chamber structure. To resolve this, the bridge was upgraded to enable increased lane capacity and support heavier traffic loads in the A9 Badhoevedorp–Holendrecht highway (GWW Bouw, 2024).

Potential Future Demands

Future-proof infrastructure through the integration of advanced technologies has become a key objective of the Ministry of Infrastructure and Water Management, beyond the aim of extending the lifespan of ageing structures in the Netherlands (Bridgeweb, 2018; IO+, 2024). This approach is essential to prevent future malfunctions (Bridgeweb, 2018) and to maintain the overall functionality and reliability of national infrastructure (IO+, 2024). The need for the renewal and renovation program to be adaptable towards future demands is also emphasised by the external consultant (B.2).

> *"The renewal decisions for the infrastructure are the backbone of many things in our society. And I think the objectives (of renewals) are the future robust functions and adaptability to the changing functions of society, changing demand and not starting solely from the technical conditions. So being all the early enough or within the time span we should already be. We should spend more attention on it without waiting too long for it to prove itself, or now it's too old functionally." (B.2)*

Several emerging trends are expected to shape future bridge requirements. Advances in smart mobility, especially autonomous vehicles, may necessitate significant modifications to existing bridges. The advisor from Rijkswaterstaat (A.1) illustrated that these new demands will influence how bridges are designed and built in the future.

> *"What I do now, we're not going to build the same way as we did. We're not going to make bridges like this anymore because these bridges are being used by cars that use fossil fuels. So in the next future there will be automatic cars, smart mobility. Do you need these kinds of bridges for cars that move independently? I don't think so. All these markings. These computers steer. Cars don't need the white stripes and the blue signs, and they don't need them, so they are going to be things. 10 years ago, we still had telephones next to the road. So if you had your car break down, you could phone. Thus, all have gone because we all have mobile phones. " (A.1)*

Besides smart mobility, over the past decades, growing sustainability awareness has driven a modal shift toward public transportation, cycling, and electric mobility (Ministry of Infrastructure and Water Management, 2023). This shift affects structural requirements such as lane width, load distribution, and usage patterns, necessitating adaptations in bridge design and function to accommodate evolving transportation preferences within the network.

System advancement for bridges in the future will become important to facilitate a shift from reactive to proactive infrastructure management, thereby enhancing safety, operational efficiency, and long-term sustainability (Allaix & Vliet, 2023). Ageing bridges may face interoperability challenges when interacting with modern technologies (Wang et al., 2021) in the future, since many of these bridges were not originally designed to accommodate advanced monitoring technologies. Consequently, significant modifications are often required to enable such integration.

4.2.2. Enablers for Ageing Bridges Renewal and Renovation

Enablers are factors that support and facilitate the successful renewal and renovation of ageing bridges. They play a key role in accelerating implementation by responding to drivers and helping to overcome barriers. Figure B.2 illustrates the relationships among enablers. The importance of asset management as a central enabler of the renewal and renovation of ageing bridges is strengthened by other enablers such as political prioritisation and technological innovation.

Asset Management

At Rijkswaterstaat, asset management encompasses maintenance, replacement, and renovation of infrastructure. The advisor from Rijkswaterstaat (A.1) described the task of asset management in comparison to a second-hand car dealership that emphasises keeping the assets at certain performance levels.

> *"They (second-hand car dealerships) have to do a lot of maintenance, but they always make sure that the cars are on average performance and, yes, that's asset management. Lease companies are doing infra providing, second-hand dealerships are doing asset management. They're looking after your car. Every year do their inspection, they do maintenance, and they know that once in a while, the car is failing. But that's something that happens with second-hand cars, while the lease company make sure that you can always have a car." (A.1)*

Asset management approach represents a shift from incident-driven responses to prediction-based anticipation. It needs to be conducted at the area level with big data and a national overview, instead of the individual structure level (TNO, 2021). By estimating the technical residual life of all structures at the area level, asset managers can identify critical structure types and components to be examined in more detail. The result of the examination then becomes the basis for prioritising renewal and renovation decisions.

Asset management also enables more strategic timing of interventions, resulting in cost savings (TNO, 2021). Timely planning allows for the combination of assignments, which often leads to a lower contract price. Rijkwaterstaat is experimenting with a programmatic approach using portfolios of multiple assets tendered together (Rijkswaterstaat, 2022b). This strategy aims to better leverage market capacity, reduce wasted effort, enhance learning and development, and support standardisation.

Political Priority

Government initiatives play a critical role in enabling the realisation of renewal and renovation projects for ageing infrastructure in the Netherlands, including bridges. Many of the renewals and renovations had been delayed due to various reasons. For decades, politicians had often given little priority to preserving what is already there (TNO, 2021). Consequently, budgets for management and maintenance, particularly reserved for renewals and renovation, are often the first to suffer in cost-cutting exercises.

With the increasing unplanned maintenance due to deferred measures, the Ministry of Infrastructure and Water Management finally announced in 2023 a shift in financial resources that was intended for new construction to major maintenance of the infrastructure (Rijkswaterstaat, 2023c). The advisor from Rijkswaterstaat (A.1) also highlighted the shift in focus of the organisation from infrastructure provision to keeping existing assets in good condition.

> *"All to make the we call the mobility as good as possible, that's infra providing. We're changing from an infra providing to asset management. So the Minister has said that he doesn't think the infra providing is so important anymore. Traffic hinders and traffic jams, we will not put less emphasis on these. Instead, I find it very important that the objects and the bridges and the dams are in sound condition in good condition. My Minister finds it important that I look after my assets, asset management. So most of the money is not going to road signs, reducing traffic jams, reducing traffic in there, but more to keep our assets in good condition." (A.1)*

This priority shift aims to address the accumulation of disruption in the networks due to delayed interventions. Through this approach, Rijkswaterstaat now has access to additional budget to carry out more major maintenance on the ageing infrastructure through a Renewal and Renovation (R&R) program (Rijkswaterstaat, 2023c).

Innovation

Innovation plays a key role in enhancing the delivery of renewal and renovation efforts for ageing bridges. Starting in 2030, Rijkswaterstaat plans to execute a significantly larger volume of renewal and renovation projects, estimated to be four times greater than in 2022, guided by future-oriented and cost-effective principles (Rijkswaterstaat, 2023d). The advisor from Rijkswaterstaat (A.1) pointed out the challenge of production capacity to keep up with demand.

> *"That is, at the moment, we have the capacity to replace about five bridges a year, and we need to replace fifty bridges a year. How are we going to do that? How would you going to do that to make the productivity 10 times as much as we do now, without 10 times as many people? If we want to have 10 times, we don't have people. So, how are we going to increase productivity?" (A.1)*

To overcome this situation, Rijkswaterstaat, in collaboration with market partners, is steering innovation towards radical standardisation, project bundling, digitalisation, and sustainability. A strong emphasis is placed on the principles of standardisation and modularisation, with customisation limited as much as possible (Rijkswaterstaat, 2023d). The advisor from Rijkswaterstaat (A.1) mentioned about IFD (Industial, Flexible, and Demountable) construction methods to deal with the limited production capacity.

> *"Now that is a bridge, which is not used here anymore. You can demount it and put it somewhere else. So you need a lot of standardisation. You can make, I think, just like clothes. And you don't want to have oude-couture (bridge), but you need confection. Confection bridges in different sizes, but not so many. At the moment, we're still doing oude-couture to our bridges. That means every bridge is special and no bridges look like any other bridges." (A.1)*

The innovation is also emphasised toward forms of collaboration with market parties for the renewals and renovations. Rijkswaterstaat is using innovation-oriented procurement tools to stimulate innovation through portfolio contracts (Rijkswaterstaat, 2023a). This type of contract is expected to make it profitable for a contractor to introduce innovations, because the investment can be recouped over several projects. The advisor from Rijkswaterstaat (A.1) also pointed out the implementation of the contract for the bridge renovation program with a portfolio approach within the same kind of bridges.

> *" So this is a single individual bridge that is going to be repaired. That's not how we're going to do it in the future because it takes a lot of time and a lot of people to do. And if it is a single individual bridge, you learn nothing from this bridge to do the next bridge. So what we want to do is we say, well, we do ten of the same kind of bridges, and you start with the first. And from the first bridge, you learn a lot of things, and then you can plan how much it costs. You can do better, and then you do the next." (A.1)*

At the asset management level, Rijkswaterstaat is also pursuing innovation in the R&R program for ageing bridges by improving diagnostic methods to determine end-of-life (Rijkswaterstaat, 2023a). The main goal is to increase the accuracy of lifespan predictions, ensuring renewals or renovations occur at the right time, as replacing too early wastes capital, while replacing too late compromises safety.

4.2.3. Barriers for Ageing Bridges Renewal and Renovation

Barriers are defined as obstacles or constraints that hinder or delay the renewal and renovation of ageing bridges. Figure B.3 presents these barriers, some are interrelated, making the process more complex and challenging to manage.

Budget Constraints

Despite initial progress in planning and innovation, underfunding remains a significant barrier to the execution of Rijkswaterstaat's renewal and renovation agenda. By 2040–2050, the estimated annual financial requirement for bridge and infrastructure renewal is projected to reach €3–4 billion, rising to €4–6 billion per year beyond 2050. However, in 2021, actual renewal investments amounted to only €1.1 billion per year, highlighting a substantial funding gap (TNO, 2023). Furthermore, according to the Dutch Audit Office, an estimated €43.3 billion is needed for operation, maintenance, and renewal up to 2030, while only €22.8 billion is currently available, resulting in a budget shortfall of €20.5 billion (EW Magazine, 2025). This financial gap poses a serious risk of delaying critical bridge and infrastructure renewal projects.

The advisor from Rijkswaterstaat (B.1) underscored the shortage of budget to finance the renewal and renovation projects that led to the need for project prioritisation.

> *" We have potentially hundreds of projects all over the Netherlands. We don't have the budget to finance all of them, so we have to make prioritisation of those projects." (B.1)*

The advisor (B.1) also pointed out that budget constraints affect the measures implemented for renewal and renovation.

> *"It (renovation and renewal decision) can be economically driven. Because sometimes, renovation is somehow cheaper than renewal. Sometimes, it (the decision) depends on budget constraints or financial issues. So, when you have a limited budget, renovation is preferred." (B.1)*

Contracting Issues

Contracting issues and contractor risk aversion emerge as the obstacles in executing large bridge renewal projects in the Netherlands. Several major bridge projects, like the Van Brienenoordbrug, have faced delays as contractors are reluctant to take on risk-heavy contracts. The tender in 2022 failed because only one party was interested in the project and asked for an excessive amount (EW Magazine, 2025).

The construction industry often refuses to bear all the financial risks from the projects. The risk aversion attitude is caused by Rijkswaterstaat's tendering approach often places too much financial and delivery risk on the bidders (IO+, 2024). Additionally, unclear technical responsibility due to the uncertainty of the existing condition of the bridges makes contractors hesitant to submit competitive bids (Algemene Rekenkamer, 2013). The advisor from Rijkswaterstaat (B.1) described the unforeseen situation or condition of the object found during a renovation project.

> *"When you do a renovation, there are always ghosts or secrets. That work you don't want to fight. When you open up a wall or lock, there's always dirt coming out. You have to deal with it, and that's very complicating the project. When you renovate, you never know the exact technical state of an object, and only when you open it up or when you begin, and that is always worse." (B.1)*

The external consultant (B.2) also noted the risk of scope changes arising once the renewal or renovation project starts, potentially causing delays and affecting the project's direction and timeline.

> *"There's a scope definition, and it can finally be decided to be renewed in a certain way when you actually open the box. There (turns out) you see the scope can be much bigger than it was. While those are probably also in the risk calculations for them, the condition affects the scope that can cause delay, and of course, impacts the direction of decision and the timeline." (B.2)*

Strict penalties in DBFM contracts also make contractors hesitant to participate in tenders (Algemene Rekenkamer, 2013). Additionally, the long contract durations increase their exposure to unforeseen risks, like changes in environmental regulations, further discouraging participation.

Resources Availability

Rijkswaterstaat is facing significant constraints in human resources for executing the growing number of renewal and renovation projects for ageing bridges. Despite an anticipated fourfold increase in project volume, the organisation currently lacks sufficient capacity to meet this demand (IO+, 2024). The advisor from Rijkswaterstaat (B.1) also noted that the availability of manpower impacts the length of the process of renewal and renovation decision.

> *"The availability of manpower is at this moment the most determining factor of the length of the (decision) process, as we lack the manpower to do the regional analysis." (B.1)*

Another advisor from Rijkswaterstaat (B.3) also pointed out that limited manpower affects the organisation's capacity to carry out renewal and renovation projects.

> *"It's very good that we want to do a project, but we also need to have the resources. Last year, it was not easy to find people for renewal projects, so this is also important to check. We also have ours (the manpowers) in our system to check how many we have, which is the limit of the capacity of what we can do and what not." (B.3)*

In addition to internal manpower availability, the growing workload makes it even harder to recruit adequate numbers of skilled professionals from the market, such as engineers, inspectors, and contractors (Rijkswaterstaat, 2023d).

In addition to human resources constraints, material resource availability poses another major challenge for the renewal and renovation of the ageing bridges. For example, the availability of steel components and long delivery times can be a limiting factor in the renovation of large bridges (Rijkswaterstaat, 2022a). Many bridge components, particularly for movable spans, are not produced domestically. Steel or iron materials for the bridge are imported from other countries due to limited domestic capacity (Global Steel Trade Monitor, 2019). The advisor from Rijkswaterstaat (A.1) also discussed the option of reusing steel from existing bridges to reduce the need for new steel in bridge construction.

> *"We have no steel mines in the Netherlands. So somebody's going to say you're not going to get any steel anymore. You have to do it with the steel you already have in your country. So you have to adapt to that. If you want a new steel, you have to make sure that you have enough existing steel to use as a steel construction." (A.1)*

Regulation Changes

Regulatory changes affect the renewal and renovation process in the Netherlands. A prominent example is the regulation on nitrogen emissions. The nitrogen emissions issue has had a major impact on construction projects in the Netherlands, including delays or suspensions of infrastructure works such as infrastructure renewals and renovations (Rijkswaterstaat, 2023c). A Dutch court in The Hague mandated the government to sharply reduce nitrogen emissions, targeting 50% reduction in Natura 2000 areas by 2030 or face a €10 million daily fine for non-compliance (AP News, 2025). Consequently, construction sectors that account for 0.6% of total nitrogen emissions in the Netherlands now require thorough nitrogen assessments and nature permits under EU and Dutch environmental laws, However, this process is often difficult and lengthy. Failure to comply can result in delays, revised project scope, or even suspension of work.

An advisor from Rijkswaterstaat (B.1) noted that delays in the process can lead to new regulations being introduced, further affecting the entire renewal and renovation process.

> *" If the decision of delay is so long, we have all kinds of new regulations. Suddenly, we have a problem, or sometimes there are new regulations around cybersecurity. We have to take into account new regulations, new laws." (B.1)*

The unpredictable delivery timelines make it hard for contractors to guarantee the milestones in the project, increasing their risk exposure, thereby reshaping how renewal and renovation projects are planned and executed.

4.3. Closing Remarks: Case Study

The Renewal and Renovation (R&R) program, which serves as the case study in this research, is the initiative of Rijkswaterstaat to renew or upgrade the ageing infrastructure in the Netherlands. This program emerged in response to the growing need to replace many bridges that are approaching the end of their technical life. To develop a comprehensive understanding of the renewal and renovation of ageing bridges in the Netherlands, it is important to identify the key factors influencing the program, including its drivers, enablers, and barriers.

The drivers refer to the underlying factors that create the need for the renewal or renovation of ageing bridges through the R&R program, including structural deterioration, increased traffic loads, and anticipated future demands. However, the progress of the program may be hindered or delayed by several barriers, such as budget constraints, contracting challenges, limited resource availability, and changes in regulations. In response to these challenges, asset management serves as the main enabler, facilitating and supporting the implementation of the R&R program. The critical role of asset management is reinforced by political support and further strengthened by innovations in procurement tools and end-of-life diagnostic methods.

Understanding the key factors in the R&R program provides insight into the factors that influence the process capacity of the program to respond to the significant demand for the renewal and renovation of ageing bridges. Additionally, understanding the key factors allows for the identification of uncertainties within them, which helps anticipate both the sources of uncertainty and their potential impact on the processes within the R&R program. These insights form the basis for problem identification and support the development of the objective of the proposed solution.

5

Problem Identification and Solution

This chapter examines the uncertainties present in the renewal and renovation processes of ageing bridges, along with the existing approach to respond adaptively towards uncertainty. The gap between the identified uncertainty and the existing approach serves as serves as the basis for problem identification and the formulation of a design solution.

In this chapter, the first section explores uncertainties that emerge from the drivers, enablers, and barriers. The second section investigates the existing adaptive approaches toward uncertainty. The third section identifies the gap between uncertainty and existing approach. The final section defines the core problem and outlines the objective of the proposed solution, forming the foundation for the design development.

5.1. Uncertainty

Uncertainty can make conventional deterministic approaches problematic, underscoring the need for more adaptive methods. In the renewal and renovation of ageing bridges, various types of uncertainties are identified, highlighting the need for more adaptive approaches within the Renewal and Renovation (R&R) program. Figure B.4 illustrates the relationship between uncertainty and key factors. The key factors mentioned in the previous chapter can act as sources of uncertainty, while uncertainty itself can create uncertainty in the state of the bridge and the process of renewal and renovation, which in turn influence other key factors.

5.1.1. Structural Uncertainty

Structural uncertainty arises from insufficient knowledge about the correct model structure to accurately represent a system (W. Walker et al., 2013; Refsgaard et al., 2007). This uncertainty can arise from limited, insufficient, or incomplete data (Sargent, 2001). Renewal and renovation of ageing infrastructure face this issue due to limited knowledge of their technical condition, stemming from limited documentation of design calculations and materials used (TNO, 2021). It also includes limited information on historical conditions, such as past loads, which is vital for assessing deterioration. This lack of data complicates decision-making for renovation and renewal. The challenge of limited data availability in these decisions was also pointed out by the external consultant (B.2).

> *"I hear the joke from the counter partner, like finding the data about your decision is a project itself. So it's not like you just compile it, but then it becomes a huge project itself. That's what I also address, but the data available is yet scattered, incomplete and sometimes inconsistent." (B.2)*

Structural uncertainty can also result from incorrect or incomplete assumptions about the system's structure or relationships (Morgan & Henrion, 1990). The advisor from Rijkswaterstaat (A.1) described cases where the actual condition of a bridge deviated from prior assumptions.

> *”We did a lot of testing in the 50s and 60s of the last century on rich elements with only a height of about 30-40 centimetres, and we would extrapolate them to the bridge size of 1 metre or more. We found out that it was not a nice linear relationship. It was a declining curve relationship. So the higher your construction was, the less shear capacity we found in bridges, in higher elements and especially for high bridges, high walls, and high beams. We found out that the shape was not as good as we had expected from the test we did on smaller beams.” (A.1)*

The source of structural uncertainty faced by Rijkswaterstaat in dealing with ageing bridges may mainly stem from its limited experience with replacing many bridges within the same period, resulting in limited knowledge for handling such situations. As the advisor from Rijkswaterstaat (A.1) noted, this is the first time the Netherlands has the necessity to replace a lot of its ageing bridges.

> *” Rijkswaterstaat has no bridges that are older than 80 to 100 years. So it’s the first time we’ve experienced that we have (a lot of) bridges that have to be replaced. We have never done that before.” (A.1)*

5.1.2. Scenario Uncertainty

Scenario uncertainty refers to uncertainty about future changes in external factors beyond decision-makers’ control (W. Walker et al., 2013). It recognises that the future cannot be fully predicted or controlled. Renewal and renovation of ageing bridges face this uncertainty in anticipating future demand and traffic conditions that will determine their requirements. The advisor from Rijkswaterstaat (A.1) acknowledged that future traffic conditions and demands are inherently unpredictable.

> *” When I was studying, we had 6,000,000 cars (in the Netherlands). My professor said, well, 6,000,000 is all is is about the maximum number of cars that can be on the roads. In the Netherlands at the moment and more than 10 million. We’re going from 18 million to 20 million, so there will be even more cars. So, I cannot predict how many cars there will be. I cannot predict how many truck lorries there will be on the roads compared to water traffic and train traffic.” (A.1)*

Scenario uncertainty also includes the uncertainty of future innovations that are related to the renewal and renovation of ageing bridges. Rijkswaterstaat acknowledges that innovations are unpredictable, making it hard to know in advance what challenges will arise (Rijkswaterstaat, 2023a). New innovations may arise to meet future demands or, conversely, create new demands. The advisor from Rijkswaterstaat (A.1) noted that new types of construction materials may emerge in the future to meet demands driven by climate change.

> *”I don’t know how the Technical Universities will find out about concrete material or steel material, because I’m sure in about 20 years, we will not use the same concrete as we are doing now. We will use low CO2.” (A.1)*

The advisor (A.1) also pointed out that future innovations, such as smart mobility, may have an impact on the future of ageing bridges.

> *”We think at the moment that we’ll have a change, and I think smart mobility will have a major impact.” (A.1)*

5.1.3. Social and Stakeholder Uncertainty

Social and stakeholder uncertainty refers to the unpredictability of behaviours, preferences, reactions, and interactions among people and institutions involved in or impacted by decision-making (Reed, 2008). Bridges are vital infrastructure, and their renewal and renovation affect the social and economic activities of many people. These projects involve multiple stakeholders with their own interests.

The advisor from Rijkswaterstaat (B.1) and the external consultant (B.2) highlighted end users as key stakeholders. Both Rijkswaterstaat advisors (B.1 and B.3) also emphasised the importance of political stakeholders, such as city councils, whose preferences influence renewal and renovation decisions.

> *"Political stakeholders are very important. (Considering) the location, the surroundings, neighbourhoods, and people living by, the noise can be an issue. The City Council wants some more noise barriers or an extra cycle path, or they would like to hop on our project to have their own performance issues." (B.1)*

The external consultant (B.2) and the advisor (B.3) also mentioned the involvement of internal stakeholders in the renewal and renovation process.

> *"So in theory, all the stakeholders (in renewal and renovation) are the region and the staff of the region, the engineer, the director of every region, the engineer, the Director of network, the COO (Chief Operational Officer) office, the CFO (Chief Financial Officer) office, and the general director." (B.3)*

Social and stakeholder uncertainty stems from unclear values, norms, and preferences within stakeholder groups (Brugnach et al., 2008). Views or preferences about specific issues may shift over time. The advisor from Rijkswaterstaat (A.1) illustrated this with the potential change in social acceptability or perceptions of travel time.

> *"Society thinks that we don't want to have traffic jams or otherwise. Say if you're going from The Hague to Utrecht, you're always sure that you'll take it in half an hour. If we find that not more important than now, then that would mean an important change in policy." (A.1)*

The importance of certain values may also be perceived differently in different stages of renewal and renovation. The external consultant (B.2) noted that some aspects may not be considered important at specific stages in the decision-making process.

> *"I think they (sustainability, circularity, and social values) are important, but is it really important in every decision-making? I think they are not. I don't say not important (at all), but they are not looked at in the early decision like programming and prioritisation." (B.2)*

5.2. Adaptive Approaches toward Uncertainty

Given these identified uncertainties, adopting adaptive approaches for the renewal and renovation of ageing bridges is essential. The current approaches used by Rijkswaterstaat are assessed within the spectrum in the planning rationality framework by de Roo et al. (2021) to evaluate how well they address the uncertainty.

5.2.1. Involvement in Planning

This planning involvement spectrum ranges from top-down, expert-led planning to more participatory, negotiated approaches (de Roo et al., 2021). Figure B.5 illustrates where Rijkswaterstaat's approaches are positioned along this spectrum. Rijkswaterstaat involves experts in various aspects of renewal and renovation, including assessing the technical condition of infrastructure and forecasting end-of-life timing and budgets (Rijkswaterstaat, 2022b). Experts are also involved in quantifying thematic allowances through cost surcharges to account for developments and risks affecting R&R project costs (Rijkswaterstaat, 2022a). This expert-driven forecasting occurs in the early stages of the R&R program. While the initial stages are expert-focused, Rijkswaterstaat allows for stakeholder participation in the later stage by including citizen involvement through city councils, as noted by the advisor from Rijkswaterstaat (B.3).

> *"The city councils are involved in this also, of course. So in the process, almost, I would say. Maybe, in the Object in View stage is less because it's more focused on what we need to do. But from the moment that the project goes, they are engaging." (B.3)*

Rijkswaterstaat also aims to stimulate the participation of market parties in the creation of innovation through an active and reactive role (Rijkswaterstaat, 2023a). In its active role, Rijkswaterstaat directly collaborates, partners, and guides participation. In its reactive role, Rijkswaterstaat monitors others' actions, supports external initiatives, and creates conditions that enable others to innovate.

5.2.2. Conditioning the Possibility of Change

This spectrum highlights the tension between control and autonomy in responding to the possibility of change (de Roo et al., 2021). Figure B.6 shows where Rijkswaterstaat's current approaches lie along this spectrum. Rijkswaterstaat's funding approaches are divided into risk-driven approaches for operation and maintenance and project-driven approaches for renewal and renovation. The advisor from Rijkswaterstaat (B.3) pointed out the differences between these approaches toward anticipating future policy changes.

> *"(Budget for risk-driven approaches) is less influenced by the policy, so if changes happen in the political world, then we are not directly affected. The maintenance measures can be carried on without being interrupted by big changes in the political field." (B.3)*

For project-driven renewal and renovation, Rijkswaterstaat includes cost surcharges in its budgeting to account for future changes (Rijkswaterstaat, 2022b). These surcharges create a financial reserve to cover typical uncertainties and risks, enabling future budget adjustments. Risk surcharges are divided into object risk reserves, which address uncertainties specific to individual projects, and cross-object (portfolio) reserves, which manage systemic or shared risks across the entire renewal and renovation program (Rijkswaterstaat, 2022b).

Cost surcharges enable Rijkswaterstaat to allocate sufficient funds upfront to cover the full scope of expected costs. They do not serve as a control mechanism for project execution but help manage the overall budget envelope, preventing under-budgeting and reducing the need for repeated budget increases. While surcharges help absorb risks and uncertainties, they do not control or enforce project execution, but instead provide flexibility to respond to those risks and uncertainties. However, the implementation of cost surcharges can be limited, as they are typically based on statistical variation (Rijkswaterstaat, 2022b), which may not be effective in capturing nonlinear changes or responding to extreme scenarios.

5.2.3. Acting in Response to Change

This spectrum covers planning approaches that range from relying on initial assumptions to adjusting actions as new knowledge emerges (de Roo et al., 2021). Figure B.7 shows the position of Rijkswaterstaat's approaches along the spectrum. Rijkswaterstaat bases its initial budget planning on forecasts and expert judgement (Rijkswaterstaat, 2022b). These assumptions are updated over time if found inaccurate. For example, before 2022, Rijkswaterstaat applied a uniform 50% surcharge to all subtasks but later shifted to sensitivity analyses for thematic cost surcharges to better capture variations in scope, market conditions, and price developments, as the flat surcharge failed to reflect task diversity (Rijkswaterstaat, 2022b).

At the project implementation level, uncertainty causes assumptions derived from a successful pilot project may not always be applicable to other cases (Rijkswaterstaat, 2023a). The uncertainty encourages the organisation to reflect and adapt through learning. Rijkswaterstaat recognises the importance of strengthening its learning capacity with partners to improve processes and systems (Rijkswaterstaat, 2023a). Cross-project working and learning have become an important part of Rijkswaterstaat's innovation agenda. With learning, the projects are expected to contribute to a faster application of innovations and to actively share their lessons and experiences so that others can make use of them. This is similar to the learning concept within the portfolio approach described by the advisor from Rijkswaterstaat

(A.1) in subsection 4.2.2, about innovation.

5.2.4. The Need for A Capacity to Change

This spectrum illustrates the range of adaptive capacity, from incremental adjustments to fundamental systemic change (de Roo et al., 2021). Figure B.8 presents where Rijkswaterstaat's approaches are situated within the spectrum. The renewal and renovation of ageing bridges aim to address increasing network demands while dealing with reduced structural capacity from ageing and limited functional capacity due to design obsolescence. As many bridges near the end of their service life and demand continues to rise, Rijkswaterstaat faces a capacity shortage in delivering the renewal and renovation efforts (IO+, 2024), due to limited budgets (EW Magazine, 2025) and resource availability, which affect decision-making and construction processes.

Despite growing demand for the renewal and renovation of ageing bridges, Rijkswaterstaat does not aim to exceed its capacity to meet these demands. Instead, it focuses on maximising the use of existing capacity, as noted by the advisor from Rijkswaterstaat (A.1), who highlighted the shift of priority from infrastructure provision to asset management. This indicates that renewal and renovation efforts are driven more by available capacity than by demand. Capacity here refers not only to executing bridge renewals and renovations but also to maintaining them over time. The advisor (A.1) also emphasised the importance of considering the organisation's overall maintenance capacity when planning new bridge construction.

> *"We can only have 5000 bridges by Rijkswaterstaat. If we find it very important that the extra bridge coming here somewhere else has a bridge has to be removed because we cannot maintain so many." (A.1)*

The limited capacity of the R&R program necessitates prioritising which assets to address, as noted by the advisor from Rijkswaterstaat (B.1).

> *"So we have potentially hundreds of projects all over the Netherlands. We don't have the budget to finance all of them, so we have to make a prioritisation of those projects". (B.1)*

Maximising capacity also involves enhancing the ability to deliver renewal and renovation of ageing bridges by boosting productivity in both decision-making and construction. Decision-making can be improved through an asset management system that helps Rijkswaterstaat make informed choices within the R&R program (Rijkswaterstaat, 2023a), while construction productivity can be increased through standardised construction methods (Rijkswaterstaat, 2023d).

5.3. Problem Identification: Gap between Uncertainty and Existing Approaches

5.3.1. Structural Uncertainty in Deterministic Approaches

Rijkswaterstaat implements deterministic and expert-driven approaches in forecasting or modelling the need for the upfront planning in renewal and renovation (Rijkswaterstaat, 2022b). These forecasts serve as the basis for reserving budgets to address future uncertainty. However, such approaches carry risks, as they may not adequately account for structural uncertainty. Limited knowledge and historical data can lead to incorrect assumptions in forecasting. This increases the risk that budget allocations may not align with actual needs and potentially result in under- or over-budgeting.

Rijkswaterstaat acknowledges the structural uncertainty in the renewal and renovation of ageing bridges and is exploring ways to address this knowledge gap through cross-project learning within portfolios of objects (Rijkswaterstaat, 2023a), as also noted by the advisor from Rijkswaterstaat (A.1). By fostering learning, Rijkswaterstaat aims to manage risks associated with structural uncertainty and reduce it as new knowledge is gained over time.

Rijkswaterstaat is also experimenting with a programmatic approach with a series of objects. This portfolio is tendered all at once to better utilise market capacity, reduce inefficiencies, enhance learning and development, and support standardisation (Rijkswaterstaat, 2023a).

5.3.2. Limited Options for Scenario Uncertainty

Scenario uncertainty in the renewal and renovation of ageing bridges stems from uncontrollable external factors, such as future traffic growth, social demand, and new requirements. To address this, Rijkswaterstaat allocates budget reserves planned early in the Object in View phase (Rijkswaterstaat, 2022b). During the later Regional Analysis phase, it explores a range of promising options and narrows them down for the Plan phase. As noted by the advisor from Rijkswaterstaat (B.1), offering multiple options at earlier stages allows for flexibility in response to uncertainty in later phases .

> *"In the Plan phase, you will conduct more research and take the two or three alternatives, so there is room for flexibility because you don't know at the end of the Regional Analysis phase all the kinds that are not certain. So, it's more you know it's certain enough to conduct some research in the Plan phase and leaves some room for uncertainty." (B.1)*

This also involves narrowing down the range of the budget.

> *"Maybe in an example at the beginning of the Regional Analysis phase. You think the project can be between 5 and 50 million dollars, depending on the scope of the project. At the end of the Regional Analysis, probably, it's $30 to $40 million. So we have to narrow down the range indeed. But you don't have to say it will be $36.2 million." (B.1)*

The range of budgets and options provided in the Regional Analysis phase is later evaluated during the Plan phase to choose the best solution to follow, as noted by the advisor from Rijkswaterstaat (B.3).

> *"Then we have the Plan phase, when the different options from the Regional Analysis phase were under studied. They will then do deeper analysis to decide which option they are gonna follow." (B.3)*

While narrowing down options and budget ranges in later phases can create a sense of certainty, it also reduces flexibility if initial assumptions in selecting certain options turn out to be inaccurate and deviate from the future condition. Infrastructure projects can have a long lead time, making unforeseen situations possible to happen in the future. This creates risks that decisions made may no longer be applicable in different scenarios in the future, while no other options are available to overcome the unforeseen situation, as they have already been eliminated in the previous phases.

5.3.3. Social and Stakeholder Uncertainty toward The Urgency for Prioritisation

Social and stakeholder uncertainty influences the preferences and acceptability of the ageing bridges' renewal and renovation program. It also creates uncertainty around the demands to be addressed, which affects how the objects are prioritised. Given the limited capacity, not all societal and stakeholder demands can be met in the near future. As noted by the advisor from Rijkswaterstaat (B.3), prioritisation is necessary, along with clear criteria to guide it.

> *"Every region and every team considers their project the most important, so we also deal with this as the COO (Chief Operational Officer) office. Because we don't have the resources for every project, we need to use some criteria to prioritise the project." (B.3)*

Besides prioritisation criteria, the sequences of the project's delivery also needed to be taken into account, as noted by the external consultant (B.2).

> *"What are the essential aspects that could also be the urgency. I think they also take into account capacity, maybe in the Regional Analysis phase. Let's say ten bridges, and that they cannot be renovated at the same time. So, some sequences become essential." (B.2)*

Prioritisation criteria are important to determine project urgency, which defines how projects are sequenced. However, the perceived urgency or acceptability of outcomes from renewal and renovation can be uncertain, as they depend on the values and preferences of society and involved stakeholders. Addressing the preference and urgency of each object individually can be time-consuming, with no clear certainty when it can be finalised. Therefore, an objective and standardised prioritisation criteria and sequencing mechanism, applicable across all bridges, is needed to streamline decision-making. These mechanisms should be equipped with the option to delay, to substitute the measure, or even to ignore certain objects until their state of urgency becomes clearer.

5.4. Objective of Solutions

To address the gaps in the current approach for managing uncertainty in the renewal and renovation of ageing bridges, the following objectives for solutions are proposed. Figure B.9 illustrates the relationship between the identified problems and the objectives of solutions, along with their corresponding indicators.

5.4.1. Adaptive Approaches

Current deterministic approaches, which rely heavily on prediction, can be problematic in addressing scenario uncertainty, especially when dealing with structural, social, and stakeholder uncertainties in the context of ageing bridges. More adaptive approaches that account for future uncertainty and allow for adjustments are necessary. To support these approaches, the following key indicators are applied:

- **Flexibility:** The approaches need to allow flexibility to adjust measures in response to changing conditions.
- **Options:** Alternative options are provided in case the initial plan proves to be unsuitable.
- **Budget Reserve:** A budget reserve is allocated upfront to anticipate unforeseen situations in the future.

5.4.2. Capacity-driven Planning

Given Rijkswaterstaat's limited capacity to meet growing demand and the shift in political priority away from infrastructure provision, the renewal and renovation of ageing bridges need to place more emphasis on capacity as the foundation for planning, rather than demand. To support this approach, the following key indicators are applied:

- **Prioritisation:** An objective prioritisation criteria is in place to assess and rank the demands for ageing bridge renewal and renovation.
- **Sequence:** A sequencing mechanism is necessary to organise projects based on available capacity.

5.4.3. Portfolio Approach

Structural uncertainty resulting from limited knowledge makes learning essential. Learning helps to facilitate the capacity building of the process as new knowledge is gained. This can be facilitated through cross-project learning by managing bridges as a portfolio of objects. Furthermore, the portfolio approach allows projects to pool their capacities, making it possible to adjust and compensate across projects when changing conditions arise. This enhances the ability to respond to uncertainty more effectively. To support this approach, the following key indicators are applied:

- **Project Bundling:** Ageing bridge projects with similar conditions are grouped into the same portfolios.
- **Learning:** A knowledge transfer process is established among projects within the portfolio.

- **Capacity Building:** Capacity improvement enables more effective and efficient renewal and renovation of ageing bridges, which can be supported through continuous learning.

5.5. Closing Remarks: Problem Identification and Solution

In this chapter, the uncertainties involved in the renewal and renovation of ageing bridges in the Netherlands are identified. These include structural, scenario, social, and stakeholder uncertainty.

- Structural uncertainty stems from limited knowledge and incomplete historical documentation of the bridges, making it difficult to accurately assess their current condition and determine the drivers for renewal and renovation. This lack of clarity can result in incorrect assumptions within the deterministic planning approach currently used by Rijkswaterstaat, potentially affecting the accuracy and reliability of renewal and renovation decisions.
- Scenario uncertainty arises from unpredictable future demands and traffic conditions that influence the requirements for bridge performance and design. In response to the uncertainty, Rijkswaterstaat applies cost surcharges to allocate sufficient funds upfront, aiming to anticipate potential changes in funding needs. However, this approach may be limited in its effectiveness, as it is not well-suited to capturing non-linear developments or responding to extreme or unexpected scenarios.
- Due to limited capacity to address the growing demand, prioritising the renewal and renovation of the most urgent bridges becomes necessary. As strategic infrastructure, any intervention on a bridge can significantly impact the social and economic activities of surrounding communities. Social and stakeholder uncertainty, which arises from unclear or differing values and preferences among people, leads to varying perceptions of what should be prioritised. This diversity in viewpoints makes it more difficult to determine the level of urgency for bridges, complicating the prioritisation process.

The gaps between the identified uncertainties and the existing approaches used by Rijkswaterstaat serve as the basis for developing the objective of the proposed solutions as follows:

- **Adaptive Approaches:** The gaps drive the need for more adaptive approaches that accommodate the flexibility through options to allocate an upfront budget reserve in response to changes due the scenario uncertainty and new information gained that was not identified before due to structural uncertainty.
- **Capacity-driven Planning:** The limited capacity to address the increasing number of ageing bridges emphasises the importance of capacity-driven planning. This makes it necessary to establish objective prioritisation criteria and sequencing mechanisms that work with the different perceptions of urgency resulting from social and stakeholder uncertainty.
- **Portfolio Approach:** The structural uncertainty caused by limited knowledge underlines the need for learning. This can be supported through a portfolio approach, where bridges are grouped to facilitate cross-project learning. Such learning is expected to build the capacity of the process due to the new knowledge gained.

The objective of the proposed solution, which integrates adaptive approaches, capacity-driven planning, and a portfolio approach, serves as the foundation for the design development step in creating a process for adaptive pathways implementation. These objectives will also guide the evaluation of the applicability of adaptive pathways based on the outcomes of the demonstration step.

6
Design Development

This chapter presents the design process for the renewal and renovation of ageing bridges using the Dynamic Adaptive Policy Pathways (DAPP) approach. The first section introduces DAPP as the guiding framework for managing uncertainty in long-term planning. The second section outlines the step-by-step design process applied to develop a plan for the renewal and renovation of ageing bridges. The final section details the proposed process design for implementing adaptive pathways in the context of ageing bridges.

6.1. Design Approach

6.1.1. Dynamic Adaptive Pathways Planning Approach

This study applies the Dynamic Adaptive Pathways Planning (DAPP) approach to address the uncertainties associated with the renewal and renovation of ageing bridges. DAPP is used to design an adaptive strategy that accounts for a wide range of possible future conditions. The approach is particularly suited to this context, as it acknowledges the limitations in predicting long-term developments with certainty. By mapping out multiple plausible futures, DAPP helps planners avoid path dependency and maintain flexibility, ensuring that future options remain open (Haasnoot et al., 2019).

The DAPP approach integrates two complementary and partially overlapping adaptive planning methods: Adaptation Pathways (Haasnoot et al., 2012) and Dynamic Adaptive Planning (DAP) (W. Walker et al., 2001). Both approaches are grounded in the concept of the Adaptation Tipping Point (ATP), which serves as a critical reference for determining when a current strategy will no longer meet its objectives under changing conditions. As such, the ATP is a central element in the DAPP framework.

6.1.2. Relevance for Ageing Bridges Context

The DAPP approach is used in the study due to its feature that incorporates flexibility, which allows long-term planning to adapt to changing conditions. Though initially developed for climate resilient water management, DAPP is a generic method applicable to other long-term strategic planning challenges under uncertainty (Haasnoot et al., 2019). Ageing bridge renovations and renewals meet the planning criteria that suit the DAPP approach in addressing uncertainty, as outlined by Haasnoot et al. (2024). DAPP is particularly useful for decisions or plans that:

- involve long-term lifespans (spanning several decades) or have lasting societal impacts,
- are subject to gradual and continuous changes in their effects over time,
- face significant uncertainties, carry potentially high consequences, and may lead to path dependency.

Infrastructure assets such as bridges have long life spans and play a critical role in the overall performance of transportation networks, carrying significant long-term economic and social implications.

However, planning for the renewal and renovation of ageing bridges is often complicated by uncertainty arising from evolving conditions, including increased traffic volumes and changing functional requirements. Early decisions in the renewal or renovation process may also constrain future options, leading to path dependencies that limit the ability to optimise the network over time (Hertogh et al., 2018). These challenges underscore the suitability of the DAPP approach for managing the renewal and renovation of ageing bridges, as it supports flexible, forward-looking decision-making under uncertainty.

6.1.3. Design Steps

The DAPP approach consists of seven sequential steps (Haasnoot et al., 2019). Figure 6.1 illustrates the process for developing an adaptation strategy using this framework. Although the full methodology includes all seven steps, this study focuses on Steps 1 through 5.

The process begins by establishing the decision context, which involves defining the system boundaries and specifying objectives and outcome indicators. In Step 2, the adaptation tipping point (ATP) of the current system state is assessed to determine when the existing strategy will no longer meet its objectives under changing conditions. Step 3 involves identifying potential actions or measures and evaluating their effectiveness and the conditions under which each reaches its ATP. In Step 4, these actions are sequenced into possible adaptation pathways. Finally, in Step 5, adaptive strategies are formulated in selecting initial actions and long-term options based on a set of preferred pathways.

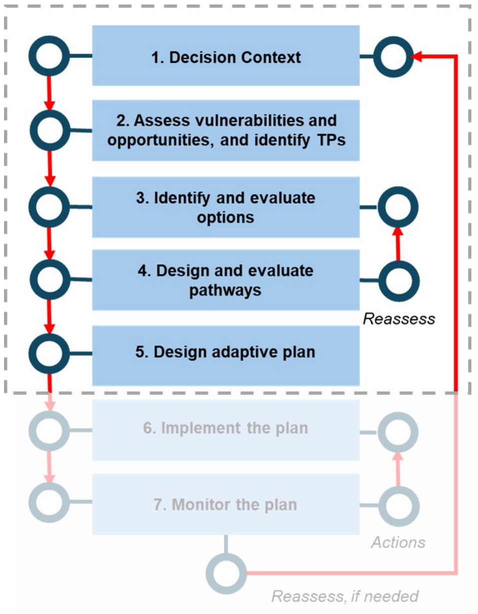

Figure 6.1: DAPP Approach Steps (Own Figure adapted from Haasnoot et al. (2019))

6.2. Design Development

6.2.1. Decision Context

System Descriptions

The ageing bridges Renewal and Renovation (R&R) program in the Netherlands is facing significant pressure, as many bridges are approaching the end of their technical lifespan in the coming decades. The program encounters multiple challenges, with uncertainty being a key factor requiring adaptive approaches. The major uncertainties faced by the R&R program for ageing bridges are as follows:

- **Structural Uncertainty:** Limited knowledge about the state of the ageing bridges in the Netherlands.
- **Scenario Uncertainty:** Uncertain future external conditions that affect the requirements and demands of the bridges.

- **Social and Stakeholder Uncertainty:** The unpredictability of societal and stakeholder preferences and acceptance regarding measures for ageing bridges.

Additionally, the long lifespan of bridge infrastructure and the extended time required for planning make it challenging to respond quickly to changing and uncertain conditions. The program's limited capacity to execute renewal and renovation efforts further complicates the situation.

Objectives

The objective of the design is to develop a framework for implementing adaptive approaches to address the gaps of the current approach towards uncertainty through adaptive pathways planning for the ageing bridges R&R program in the Netherlands at the programme level.

Targets and Key Indicators

The desired outcomes expected from the design are derived from the objective of the solutions mentioned in section 5.4 into key indicators. Table 6.1 shows the targets and indicators to be achieved through the design.

No	Targets	Indicators
1	Adaptive Approaches	Flexibility Options Budget Reserves
2	Capacity-driven Planning	Prioritisation Sequence
3	Portfolio Approach	Project Bundling Learning Capacity Building

Table 6.1: Targets and Key Indicators

Outputs

The output of the design is not a specific, detailed plan for individual bridge renewal or renovation projects. Instead, it is intended for implementation at the portfolio level during the early programmatic stage, focusing on preparing options to allow budget reserves for future adjustments. The outputs of the design include:

- **Adaptation Pathways Map:** The map illustrates a decision tree that presents the range of planning options available for ageing bridges throughout their life cycle, as shown in Figure 6.2.
- **Adaptive Plan:** The flowchart illustrates the adaptive plan for transitioning from one action to another within the adaptation pathways map, as depicted in Figure 6.6.
- **Framework for the Adaptive Pathways Approach Implementation:** The framework demonstrates how the adaptive pathways approach can be applied to the renewal and renovation program for ageing bridges in the Netherlands. It includes:
  - A flowchart for implementing adaptive approaches through adaptive pathways (Figure 6.8),
  - A flowchart for implementing adaptive pathways in capacity-driven planning (Figure 6.9),
  - A flowchart for implementing adaptive pathways in a portfolio approach (Figure 6.11).

6.2.2. Adaptation Tipping Points

The Adaptation Tipping Point (ATP) is the moment when an action no longer meets a plan's objectives (Haasnoot et al., 2012). Various approaches can be used to identify ATPs. The ATPs can be identified through top-down or bottom-up approaches. Top-down approaches are largely dependent on model-based assessments to represent the variety of relevant uncertainties and their development over time, while the bottom-up approach can rely on model-based assessments to establish the failure conditions (thresholds), or these can be specified via expert judgment or stakeholder consultation (Haasnoot et al., 2019).

In this study, a bottom-up approach is used to identify the ATPs. For ageing bridges, ATPs are linked to end-of-life indicators, which signal when a bridge can no longer meet required performance standards. However, since the end-of-life is not defined by a single indicator, identifying the ATP requires integrating multiple indicators, such as technical, functional, and economic. The bottom-up approach is particularly useful in this context, as it accommodates diverse criteria and value judgments from different stakeholders.

ATPs for the ageing bridges can be triggered by various conditions, including technical and functional ageing, as well as economic indicators. Given the complexity and interplay of these indicators, a structured decision-making process is needed to identify the most critical end-of-life criterion in certain conditions and establish the threshold at which the ATP is reached. The decision-making process can be guided by the decision flowchart presented in Figure 2.10.

6.2.3. Actions

The DAPP approach involves developing an adaptation pathways map by exploring different combinations of actions over time, guiding the system towards a range of possible future states (Haasnoot et al., 2013). In this study, the actions to respond to the ATP are categorised as follows:

- **Preservation:** focuses on slowing or counteracting the ageing process. Technical objects are maintained above the minimum quality level necessary to ensure the required performance.
- **Mitigating:** modifying functional requirements by making interventions elsewhere in the system, without altering the asset. This measure fulfils the functional needs differently from its initial functional requirement.
- **Downgrading:** accepting the effects of ageing and adjusting the asset's usage to a lower agreed-upon performance level to prevent failure. Technical obsolescence is not fully restored to an" as good as new" condition. Maintenance for this measure is performed at a lower performance level.
- **Renovation:** enhances an asset's functional performance by upgrading or adding existing structures. The improvement measure includes increasing the utility value of the infrastructure.
- **Renewal:** involves one-to-one replacement, where a new object replaces the ageing one. It marks the start of a new lifespan in the system.

These actions are expected to extend the lifespan of ageing bridges. In addition to lifespan, they also affect key life cycle management indicators: cost, risk, and performance. An expert interview with an experienced bridge engineer from a contractor (D.1) was conducted to give insights for evaluating and comparing the impact of these actions on those indicators. Due to the limited number of respondents involved in this topic, the results of the interview will be combined with other sources. The finding will serve as the basis for the design evaluation phase.

Cost Impact

Regarding cost impacts, the engineer (D.1) viewed preservation as a cost-efficient way to extend a bridge's lifespan. In terms of the cost impacts from the actions, the engineer (D.1) considered preservation as a cost-efficient measure to extend the life span of the bridge. However, conducting a proper preservation requires skilled people or organisations. Despite the higher cost for maintenance in preservation, the structure of the bridge can withstand more external factors, making it last longer.

> *"You do not have to look only at the maintenance cost. The maintenance costs are a little factor, but it's a little factor with a huge effect." (D.1)*

The engineer (D.1) considers mitigating and downgrading measures to be moderately cost-efficient. Although renewal has a higher initial cost, it is justified by the resulting performance gains. For renovation, the engineer pointed out the risk of underestimated costs that may arise during execution.

> *"In renovation, you don't always know what you are getting when you are working on such a bridge during the engineering and execution stages. There are new problems often, so the cost is often underestimated." (D.1)*

Cost components include not only direct costs but also indirect costs, such as user delay costs that reflect the economic value of lost time for network users, and environmental costs related to material production and transport during construction (Stipanovic et al., 2020). While major interventions may involve higher initial costs, they can enhance asset condition, leading to more efficient maintenance and improved availability. On the other hand, delaying such measures may increase ongoing maintenance needs and disruptions, resulting in higher indirect costs.

Performance Impact

In terms of performance, the engineer (D.1) viewed renewal as the most effective measure for enhancing bridge functionality, as it allows for upscaling through a larger and more robust structure. Preservation is also effective in maintaining performance, though only for a limited period. On the other hand, the engineer (D.1) considered mitigating and downgrading measures to be less effective in maintaining bridge performance. Mitigation may not adequately address rising traffic demand, and downgrading also performs poorly in sustaining functionality to meet future needs.

Risk Impact

The engineer (D.1) identified preservation and renewal as the most effective measures for reducing risks associated with ageing bridges, such as long-term failure and user dissatisfaction. Renovation and mitigation were also seen as useful for making these risks more manageable. However, for the dowgrading measure, the engineer (D.1) noted that relying on this measure in the long run will increase the risk to the ageing bridges.

6.2.4. Adaptation Pathways Map

Once the actions are identified, portfolios of actions that are enacted simultaneously can be developed into an adaptation pathways map (Haasnoot et al., 2019). The map visualises all possible actions and the logical sequences through which the specified objectives can be achieved under changing conditions. It enables the identification of opportunities, no-regret actions, potential lock-ins, and the timing of actions or interventions.

Figure 6.2 illustrates the possible adaptation pathways map for the ageing bridges. Hovever, the length of the actions presented in this map does not indicate the duration of the extended lifespan. The map offers flexible decision-making by showing alternative options for actions. Each action includes an Adaptation Tipping Point (ATP) that represents a moment when it no longer meets its objectives. When the ATP is reached, the pathway needs to shift to the other available options.

An ageing bridge may follow multiple pathways or sequences of actions that support adaptive goals and help avoid decision lock-in. Each action within a pathway influences the feasibility of subsequent actions, creating path dependencies. The transition from one pathway to another is determined by the occurrence of ATPs.

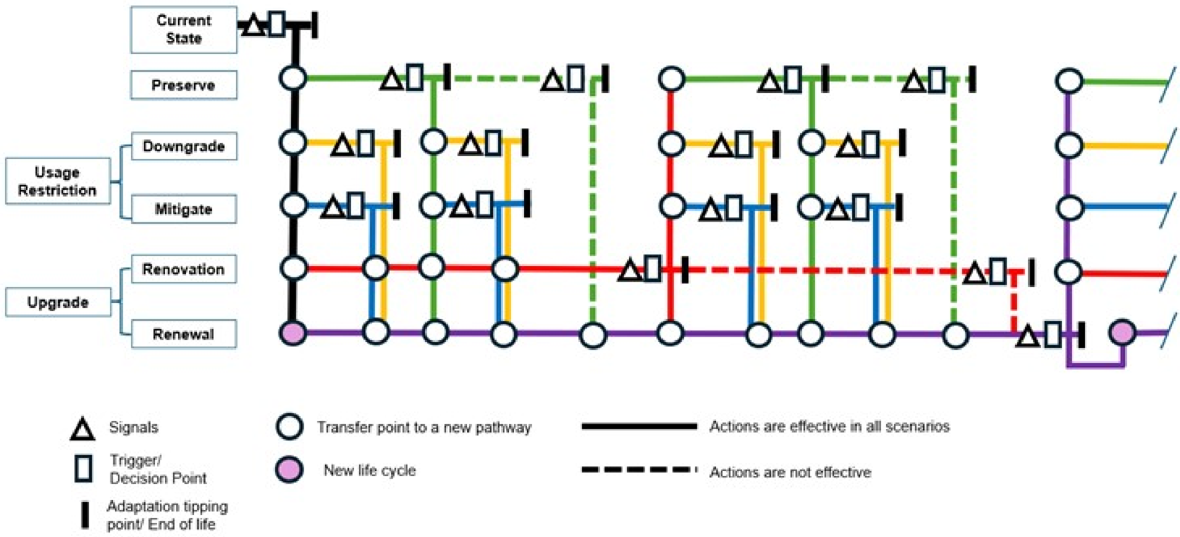

Figure 6.2: Adaptation Pathways Map for Ageing Bridges (Own Figure)

An action may have two ATPs, as seen in the case of preserving action. In that condition, it becomes no longer financially viable to keep increasing the level of the maintenance regime, even though the bridge still has the capacity to serve its objectives. This raises the urgency to shift to other feasible actions.

If the bridge remains structurally sound but shows reduced performance, actions such as downgrading or mitigating through usage restriction can be taken before the first ATP is reached. Preservation action may still continue beyond the first ATP until the final ATP, when the bridge can no longer fulfil its intended role. However, continuing this preservation action beyond the first ATP is inefficient, and eventually, a major upgrade is still necessary in the end.

Downgrading and mitigating restrict bridge usage to match its reduced capacity from ageing, helping avoid costly maintenance. These actions reach their ATP when the bridge hits its technical end-of-life. The upgrade measures, like renovation and renewal, become the next feasible options, as increasing the maintenance regime through preserving measures will not be possible to restore the bridge's physical condition.

Renovation and renewal serve as major upgrades for ageing bridges. Renovation extends the bridge's lifespan, while renewal starts a new life cycle (Rijkswaterstaat, 2022b). Although multiple major renovations are possible during a bridge's life, doing them consecutively is often inefficient, especially when deterioration is severe (FHWA, 2018). In such cases, further renovations may not be more cost-effective than renewal. Additionally, hidden damage like fatigue cracks can persist despite surface improvements (NCHRPP, 2012), and the bridge may no longer comply with updated loads or design standards (FHWA, 2012). Renewal becomes the final option when all other actions are no longer sufficient.

Each pathway is then evaluated based on its life cycle management parameters, such as the cost, performance, and risk. The evaluation results help illustrate the trade-offs among pathways and support the identification of a manageable set of promising and preferred pathways. The results may change over time, requiring periodic updates to reflect changing conditions and new information. The impact of the pathways can be assessed with these aspects as follows:

Path Dependency

Path dependency refers to the extent to which early decisions constrain future options, limiting the adaptability of pathways. It occurs when choosing a specific action or sequence reduces flexibility to adjust later due to factors like sunk costs, technical lock-in, institutional inertia, or social acceptability

(Haasnoot et al., 2013). In the context of ageing bridges, path dependency often arises from high-cost actions that require huge investment, such as renewal and renovation, making them more committed and harder to reverse.

Switching Cost

Switching cost refers to the difficulty or cost of transitioning from one action to another within a pathway. High switching costs may arise from physical, institutional, or financial barriers and should be considered when assessing pathway flexibility (Haasnoot et al., 2013). The higher switching cost can be attributed to the number of transitions, as the more transitions mean more switching effort. It is also related to the compatibility of the action. If an earlier action does not align with or support the next, the cost of transitioning can be significantly higher.

Timing

Timing refers to when effective actions are taken early enough to prevent a crisis. It is critical, as acting too soon may waste resources, while delays can result in irreversible damage or missed opportunities (Haasnoot et al., 2013). In the context of ageing bridges, better timing can be measured by how early high-performance actions are implemented. The earlier they occur, the sooner issues can be addressed. However, delaying such actions does not necessarily indicate poor timing if the delay serves to prepare for their effective implementation. For example, renewal may be highly effective in addressing ageing, but it requires significant investment and a long preparation period. In such cases, lighter measures can be applied early as temporary actions while preparing for full renewal.

Regret Potential

Regret potential refers to the risk of a poor outcome if the future unfolds differently than expected. Regret is defined as the performance gap between the chosen strategy and the optimal one that would have been selected with perfect foresight (Haasnoot et al., 2013). A low-regret strategy performs reasonably well across a wide range of plausible futures, even if it is not always the best. In the context of ageing bridges, regret is high when early actions have low performance and cannot be adjusted in time. For instance, renewing a bridge too early may lead to regret if future traffic declines, leaving a costly investment underused, while relying solely on preservation may also lead to regret if unexpected deterioration demands urgent and costly renewal or renovation measures.

6.2.5. Adaptive Plan

An adaptive plan is needed to define the initial actions and long-term options associated with the preferred pathways in the adaptation pathways map. This plan must be supported by a monitoring system that outlines relevant signposts and corresponding trigger points or indicators that signal when it is necessary to implement subsequent actions (Haasnoot et al., 2019). The monitoring system gives signals before a decision needs to be taken to implement actions before a decision point.

Despite the importance of an adaptive plan for implementing adaptive pathways, this study will not develop the adaptive plan itself due to time constraints and the complexity of the ageing bridges case. Instead, the focus is on assessing Rijkswaterstaat's organisational readiness to implement the adaptive plan for adaptive pathways implementation. This will help to determine to what extent the adaptive pathways can be implemented in the case of ageing bridges managed by Rijkswaterstaat. Document analysis and interviews with the consultant (C.1) and program manager (C.2) from Rijkswaterstaat were conducted to explore the process of signal monitoring and detection that triggers the need for further measures in ageing infrastructure.

Signals

Signals differ from Adaptation Tipping Points (ATPs), which are more directly associated with the failure to meet predefined objectives. Signals may arise not only from observed impacts but also from driving forces, such as environmental trends, human-induced system pressures, technological advancements, or shifts in societal values and perspectives (Haasnoot et al., 2019). Signals serve as early warnings that adaptation may be needed, while adaptation tipping points mark the threshold beyond which existing strategies no longer meet performance objectives and must be replaced.

Figure 6.3 illustrates the process, from the detection of early signals to the execution of corresponding actions. A detected signal must reach a defined threshold to trigger a decision for further intervention. Once this threshold is met, a specific action is selected and subsequently implemented. The time between each milestone is referred to as lead time. The monitoring system helps to manage the lead time of the overall process.

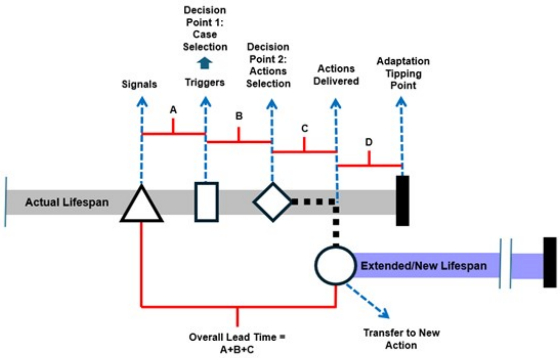

Figure 6.3: Signal Detection to Action Delivery (Own Figure)

In the context of ageing bridges renewal and renovation, the signals can be classified based on the life cycle indicators, which are cost, risk, and performance. The development of those indicators can be the trigger for the pathways or new actions. In the Rijkswaterstaat, the signals can be identified as follows:

- **Cost**

  Cost is one of the key triggers for deciding whether to maintain, renovate, or renew infrastructure. To assess this, Rijkswaterstaat uses the Economic End of Life Indicator (EELI) to identify potential candidates for renewal (Bakker et al., 2025). EELI evaluates the economic advantage of preserving components versus renewing the entire object by calculating a cost ratio between two preservation scenarios. When the EELI exceeds 1, renewal is considered more cost-effective, serving as the threshold for initiating renewal measures.

  Currently, the practical application of EELI within Rijkswaterstaat remains experimental, and its outcomes are not yet reliable enough to support final decision-making (Bakker et al., 2025). However, as many infrastructure are approaching their end of life, the EELI is expected to play an increasingly important role in future decision-making processes.

- **Risk**

  The risk of failure of the ageing bridges becomes the trigger that raises the urgency for further measures. One of the ways to identify the risk of failure on the bridge is by monitoring the deformation of the bridges, as noted by the consultant from Rijkswaterstaat (C.1). Every year, the measurement of the deformation is conducted to see if there are any changes in the construction. The findings are then categorised into three levels: elevated risk, normal risk, and low risk. The consultant also mentioned certain limits or thresholds by the Rijkswaterstaat to consider the significance of the deformation.

  > *"We set limits for ourselves on what is a significant deformation and what is more than just noise in the measurements. I would say the ongoing deformation. So we see a trend that doesn't slow down, that keeps on going or actually accelerates. Those are signals that need further investigation, maybe measures." (C.1)*

  Rijkswaterstaat also conducts upfront risk analyses to identify potential risks associated with each asset, as noted by the program manager from Rijkswaterstaat (C.2). The risk profile serves as a basis for planning the necessary measures and includes the timeframe in which those measures should be realised.

> *"We basically just come with a risk profile that we state, and then we apply a measure, which might be replacing or repairing something. Then we say this measure costs this amount, and you should deal with it within a certain amount of time. So, we give a time frame for that as well. Ideally, you should perform it between three and five years or between now and two years, for example." (C.2)*

The risk is associated with safety hazard performance, including the safety of network users, local residents, third-party personnel, and Rijkswaterstaat employees (Rijkswaterstaat, 2023c). This aspect is assessed against a performance standard allowing a maximum deviation of 3% as the threshold. Expert judgment is also used to evaluate whether the desired safety level is met. When needed, additional inspections or management measures are carried out.

- **Performance**

  The performance of the bridges can be determined by several criteria such as functionality, environment, safety, serviceability, economic and other related aspects. The performance of these indicators can become the trigger for further measures. However, assessing overall performance is challenging due to the number of criteria involved. To address this, Rijkswaterstaat, in collaboration with several master's students, has conducted several studies to develop the concepts of integrated performance indicators, for example, through Performance Age (Xie, 2017; González, 2018; Mooren, 2022). The concept aims to identify the functional state of assets based on their performance.

  The initial concept of Performance Age estimates an asset's residual life based on the assumption of an 80-year maximum technical lifespan (Xie, 2017). In a later study, this concept was refined, reframing residual life as remaining functional life, which accounts for non-linear ageing patterns (González, 2018). Both versions aim to indicate the appropriate timing for renewal based on performance.

  In addition, a different approach was conducted to compare the development of the different functional performance indicators of the bridge using a simulation model (Mooren, 2022). The model is designed to visualise critical infrastructure and simulate the development of performance indicators under different traffic scenarios. It provides asset managers with a clear overview of when each bridge approaches a critical threshold, thereby signalling the need for timely interventions or further measures.

Monitoring System

The monitoring system enables the timely implementation of actions before an adaptation tipping point is reached. Rijkswaterstaat already develops and implements monitoring systems to monitor the development of lifecycle indicators of its assets.

- **Cost Monitoring**

  To monitor life cycle costs, the EELI is visualised on a map highlighting areas where structures within certain networks are recommended for renewal based on cost considerations (Bakker et al., 2025). EELI values are colour-coded to easily distinguish assets, helping identify networks approaching the threshold value of 1, which indicates full renewal may be more cost-effective than continued maintenance. However, to be operationally reliable, the practical use of EELI still requires further development. Current limitations to implementing EELI as a cost monitoring system include insufficient data quality, incomplete preservation plans, and renewal forecasts that are not regularly updated, as the source relies on its own dataset.

Figure 6.4: EELI Map for Assets in the Rijkswaterstaat Network Based on Experimental Data (Bakker et al., 2025)

- **Risk Monitoring**

  Rijkswaterstaat carries out proactive measures to monitor the risks associated with its assets, as highlighted by the consultant (C.1) and the program manager (C.2). These measures include inspections every six years and routine annual monitoring. Additionally, predictive maintenance is employed as a proactive measure to predict beforehand how long certain elements will last.

  > *"For example, we know painting will last for 10 or 15 years. So once we come there every six years, then we see and look at when it was last painted and when it should be redone again. If it's 15 years already, and we think the paint job is very good still, then we postpone it." (C.2)*

  Besides proactive monitoring, both noted that when there is something not right with the object, the reactive measures can be conducted. This often leads to more frequent and targeted monitoring of the affected object.

  > *"Proactive monitoring is conducted to see if things are moving or things are moving too fast or not as we designed, while reactive monitoring is when inspection programs see signs of deformation for construction that we never measured before. Then we can start measuring to see if things are still moving or have stopped moving. So I would say the monitoring by Rijkswaterstaat is mostly proactive, but also partly reactive." (C.1)*

  Rijkswaterstaat's current monitoring measures face several challenges. According to the program manager (C.2), these include the lack of information beforehand and limited time and access to inspect all aspects and sides of the object. The consultant (C.1) also highlighted a shortage of monitoring personnel and traffic disruptions caused by inspections, underscoring the need for improved techniques in the future.

  > *"We see there are not enough people to do all these measurements. It takes time. It causes hindrance on the roads to do measurements because we have to close some lanes or the tunnel for measurements. So I hope there will be new techniques in the future that can make measurements even easier, quicker, safer." (C.1)*

- **Performance Monitoring**

  Each year, Rijkswaterstaat evaluates the performance of its infrastructure assets, and the results are compiled in the annual report The State of Infrastructure Rijkswaterstaat (Rijkswaterstaat, 2023c). These assessments are carried out by experts and are based on key performance criteria, including safety, lifespan, reliability, availability, and technical condition. Assets are rated as 'moderate,' 'average,' or 'good' for each criterion. The findings of this report serve as a foundation for determining necessary follow-up measures across the asset network.

Proactive performance monitoring in the Rijkswaterstaat can be conducted by utilising the concept of Performance Age. This approach involves regularly assessing the performance of bridges to estimate their remaining useful life, thereby enabling early identification of assets with performance deterioration (Xie, 2017; González, 2018).

While Performance Age shows an integrated asset performance criterion, individual performance criteria can be monitored using the simulation model developed by Mooren (2022). This model, built upon the Rijkswaterstaat DISK database and linked to the national road network, visualises the values of specific performance indicators geographically. It allows asset managers to monitor and compare the development of performance over time across different scenarios. This can help the asset manager to prepare ahead the necessary measures. However, caution is required when using these performance indicators. The assigned values can be subjective and often depend on intensive, high-quality data inputs to ensure their reliability and validity.

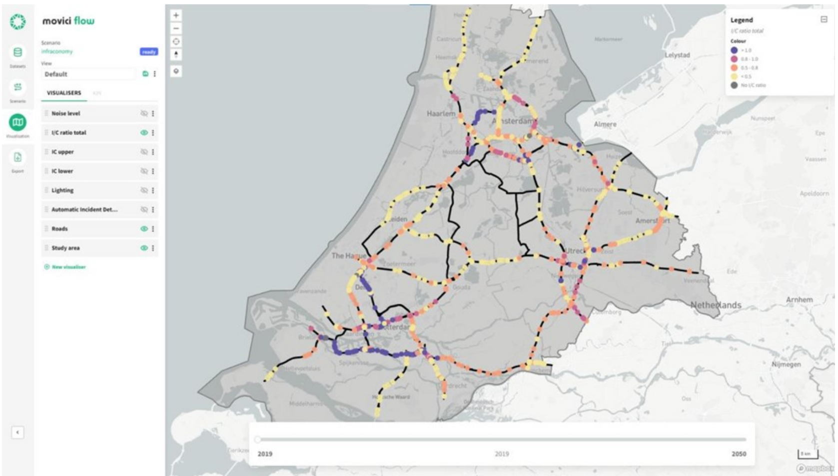

Figure 6.5: Map of Simulation on a Selected Performance Indicator (Mooren, 2022)

Contingency and Preparatory Actions

The adaptive plan needs to be incorporated with preparatory actions and contingency actions. Preparatory actions help to enable the implementation of future options, while contingency actions are only implemented when the condition demands it or the specific trigger occurs (Haasnoot et al., 2013).

- **Preparatory Actions**

  Preparatory actions are proactive measures taken in advance to enhance readiness and facilitate the implementation of future actions when needed (Haasnoot et al., 2013). These actions enable adaptive responses by reducing uncertainty and building capacity before critical problems arise. In the context of infrastructure projects, preparatory actions are particularly important for addressing long lead times and high investment costs, ensuring that timely interventions remain feasible when conditions change.

  In the context of renewing and renovating ageing bridges, preparatory actions may include the adoption of industrialised or standardised construction methods to reduce lead times and improve the speed of action delivery. To address investment-related uncertainties, allocating flexible budget reserves that accommodate a range of possible future options can be effective. Additionally, enhancing the organisation's capacity for rapid response is essential. This can be supported through more flexible planning processes or adaptable contract arrangements that explicitly account for future uncertainties.

  Rijkswaterstaat has already undertaken several preparatory actions that contribute to managing uncertainty, even if they are not explicitly intended to support an adaptive plan. For example, Rijkswaterstaat is developing innovations in industrialised and standardised construction methods to enhance productivity and reduce lead times (Rijkswaterstaat, 2023a). Additionally, Rijkswaterstaat recognises the importance of budget reserve by incorporating cost surcharges into project budgets, allowing for adjustments in response to future changes and unforeseen developments (Rijkswaterstaat, 2022b).

- **Contingency Actions**

  Contingency actions are reactive measures designed to respond quickly and effectively when conditions worsen or unexpected changes occur. These actions are triggered once a defined threshold or tipping point is reached, allowing the response to proceed without the need to redesign the entire strategy under time pressure. Contingency actions typically follow 'if-then' decision rules, where predefined responses are linked to specific conditions (Haasnoot et al., 2013). For example, 'if' a certain indicator exceeds a critical threshold, 'then' a particular action is implemented.

  In the context of renewing and renovating ageing bridges, contingency actions are essential when signs of structural deterioration. For instance, in response to potential structural failure, such as lane closures or traffic restrictions measures should be implemented to mitigate risk (Rijkswaterstaat, 2023c; Bakker et al., 2025). These contingency actions help manage the risk and preserve the performance of the asset until more permanent solutions are in place.

Implementation of Adaptive Plan in Rijkswaterstaat

Rijkswaterstaat has already acknowledged the importance of detecting signals through life cycle indicators such as cost, risk, and performance. The organisation is equipped with routine monitoring systems that help identify and respond to the development of these indicators. It is also experimenting with the development of objective ageing indicators and working to integrate monitoring systems across the asset network. While some indicators and tools are still under development, these efforts show that Rijkswaterstaat has the basic capacity to implement signal detection as part of an adaptive plan.

In addition, Rijkswaterstaat recognises the role of preparatory actions in dealing with future uncertainties and contingency actions for responding to critical situations. This suggests that the organisation has the potential to apply adaptive planning in the renewal and renovation of ageing bridges. As more knowledge becomes available, monitoring systems can be improved, and preparatory and contingency actions can be planned more thoroughly. Together, these efforts are expected to strengthen organisational readiness for adaptive implementation.

Figure 6.6 illustrates the implementation of an adaptive plan for the renewal and renovation of ageing bridges by Rijkswaterstaat. The adaptive plan is used to accommodate the use of the adaptation pathways map. It supports signal detection that triggers the initial action or a shift to new actions in the pathway. The flowchart also shows the role of contingency actions in keeping the pathway on track and preparatory actions to accommodate changes in the pathways.

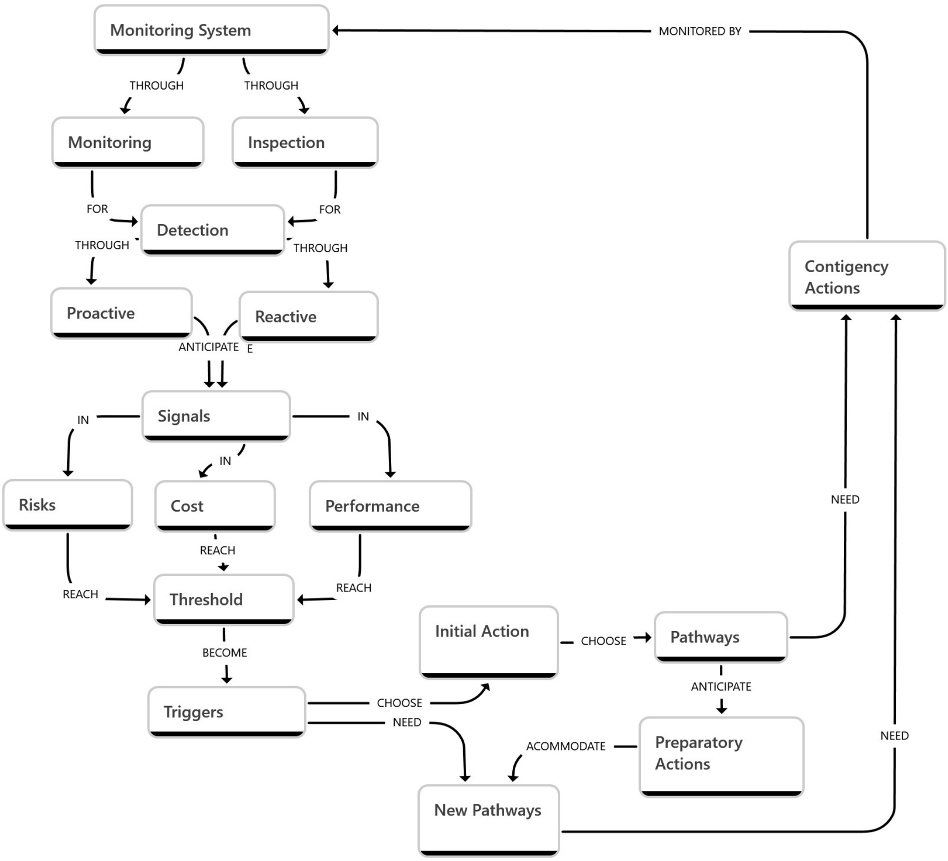

Figure 6.6: Adaptive Plan Implementation Flowchart (Own Figure)

6.3. Process Design for Adaptive Pathways Implementation

6.3.1. Adaptive Pathways to Accommodate Adaptive Approaches

Adaptive pathways offer a way to manage uncertainty by outlining possible sequences or pathways of actions for the renewal and renovation of ageing bridges over time. These pathways provide a structured range of decisions that help anticipate budget needs and account for lead times. Figure 6.7 shows the possible sequences of actions derived from the adaptation pathways map in the figure 6.2.

No	Pathways
1	A → A' → E
2	A → B → D → E
3	A → B → D → A' → E
4	A → B → D → A' → B' → E
5	A → B → D → A' → C' → E
6	A → B → D → B' → E
7	A → B → D → C' → E
8	A → B → E
9	A → C → D → E
10	A → C → D → A' → E
11	A → C → D → A' → B' → E
12	A → C → D → A' → C' → E
13	A → C → D → B' → E
14	A → C → D → C' → E
15	A → C → E
16	A → D → A' → B' → E
17	A → D → A' → C' → E
18	A → D → A' → E
19	A → D → B' → E
20	A → D → C' → E
21	A → D → D' → E
22	A → D → E
23	A → E

No	Pathways
24	B → D → A' → C' → E
25	B → D → B' → E
26	B → D → C' → E
27	B → D → D' → E
28	B → D → E
29	B → E
30	C → D → A' → C' → E
31	C → D → B' → E
32	C → D → C' → E
33	C → D → D' → E
34	C → D → E
35	C → E
36	D → A' → C' → E
37	D → B' → E
38	D → C' → E
39	D → D' → E
40	D → E
41	E

A: Preserve
B: Downgrade
C: Mitigate
D: Renovate
E: Renewal

Figure 6.7: Possible Sequenses of Actions (Own Figure)

When many pathways are available, they can be evaluated based on their impacts on regret potential, timing, switching cost, and path dependency. This evaluation helps narrow down the options to only those pathways that have acceptable and preferred outcomes based on the selected criteria. With fewer, more targeted pathways remaining, planning for budget reserves becomes more efficient and helps reduce the lead time of the overall process. This process is expected to support the objective of adaptive approaches by addressing key indicators such as flexibility, available options, and budget reserves. Figure 6.8 illustrates the implementation of adaptive approaches using adaptive pathways.

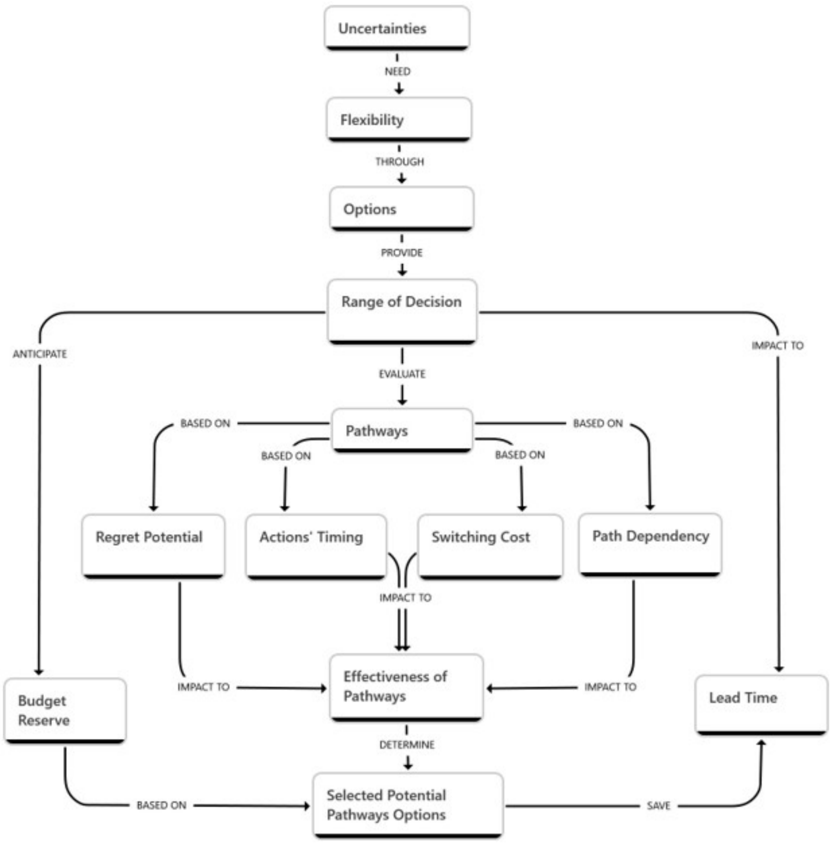

Figure 6.8: Adaptive Approaches through Adaptive Pathways (Own Figure)

6.3.2. Adaptive Pathways for Capacity-driven Planning

Adaptive pathways can be used to help plan the sequence of actions across multiple objects by considering both the demand for intervention and the available capacity to meet that demand. This involves prioritising objects based on urgency, which in turn shapes the sequence of project actions. Figure 6.9 illustrates how adaptive pathways can be applied for object prioritisation. The prioritisation is based on the required measures for each object and the time horizon within which these measures need to be implemented. The execution of these demands is then adjusted according to available capacity and the urgency of actions. Adaptive pathways assist in arranging the sequences based on the following principles:

- **Prioritise** necessary actions for bridges in urgent condition.
- **Delay** actions for bridges in non-urgent conditions when capacity is constrained.
- **Substitute** necessary actions with alternative measures until sufficient capacity becomes available.
- **Prepare** for future large-scale actions during the delay period by using the time to build capacity and readiness.

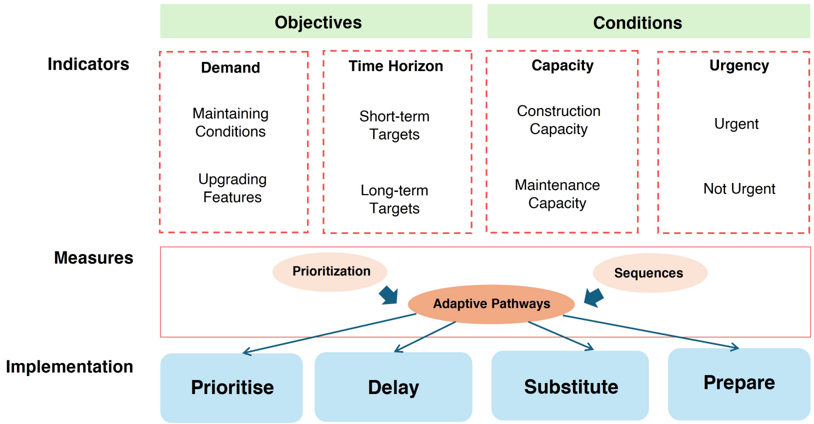

Figure 6.9: Adaptive Pathways for Capacity-driven Planning (Own Figure)

6.3.3. Adaptive Pathways Implementation in Portfolio Approach

In the context of ageing bridge renewal and renovation, the portfolio approach can be applied by grouping objects with similar conditions or shared objectives. This approach allows multiple projects to pool their capacity to better manage uncertainty. To address uncertainty at the project level, each object is typically assigned a budget reserve. Under the portfolio approach, these individual reserves can be combined to create a collective budget reserve for the entire portfolio. Figure 6.10 illustrates the concept of applying the portfolio approach across multiple objects.

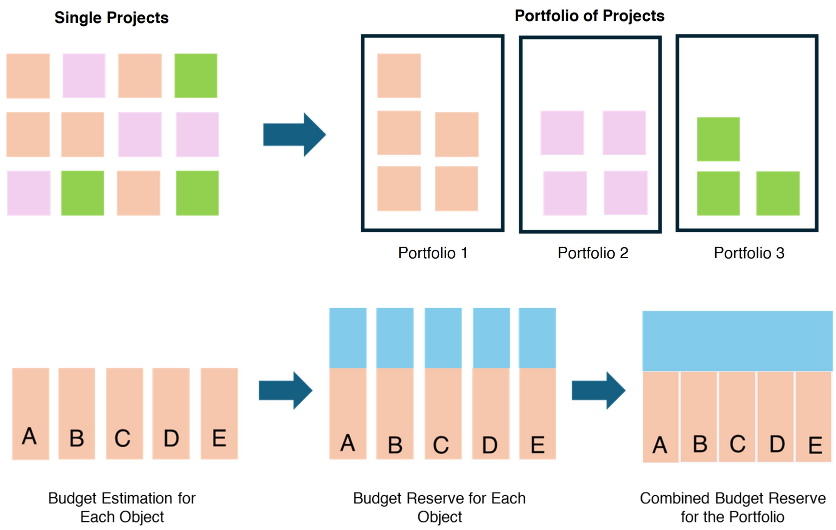

Figure 6.10: Porfolio Approach Illustration (Own Figure)

The objects within the portfolio are implemented in a sequence that allows each project to learn from the previous one. Adaptive pathways can be used to plan the distribution of actions and the sequencing of projects in a way that facilitates learning across objects. This learning process is expected to generate new insights throughout implementation, enabling improved evaluation of available options for subsequent objects in the pathway. In addition, the portfolio's overall capacity can be strengthened over time as knowledge accumulates. Figure 6.11 illustrates how the portfolio approach can support programmed learning through the use of adaptive pathways.

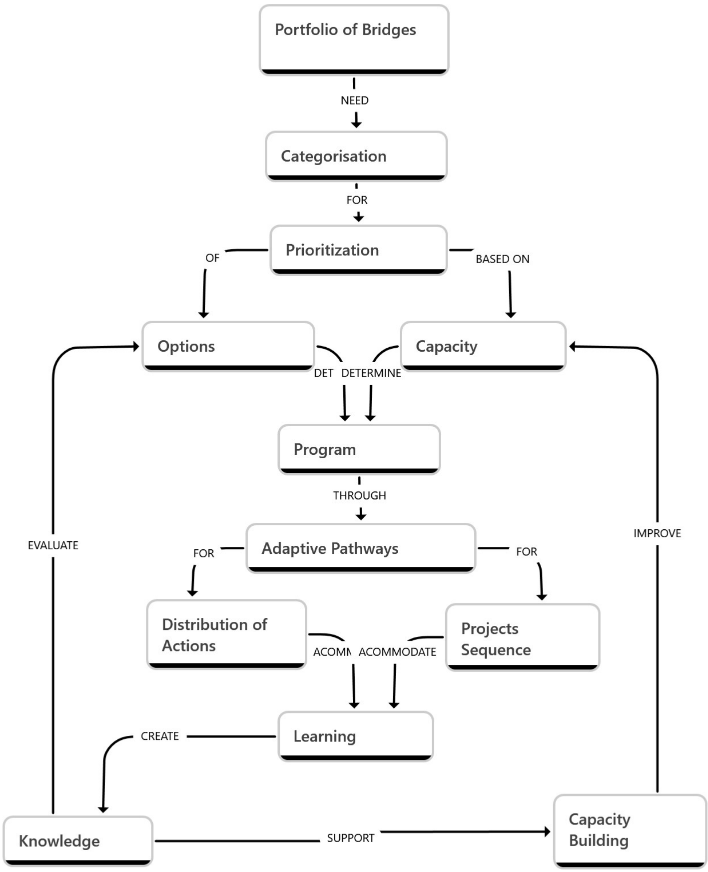

Figure 6.11: Adaptive Pathways in Portfolio Approach (Own Figure)

The portfolio approach, combined with a learning process structured through adaptive pathways, can support the renewal and renovation program in managing the impacts of uncertainty associated with ageing bridges. Figure 6.12 illustrates how uncertainty affects a portfolio of objects and how learning can be used to anticipate and mitigate its consequences. High uncertainty is expected during the execution of the first object in the sequence, potentially leading to cost overruns due to unforeseen conditions. As knowledge accumulates from earlier projects, cost estimations for subsequent objects become more comprehensive, reflecting a broader understanding of relevant factors. Although estimates may increase, cost overruns are expected to decrease over time as planning becomes more informed. The combined budget reserve within the portfolio helps to compensate for higher costs in early projects with better efficiency and cost control in later ones.

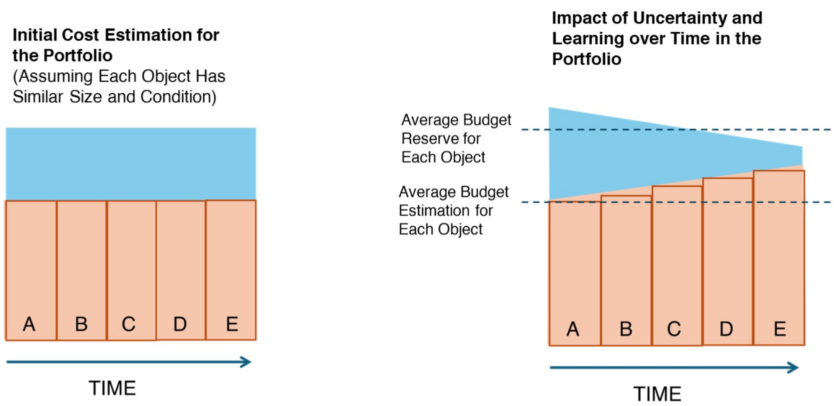

Figure 6.12: Impact of Uncertainty and Learning in the Portfolio (Own Figure)

The portfolio approach also helps anticipate potential budget deficits when uncertainty turns out to be greater than expected. Figure 6.13 illustrates how sequencing within the portfolio approach creates lead time to accommodate future adjustments. This sequencing allows time to prepare options for addressing possible budget deficits without halting overall progress. It enables the portfolio to plan for additional funding in later projects or, if necessary, to omit certain later objects in order to compensate for cost overruns from earlier ones.

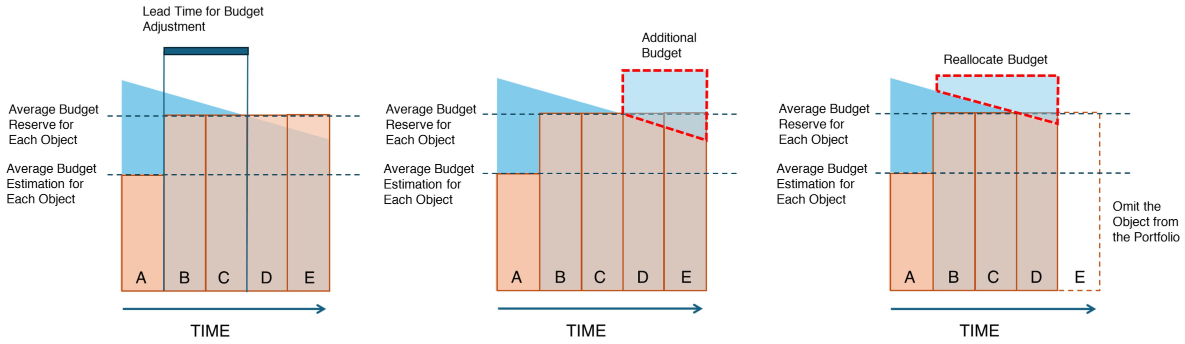

Figure 6.13: Lead Time for Future Adjustment (Own Figure)

6.4. Closing Remarks: Design Development

The design development step is carried out to explore the potential of incorporating adaptive pathways into the planning process for the renewal and renovation of ageing bridges. The Dynamic Adaptive Policy Pathways (DAPP) approach is applied to offer a stepwise method for designing this process. This approach is well aligned with the context of ageing bridges, which are characterised by long lifespans, gradual changes over time, and exposure to significant uncertainties.

Out of the seven steps in the DAPP approach, this study includes only the first five steps, as the remaining steps are typically carried out during the operational phase and fall outside the scope of this research.

- **Decision Context:** The design process begins by establishing the decision context, which involves identifying and describing the specific challenges encountered in the renewal and renovation of ageing bridges.
- **Adaptation Tipping Point (ATP):** In the context of ageing bridges, the ATP is associated with various end-of-life indicators, such as performance, risk, and cost indicators, which makes identifying the ATP more complex and multifaceted.
- **Actions:** The actions to respond to the ATP are identified, including preservation, usage restriction through mitigating and downgrading, and upgrading through renovation and renewal measures. In addition to the aim of extending the asset's lifespan, evaluating the effectiveness of these actions requires assessing their impact on key life cycle indicators such as cost, performance, and risk.
- **Adaptation Pathways Map:** An adaptation pathways map is developed to outline and visualise the possible and logical sequences of actions over the asset's life cycle. Identifying these pathways in advance helps to anticipate the effects of path dependency, switching costs, timing, and regret potential over the life cycle. This enables decision-makers to evaluate which pathways are likely to have acceptable impacts and align with specific objectives or scenarios.
- **Adaptive Plan:** An adaptive plan plays a key role in enabling the ability to switch between pathways when different measures become necessary. Through signal detection and monitoring, the adaptive plan helps ensure that appropriate measures are implemented before the ATP is reached. The contingency and preparatory actions in the adaptive plan enable a quick response and accommodate changes in the pathways. In the context of ageing bridges, implementing such a plan requires organisational readiness, including effective monitoring systems and the capacity to execute preparatory and contingency actions, which not all organisations are structured with.

> However, Rijkswaterstaat has the potential to adopt adaptive planning in supporting the implementation of adaptive pathways for the renewal and renovation of ageing bridges, even though current efforts are still somewhat fragmented.

The output of the process design remains limited to a conceptual framework that outlines how adaptive pathways can be applied within the context of Rijkswaterstaat's Renewal and Renovation (R&R) program. This design accommodates the objective of solutions developed in the previous chapter. It offers a method for managing uncertainty by mapping possible sequences of actions through the adaptation pathways map and evaluating their impacts in advance to support proactive budget planning.

In relation to the objective of capacity-driven planning, the design introduces a prioritisation guide that helps arrange action sequences. This includes reframing the delay of non-urgent bridge interventions by substituting with lighter measures until sufficient capacity becomes available, and using it to build capacity for larger-scale actions.

Additionally, the design incorporates a portfolio approach that enables shared budget reserves and fosters cross-project learning. These elements are expected to reduce the impacts of uncertainty and help anticipate potential budget deficits when conditions deviate significantly from those anticipated.

The process design developed in this chapter will be demonstrated to examine the applicability of adaptive pathways in planning the sequence of measures for ageing bridges within a portfolio constrained by limited capacity. The demonstration will then be evaluated against the objective of solutions established previous chapter to assess the extent to which the design achieves its intended goals.

7 Demonstration

This chapter demonstrates the process design developed in the previous chapter to explore its implementation in practice. The first section introduces the demonstration setup and provides a description of the fictional case used. The second section presents the implementation of the adaptive pathways, along with an assessment of the pathways based on the case scenario. The final section discusses the limitations of the demonstration and identifies potential areas for refinement in future applications.

7.1. Demonstration Overviews

7.1.1. Demonstration Description

To provide a clearer understanding of how adaptive pathways can be applied, a demonstration is conducted. The objective is to illustrate how adaptive pathways can be used to program the prioritisation and sequencing of ageing bridges within a portfolio. Due to time constraints and the complexity of real-life cases, a fictional case is used. Although it does not reflect the full complexity of actual projects, the fictional case is intended to represent key processes typically encountered in implementing adaptive pathways for the renewal and renovation of ageing bridges.

7.1.2. Case Description

The fictional case assumes a portfolio of five bridges, each facing similar technical ageing issues. These bridges are grouped within the same portfolio, with the aim of resolving the identified problems within a ten-year portfolio timeframe. Each bridge is assumed to have distinct objectives and technical conditions. The technical conditions include fictional adaptation tipping points (ATPs), along with assumptions about when these ATPs may be reached.

In addition to the condition of the bridges, the fictional case also incorporates a hypothetical scenario regarding organisational capacity and lead time for project execution. For the purpose of this demonstration, the quantification of capacity is entirely hypothetical and may not reflect actual conditions. In real-world applications, the assumption for the capacity can be derived from expert prediction or by looking at the historical condition. For this demonstration, the assumed capacities and durations are defined as follows:

- **Construction Capacity** refers to the number of construction activities the organisation can carry out simultaneously. It may also reflect the extent of construction-related disruptions the network can accommodate.
- **Maintenance Capacity** refers to the number of maintenance activities the organisation can manage at a given time.
- **Lead Time for Portfolio Preparation** refers to the assumed duration required to prepare the overall portfolio for execution, including budgeting, tendering, design processes, etc.

- **Lead Time to Construction Project Preparation** refers to the estimated time needed to prepare for the construction of an individual project within the portfolio, including the adjustment of design, cost, schedule, etc.
- **Construction Time** refers to the assumed duration required to complete the construction of a single object.

Table 7.1 presents the initial capacity assumptions used in this demonstration. In the scenario, these capacities are expected to change as new knowledge is gained during project execution, reflecting the uncertainty that may influence adjustments in the portfolio plan.

Activity	Capacity
Construction Capacity	1 per year
Maintenance Capacity	2 per year
	Duration
Portfolio Preparation	1 year
Construction Project Preparation	1 year
Construction Activity	2 years

Table 7.1: Assumptions on Capacity and Duration

In the demonstration, the activities within the portfolio are represented by different colours or patterns, as shown in Figure 7.1. These activities include preparation, maintenance, usage restriction, and construction. Preparation covers both portfolio-level and individual project readiness. Maintenance refers to preservation efforts, while usage restriction includes downgrading and mitigating measures. Construction activities encompass both renovation and renewal interventions.

Figure 7.1: Codes Description for Activities (Own Figure)

Table 7.2 shows the fictional details of each bridge. The table includes questions to guide the decision process towards the necessary measure and to figure out the possible time frame for the measure. The answers are only hypothetical and may not totally reflect the real condition. In the real application, the questions can be answered by making an initial assumption by involving expert judgment or making a prediction based on the available knowledge. However, there are still possibilities to adjust or change the answer over time as new knowledge is gained once the project starts. The topics of questions are listed as follows:

- **Technical Objective:** Explores the desired technical condition of the bridge in relation to risks posed by the current state.
- **Functional Objective:** Explores the expected performance of the bridge in meeting long-term functional demands.
- **ATP of the Existing Condition:** Estimates how long the bridge's current condition can continue to meet its objectives before reaching an adaptation tipping point.
- **Preservation Measures:** Assesses the feasibility of implementing preservation measures to address current issues and extend service life.
- **Economical Comparison:** Evaluates whether maintenance remains economically viable compared to renovation or renewal, possibly based on EELI calculations.

- **ATP of the Preservation Measures:** Estimates how long preservation efforts can sustain the bridge's ability to meet its objectives.
- **Usage Restriction Measures:** Examines the potential for implementing restrictions to maintain function while reducing risk.
- **ATP of the Usage Restriction Measures:** Estimates how long usage restrictions can effectively support the bridge's objectives.
- **Renovation Measures:** Assesses the feasibility of renovation, considering design compatibility, condition severity, and technical requirements.
- **Knowledge Availability to Conduct A Renovation:** Evaluates whether sufficient knowledge of the bridge's technical state and history exists to support renovation.
- **ATP of the Renovation Measures:** Estimates the duration that renovation measures will enable the bridge to serve its intended objectives.
- **Necessary Measures:** Identifies the most appropriate long-term intervention to ensure the bridge meets its expected objectives.
- **Possibility to Delay Long-Term Measures:** Considers whether lighter, temporary measures could delay the need for major interventions.
- **Options to Delay Long-Term Measures:** Lists the available short-term measures that can temporarily substitute long-term solutions.
- **Overall ATP of the Temporary Measures:** Accumulates the total time temporary measures can sustain the bridge before a major intervention becomes necessary.

	Bridge 1	Bridge 2	Bridge 3	Bridge 4	Bridge 5
Technical Objective?	Keep the bridge safe	Upgrading Load Capacity	Maintaining Load Capacity	Upgrading Load Capacity	Maintaining Load Capacity
Functional Objective?	Availability	Upgrading functional performance	Maintaining functional performance	Upgrading functional performance	Maintaining functional performance
The estimated tipping point of the existing condition?	2 years	2 years	5 years	5 years	8 years
Can it be solved by increasing the maintenance regime?	Yes	No	No	Yes	Yes
Is it more economical to maintain?	Yes			Yes	No
The estimated tipping point of increasing maintenance measure?	5 years			5 years	
Can be solved by usage restriction?	Yes		Yes	No	Yes
Does the usage restriction have major negative impacts?	No		No		Yes
The estimated tipping point of usage restriction measure?	3 years		2 years		
Can be solved by renovation?	Yes	No	Yes	Yes	No
The estimated tipping point of renovation measure?			30 years	20 years	
Necessary Action?	Renewal	Renewal	Renovation or Renewal	Renovation or Renewal	Renewal
Options to delay action?	Increasing maintenance regime (Preservation) or usage restriction (Mitigating or Downgrading)		Usage restriction (Mitigating or Downgrading)	Increasing maintenance regime (Preservation)	Increasing maintenance regime (Preservation)
Accumulation of tipping points of maintenance measures?	10 years	2 years	7 years	10 years	8 years

Table 7.2: State of the Bridges in the Fictional Case

7.2. Demonstration

7.2.1. Adaptive Pathways in Portfolio Approach Implementation

In this demonstration, adaptive pathways are used to plan the sequencing of bridges within the portfolio. The sequence is determined based on the urgency of required actions, guided by the defined objectives, the availability of alternative measures, and the time frame for achieving those objectives.

Figure 7.2 illustrates the initial sequence planning based on the urgency and the available delay options for each bridge, as derived from the information in Table 7.2. In developing the sequence, the main necessary action for each bridge is identified first. Bridges without feasible options to delay major or high-cost actions are prioritised earlier in the sequence. Conversely, bridges with viable alternatives and longer potential delay periods for major interventions are scheduled later. The rationale for the sequencing of each bridge is as follows:

- **Bridge 1** has the possibility to delay its renewal through preservation and downgrading measures. Without considering the sequencing in the adaptation pathways map (Figure 6.2), Bridge 1 has two initial options: to apply either preservation or downgrading first.
- **Bridge 2** has no available options to delay its renewal, making it the most urgent. Therefore, it is placed first in the sequence.
- **Bridge 3** is planned for renovation starting in year 6, based on the total time available to delay the major intervention through its current tipping point and the downgrading measure.
- **Bridge 4** can delay its renovation due to a long tipping point in the existing condition and the availability of preservation measures. This allows it to be scheduled later in the portfolio sequence.
- **Bridge 5** does not have alternative measures to delay its intervention, but the long adaptation tipping point of its existing condition makes it possible to schedule construction at a later stage.

The sequencing of actions for the bridges is analysed against the organisation's capacity to carry out maintenance activities. Referring to the sequence shown in Figure 7.2, the number of maintenance activities remains within the maximum maintenance capacity defined in Table 7.1. However, the current arrangement results in construction activities in years 7, 9, and 10 exceeding the organisation's construction capacity. In this case, the sequence must be revised to better align with available capacity.

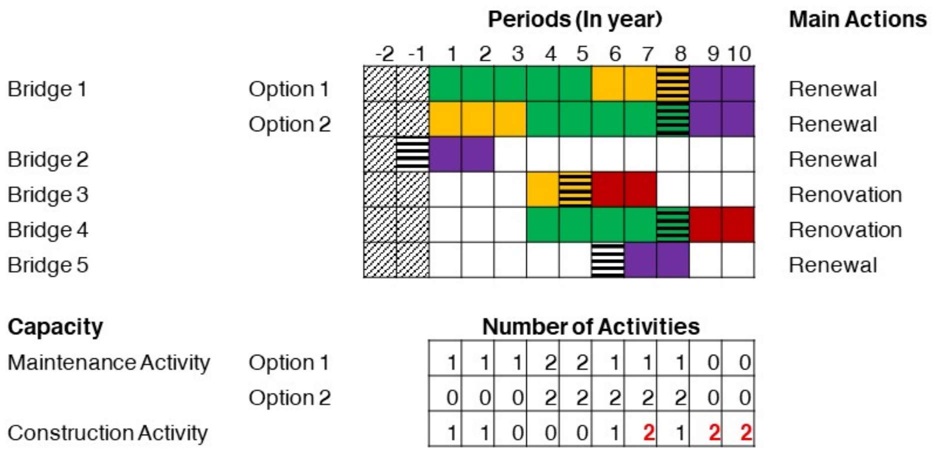

Figure 7.2: Portfolio Sequence Plan (Own Figure)

In addition to capacity considerations, the sequences can also be analysed using the adaptation pathways map to identify feasible options. Figure 7.3 illustrates the pathways for the bridges within the portfolio. This mapping helps identify sequences that are not feasible within the available options, such as Option 2 for Bridge 1, thereby supporting the selection of a viable range of options in the sequence arrangement. By aligning the sequences with the pathways, the available options for each bridge become clearer, enabling the identification of alternative sequences. This approach helps anticipate potential changes in planning due to future uncertainty

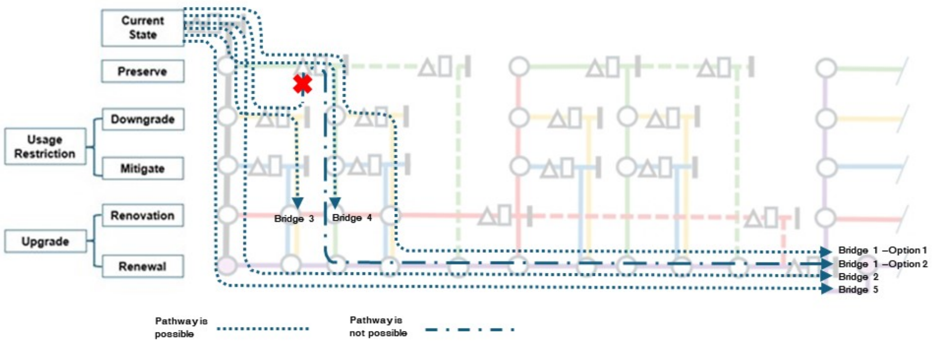

Figure 7.3: Sequences Arrangement in the Adaptation Pathways Map (Own Figure)

Based on the capacity analysis and pathways mapping, the initial sequence of the portfolio is revised. Figure 7.4 presents the updated plan, which accounts for both organisational capacity and the feasibility of the pathways. In this revised plan, Option 2 for Bridge 1 is omitted. The timing of several bridges is adjusted, for example, the renovations of Bridge 3 and Bridge 4 are scheduled earlier, and the renewal of Bridge 5 is also brought forward. These adjustments help optimise the distribution of actions in alignment with the organisation's available capacity.

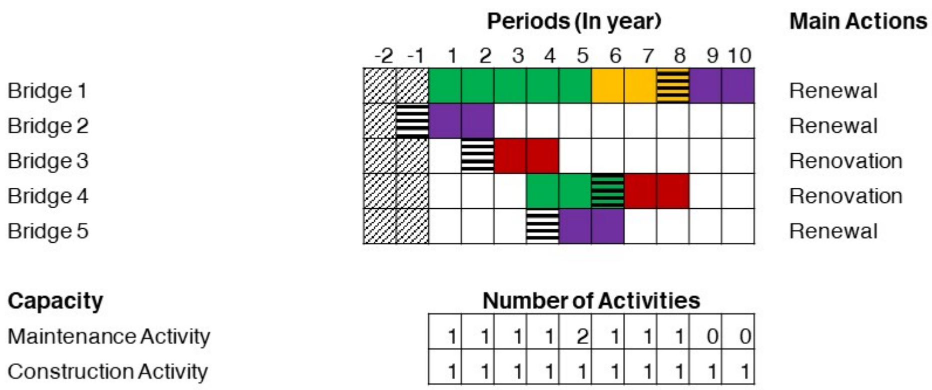

Figure 7.4: Optimised Sequences (Own Figure)

To illustrate the impact of uncertainty on the sequence plan, new fictional scenarios are introduced. In this scenario, two years after the construction of the first bridge begins or four years after the portfolio preparation, new conditions or assumptions emerge that require adjustments to the original plan. These new conditions are described as follows:

- The renewal of Bridge 2, which is the first construction activity in the portfolio, takes one year longer to complete than initially predicted due to unforeseen conditions encountered during construction.
- For Bridge 1, after four years of portfolio implementation, it is assumed that the preservation measure has failed to maintain the bridge's performance, making renewal necessary within the next four years.
- As new knowledge is gained during the execution of the portfolio, it is assumed that the renovation of bridges can now be completed in one year instead of the initially estimated two years.
- Once the renewal of Bridge 1 is completed, a mitigating measure, such as traffic rerouting, becomes feasible to be applied to Bridge 4 to delay its renovation. This measure is expected to reduce the preservation costs for Bridge 4.

Figure 7.5 shows the revised sequence arrangement in response to the new conditions. The renovation of Bridge 3 is delayed by one year due to the extended completion time of Bridge 2. As the urgency of Bridge 1 increases, its construction, which is originally planned as the last, must now be scheduled earlier. Consequently, the renovation of Bridge 4 is postponed further to accommodate the more urgent renewal of Bridge 5. To delay Bridge 4's renovation, a mitigating measure is implemented when it becomes feasible, as an alternative to ongoing preservation efforts.

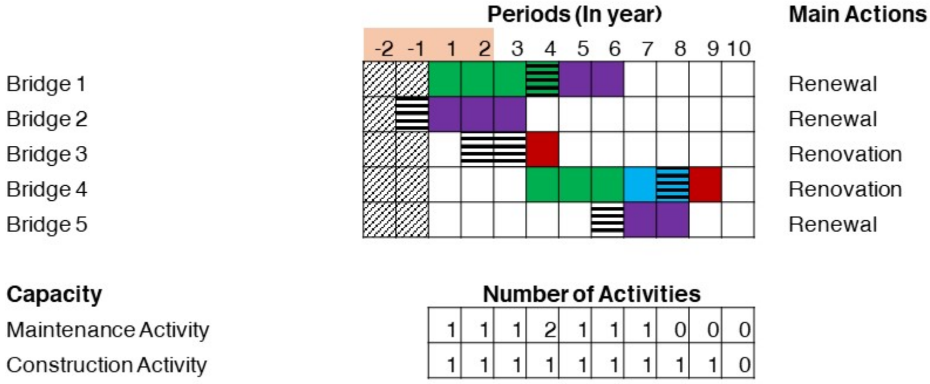

Figure 7.5: Sequences Arrangement for New Conditions Adjustment (Own Figure)

Figure 7.6 shows the changes in the pathways of Bridge 1 and Bridge 4 resulting from shifts in their conditions. Using the adaptation pathways map, available options can be anticipated in advance, allowing preparatory actions to be planned ahead to accommodate changes when uncertainty arises. By mapping and anticipating possible pathways early on, necessary adjustments can be made without interrupting progress or delaying implementation while preparations are made for those changes.

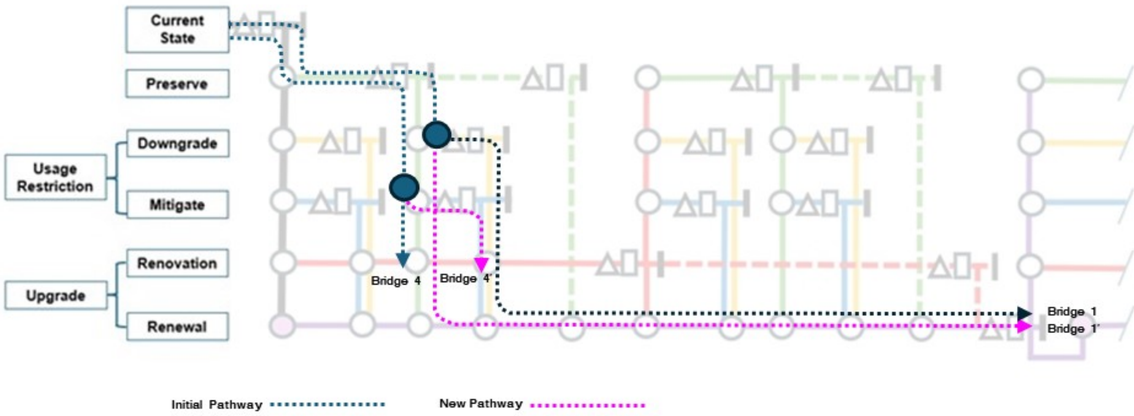

Figure 7.6: Pathways Adjustment towards Changing Conditions (Own Figure)

7.2.2. Adaptive Pathways Assessment

The demonstration includes an assessment of the available pathway options to support the selection of preferred pathways under specific conditions. Each pathway has distinct characteristics that may influence outcomes and can be anticipated during the initial planning stage. Pathways can be evaluated based on factors such as the length of the pathway, initial action, and type of action switch.

Length of Pathway

The length of a pathway can be defined by the number of actions sequenced within it. The more actions included, the longer the pathway. For example, in the optimised sequence shown in Figure 7.4, Bridge

1 has the longest pathway, consisting of the sequence Preservation–Downgrading–Renewal. Longer pathways offer greater potential in the following ways:

- A longer pathway can help defer major, irreversible costs, providing more time to plan, adjust, and build financial reserves for the main intervention. In the case of Bridge 1, preservation and downgrading measures temporarily delay the need for renewal.
- It allows for keeping options open and making adjustments as new knowledge emerges. For example, Bridge 1's delaying measures make it possible to omit the downgrading step and proceed directly to renewal if needed.
- Longer pathway helps reduce financial risk by avoiding premature investment in high-cost measures, thereby minimising the regret potential associated with unsuccessful or unnecessary interventions.
- It also offers an opportunity to prepare stakeholders and mitigate political or social resistance, as sudden large-scale interventions often face public pushback.

However, longer pathways also present certain risks. If the necessary action is delayed for too long, the bridge's performance may decline before the appropriate measure is implemented. A greater number of sequential actions also requires robust monitoring to detect the triggers for each next sequence. Additionally, the longer the pathway, the more complex it becomes to manage, particularly due to the potential need for technical or institutional adjustment when switching between actions.

Initial Action

The initial action in an adaptive pathway serves as the foundation for all subsequent steps, influencing the pathway's timing, path dependency, and regret potential. It determines whether the pathway can respond early enough to emerging risks or deterioration. If the initial action involves high costs, it may lead to early lock-in, limiting flexibility and creating path dependency. Moreover, if the initial action performs poorly under certain future conditions, it can result in significant regret. The initial action of a pathway can be assessed against the following aspects:

- **Purpose of the Action:** The purpose of the initial action needs to be clear, either to address urgent problems or to set up the conditions for better actions later. In the demonstration, high-cost measures are applied earlier to bridges with high urgency, such as Bridge 2. Other bridges that require more preparation due to their significant impacts can be planned later. In such cases, the initial action should also accommodate learning to support future decisions.
- **Flexibility:** The initial action should be selected with consideration for its flexibility under future conditions. For example, conducting renewal too early without anticipating future demand may result in the bridge becoming obsolete. Lighter initial actions, such as preservation or usage restrictions, can buy time to observe developments of the situation and revise the plan as needed.
- **Impact on Life Cycle Management Indicators:** The choice of initial action should consider cost, risk, and performance. In terms of cost, the action should be evaluated for affordability and how the cost is distributed, whether spread out or front-loaded. The action should also be assessed for its ability to address immediate safety or failure risks and meet short-term performance needs.

Action Switch

The type of action switches in the pathways impacts the switching cost or the difficulty of transitioning from one action to another. This switching cost needs to be considered when planning the sequence in adaptive pathways. Based on the type of action switch, several aspects need to be anticipated:

- **Switching to A Bigger Action:** This transition is illustrated at Bridge 1 in the new sequences arrangement in Figure 7.5, where the approach shifts from preservation to renewal. Moving to a larger-scale action requires evaluating technical feasibility, such as whether the current structure can accommodate the upgrade. Additionally, it is important to assess the availability of funding, institutional capacity to conduct the bigger measure, and the willingness of stakeholders to accept potential increases in cost and disruption.
- **Switching to A Lighter Action:** This switch is shown at Bridge 1 in the initial sequence in Figure 7.2, where the strategy shifts from preservation to downgrading, resulting in usage restriction for

the bridge. Switching to a lighter action can elevate safety risks due to reduced service levels. Therefore, evaluating how this performance decline affects the bridge's ability to meet current and future demands is essential. User acceptance and compliance with regulatory standards under the reduced service must also be considered. Additionally, the potential to scale back up to bigger actions in the future should be examined after implementing the downgrade.

7.3. Limitation of Demonstration

This demonstration presents several limitations in illustrating the implementation of adaptive pathways for the renewal and renovation of ageing bridges, which can be refined further in future studies, as outlined below:

- The use of a fictional case may not fully capture the real-world complexity of ageing bridge scenarios. Moreover, the assumptions made in the fictional context may oversimplify actual conditions.
- Due to time constraints, the demonstration includes only five bridges over a ten-year portfolio period. This relatively short timeframe limits the variety of possible sequences being shown in the demonstration. However, extending the timeframe would require including more bridges to create a meaningful sequence, which in turn would require additional time and effort to prepare the demonstration.
- To simplify, this demonstration only considers maintenance and construction capacities. Future studies could broaden this by incorporating additional capacity indicators such as manpower capacity for the preparation, traffic capacity during usage restriction, and total budget capacity for the entire portfolio.
- In future studies, a wider range of scenarios could be introduced to better illustrate uncertainty, for example, regulatory or demand changes that could delay or halt projects, adjustments to the portfolio's timeframe, or the addition of new bridges within the portfolio.

7.4. Closing Remarks: Demonstration

The demonstration aims to illustrate the application of adaptive pathways based on the process design from the previous chapter. A fictional portfolio of ageing bridges is used to represent key processes involved in implementing adaptive pathways for renewal and renovation, though it may not fully capture the complexity of real-world cases. The demonstration yields the following key remarks:

- The demonstration incorporates a hypothetical scenario regarding organisational capacity and project lead time, which creates the need for prioritisation. The prioritisation is based on each bridge's objectives, major required actions, available options to delay using lighter measures, and the possible duration to delay.
- In the demonstration, adaptive pathways analyse potential sequences by identifying those that are not feasible within the available options. Aligning the sequences with the pathways helps to map out the possible options for each bridge, supports the identification of alternative sequences, and enables anticipation of possible changes in the planning process.
- The demonstration illustrates the potential changes that may arise due to uncertainty. It shows how uncertainty can be addressed not only as a challenge to be managed but also as an opportunity to improve the sequencing of actions. When approached effectively, uncertainty has the potential to generate beneficial outcomes.
- The demonstration also highlights the importance of assessing adaptive pathway options to guide the arrangement of sequences within the portfolio. This assessment enables forward-looking planning by anticipating the potential impacts of selected sequences and identifying appropriate actions to mitigate those impacts effectively.

The remarks from the demonstration will be evaluated in the next step against the previously established objective of solutions. This evaluation aims to assess the extent to which the proposed process design meets those objectives.

8 Design Evaluation

This chapter investigates how well the process design aligns with the expected objectives and key indicators, based on the outcomes of the demonstration. The first section evaluates the process design's ability to accommodate adaptive approaches. The second section examines how the design supports capacity-driven planning. The final section assesses the extent to which the process design incorporates the portfolio approach.

8.1. Adaptive Approaches

The adaptive approach requires that the process design considers future uncertainties and allows adjustments when needed. This objective is evaluated using the following indicators:

- **Flexibility:** To meet this indicator, the process design must enable adjustments when future developments deviate from the initial plan. In the demonstration, the process design allows the portfolio to adjust the sequence arrangement as long as it is within the capacity of the portfolio. Adjustments to the action sequence for each bridge can be made, given that they remain consistent with the predefined paths or routes specified in the adaptation pathway map.
- **Options:** This indicator highlights the importance of having alternative courses of action when the initial plan becomes unfeasible. In the demonstration, the process design addresses this by utilising the adaptation pathway map, which enables early anticipation of different routes or pathway options.
- **Budget Reserve:** This indicator reflects the need to allocate a budget reserve in advance to address unforeseen future events. Although not explicitly demonstrated, this aspect is incorporated in the process by anticipating the cost impacts of the options available in the adaptation pathway map. The pathways are assessed in advance using criteria such as pathway length, initial actions, and types of action switches. This assessment helps identify the conditions under which each option is applicable and its potential impact, thereby supporting the allocation of an upfront budget reserve.

8.2. Capacity-driven Planning

The objective of capacity-driven planning emphasises capacity as the determining factor in the planning, instead of solely accommodating the demands. This objective is reflected in the following design indicators:

- **Prioritisation:** This indicator requires the process design to support prioritising bridges that need urgent attention. In the demonstration, a set of guiding questions is used to evaluate the state of each bridge, helping to determine the urgency level and appropriate execution timeframe. This evaluation serves as the basis for prioritisation, especially when capacity is limited.
- **Sequence:** This indicator focuses on the mechanism or rules used to arrange the sequence

of actions. In the demonstration, sequencing is primarily determined by the urgency level and timeframe, which are informed by each bridge's adaptation tipping point and adjusted according to available capacity. The adaptation pathway map provides guidance in the process for sequencing by outlining the feasible routes of action for each bridge.

8.3. Portfolio Approach

The objective of the portfolio approach is to foster learning and enable the combination of capacities to better address uncertainty in the case of ageing bridges. This objective is assessed through the following indicators:

- **Project Bundling:** This indicator highlights the importance of grouping bridges with similar conditions within the process, rather than treating each bridge as an isolated, individual project. In the process design, the bridges are treated as part of a portfolio with shared capacity. However, the demonstration does not explicitly show the process for grouping, as it assumes that all bridges already share similar conditions. The approach for categorising and bundling bridges within the portfolio is not yet defined in the process design, leaving room for further development and refinement.
- **Learning:** This indicator emphasises the importance of facilitating knowledge transfer across projects within the portfolio. One way to implement this is by sequencing projects in the portfolio to enable learning from earlier ones. However, the demonstration does not explicitly incorporate learning as a criterion for sequencing in the process design. The impact of learning is only referenced in the fictional scenario as a way to illustrate potential future developments or changes. In future studies, the sequencing approach within the bridge portfolio could be further developed to accommodate learning, enabling knowledge gained from earlier projects to inform and improve subsequent ones.
- **Capacity Building:** This indicator expects the process design to support capacity improvement through cross-project learning in the portfolio. Although the demonstration does not explicitly show how capacity building is achieved, Figure 6.11 illustrates the process where learning contributes to enhanced capacity. However, this remains a plan rather than a demonstrated outcome. A more detailed and explicit demonstration would be needed in future studies to effectively illustrate how capacity building is integrated into the process design.

8.4. Closing Remarks: Design Evaluation

The design evaluation aims to assess how well the demonstrated process design aligns with the objective of solutions established in the previous chapter, as outlined below:

- The demonstrated process design supports the implementation of adaptive approaches. It allows the portfolio to adjust the sequence of actions as long as it is within its capacity. By utilising the adaptation pathways map, the process enables early anticipation of alternative routes or options by allocating upfront budget reserves for potential changes.
- The demonstrated process design supports capacity-driven planning by introducing a set of guiding questions to assess urgency and determine appropriate execution timeframes. These questions serve as a basis for prioritising and sequencing actions when capacity is limited.
- The demonstrated process design does not explicitly present how the portfolio approach is implemented. Instead, the portfolio serves as the contextual basis for the demonstration scenario, influencing sequence arrangements through factors such as learning effects that may reduce lead times and enhance future capacity.

The results of the design evaluation indicate that the demonstrated process design sufficiently accommodates the objectives related to adaptive approaches and capacity-driven planning. However, its limitations in addressing the portfolio approach highlight areas for improvement, which can be further explored in future research to enhance the overall effectiveness and applicability of the proposed design.

9 Discussion

In this chapter, the findings from the case study and the evaluation of the demonstration are discussed and connected to relevant theories, enabling a deeper interpretation of the results. The first section explores how the findings relate to theories on uncertainty, adaptive capacity, adaptive pathways implementation, and life cycle management. The second section outlines the theoretical and practical contributions of the research. The final section addresses the methodological limitations of the study.

9.1. Discussion of Research Findings

9.1.1. Uncertainty in Ageing Bridges Renewal and Renovation

Perception of Uncertainty

W. Walker et al. (2013) defines uncertainty as the lack of complete knowledge about past, present, or future events. Such knowledge gaps are evident in the context of renewing and renovating ageing bridges in the Netherlands. Uncertainty arises from incomplete information regarding the historical loads experienced by the bridges and the future demands they are expected to meet. Furthermore, Marchau et al. (2019) highlights the subjective nature of uncertainty, noting that it is shaped by values, assumptions, and perspectives, and depends on the level of confidence in existing knowledge. Given the strategic importance of bridges to the Netherlands' social and economic well-being, plans for their renewal and renovation are likely to provoke varied public responses, contributing to ambiguity regarding the desired outcomes. As this is the first large-scale effort to replace ageing bridges in the country, the planning process heavily relies on expert judgment and assumptions, which further introduces subjectivity in how uncertainty is perceived and addressed.

Spectrum of Uncertainty

Marchau et al. (2019) introduces a spectrum of knowledge that ranges from deterministic conditions, where all relevant information is known with confidence, to total ignorance, where no credible data, models, or expectations exist to anticipate future events or system behaviour. Within this spectrum, the renewal and renovation of ageing bridges fall under the condition of deep uncertainty. This type of uncertainty is marked by incomplete knowledge, the inability to assign reliable probabilities, and the presence of competing values and perspectives that influence decision-making (Lempert et al., 2003).

In conditions of deep uncertainty, the outcomes of the renewal and renovation of ageing bridges are only partially known. Technical outcomes, such as structural behaviour and deterioration patterns, can be assessed using engineering models. However, the broader outcomes are more difficult to predict due to external factors that lie beyond the control of planners, such as future traffic increases or evolving functional demands. Additionally, ambiguity in values, norms, and stakeholder preferences adds further complexity, making it challenging to define a clear set of expected outcomes for the renewal and renovation of ageing bridges.

The probability of aspects related to the ageing of bridges, such as material properties or loading, can be quantified using historical statistical data. However, the limited availability of historical documentation often makes it difficult to generate reliable probability estimates. In addition, the non-technical aspects involved in the renewal and renovation of ageing bridges, such as cost, regulation, and future demand, are even more difficult to quantify. These factors are influenced by scenario uncertainty as well as social and stakeholder uncertainty, which cannot be addressed effectively through a purely probabilistic approach.

In the ageing bridges, the models related to the structural performance of ageing bridges are mostly available and agreed upon. However, in the context of renewal and renovation, reaching consensus on appropriate models becomes more challenging due to the involvement of numerous key factors beyond structural aspects. Non-technical aspects, such as social and economic impacts, are often difficult to model accurately. Additionally, the interrelatedness among these factors can be highly complex, making it difficult to develop an integrated model that adequately represents the entire system involved in the renewal and renovation of ageing bridges.

Response towards Uncertainty

The spectrum of uncertainty shapes the strategy in navigating the response towards uncertainty. A deterministic approach assumes that outcomes are predictable and follow a fixed relationship, enabling clear predictions and decisions. In contrast, recognising the presence of unknowns highlights the limitations of relying solely on statistical reasoning and underlines the importance of applying fundamental principles, such as keeping options open, avoiding irreversible consequences, and creating room to buy time.

In the context of renewing and renovating ageing bridges, knowledge is often partial and fragmented, making it difficult to model the system or form reliable assumptions. Past experiences have shown that certain assumptions have deviated significantly from actual developments, exposing the limitations of deterministic approaches in managing such complex situations. Although uncertainty is acknowledged in the Rijkswaterstaat Renewal and Renovation (R&R) program, the current strategy remains limited in areas such as preparing budget reserves to accommodate unforeseen changes.

Furthermore, the practice of developing alternative options is often constrained by a tendency to search for the single best solution among available choices, rather than keeping options open for future planning. However, it is also important to acknowledge that generating too many options can lead to decision paralysis, where no action is taken because every option may appear equally unknown or risky. Therefore, it becomes essential to establish an assessment process that helps identify the most promising options under specific scenarios, supporting timely and informed decision-making.

The proposed process design, which adopts adaptive pathways for the renewal and renovation of ageing bridges, offers a way to operate within the spectrum between deterministic understanding and total ignorance. It allows for the development of multiple options to accommodate different future scenarios, while also enabling deterministic analysis to assess the feasibility of each option under varying conditions related to the renewal and renovation process.

9.1.2. Adaptive Capacity of Ageing Bridges in R&R Program

Capacity-driven Approach

Kwadijk et al. (2010) criticised the classical top-down approach that heavily depends on future projections to define policy scenarios. The top-down approach starts with scenarios of the future as the starting point in developing a response towards uncertainty without acknowledging system capacity. In contrast to the top-down approach, Carter et al. (2007) proposed a bottom-up approach that prioritises assessing the adaptive capacity of a system and identifying measures to enhance its resilience under changing conditions. In this case, in response to the insufficient capacity, Rijkswaterstaat changes its priority from infrastructure provision, which emphasises accommodating demand, to asset management, which focuses on keeping the asset into keeping asset in good condition. Without putting aside the need to accommodate the demand, this makes the capacity an important starting point for the R&R program in the Rijkswaterstaat, underscoring the need for a bottom-up approach.

Adaptive Capacity

Folke et al. (2002) describes adaptive capacity as a system's ability to adjust to changing conditions and cope with current and future stresses without losing future options. In the proposed process design, the range of available options is limited by the capacity to implement the R&R program. However, by applying a portfolio approach, the design allows projects to adjust their sequences in response to shifting demands and available capacity within the portfolio. This flexibility enables the system to remain adaptive under different future scenarios while preserving its operational capacity.

The proposed process design anticipates cross-project learning, which contributes not only to improved knowledge but also to enhanced organisational capacity. This learning process aligns with the core philosophy of adaptive management, which is described as "learning to manage by managing to learn." It involves learning cycles and the continuous revision of plans based on feedback and new insights (Pahl-Wostl, 2006; Zevenbergen et al., 2015). This shows that the planning approach is not only focused on adapting to changing conditions but also on building the capacity needed for deeper, systemic improvement. This aligns with one of the planning modes in the adaptive planning spectrum described by de Roo et al. (2021), which goes beyond behavioural adjustment and aims to build the capacity to reshape the underlying structures of the system.

Adaptation Tipping Point

Kwadijk et al. (2010) further developed the bottom-up approach through the concept of the adaptation tipping point (ATP), which refers to the magnitude of change at which an existing management strategy no longer meets its intended objectives (Kwadijk et al., 2010; Haasnoot et al., 2013). Similar to the bottom-up approach, ATP uses system capacity as the starting point. It focuses on evaluating the robustness of current measures by identifying the conditions and timing when these measures will no longer be effective. In the context of ageing bridges, ATP is understood as the moment when alternative measures are needed to ensure that the bridges continue to fulfil their intended functions. Determining ATP in this case is particularly challenging because it involves multiple interrelated end-of-life criteria, including technical, functional, and economic aspects. These criteria must be considered to assess whether a given measure remains appropriate, as the perceived importance of one criterion to another can be varied in different cases or stakeholders. Due to the complexity in determining the ATP, the current proposed process design is currently limited only to providing a decision flow to guide in which situations a criterion needs to be considered to determine the end-of-life of the bridge.

9.1.3. Adaptive Pathways Implementation for R&R Program

Dynamic Adaptive Pathways Planning (DAPP) serves as the framework for developing the proposed process design for adaptive approaches implementation in R&R program of ageing bridges. The DAPP approach incorporates the use of the adaptation pathway map (Haasnoot et al., 2012) and Dynamic Adaptive Planning (DAP) (W. Walker et al., 2001) to navigate long-term uncertainty.

Adaptation Pathway Map

Haasnoot et al. (2013) describes the adaptation pathways map as the illustration of alternative routes to get to the same desired point in the future, with each route meeting a predefined minimum performance threshold that determines acceptable outcomes. In the proposed process design, the adaptation pathways map is interpreted as a visualisation of all possible actions and the logical sequences, illustrated as routes or pathways, that a bridge can follow throughout its lifespan. In many applications, adaptation pathways maps are developed for a specific, holistic case with a predefined timeframe that indicates when a certain action becomes ineffective and needs to be replaced by another. In contrast, the proposed design uses the adaptation pathways map as a general guiding tool that can be applied to multiple bridges. It serves as a foundation for sequencing and upfront preparation at the programming level. This version of the map does not include a fixed timeframe, as each bridge may have distinct circumstances that cannot be generalised into one map. At the project level, a more detailed adaptation pathways map can later be developed to address the specific components and complexities of each individual bridge.

The application of upfront planning with predefined options in adaptive pathways reflects the "leading" behaviour of adaptive planning described by de Roo et al. (2021), which involves proactively creating conditions for change before external pressures arise. By offering multiple options, the adaptive pathways approach allows the planning of ageing bridges to adjust to changing conditions, rather than attempting to control outcomes through a single, fixed plan.

Adaptive Plan

While incorporating adaptive pathways offers a promising approach to managing uncertainty, successful implementation depends on the organisation's readiness to adopt an adaptive planning process. This includes ensuring that switches between actions occur before tipping points are reached. To support this, an adaptive plan must be in place, which involves clear signal detection and monitoring systems, along with preparatory and contingency plans in response to those signals (Haasnoot et al., 2013). In the context of ageing bridges, detecting signals is particularly challenging because it requires monitoring multiple factors, such as cost, risk, and performance, to identify when further action is necessary. Additionally, defining appropriate indicators and thresholds for each signal adds complexity, as interpretations of what constitutes acceptable levels for cost, risk, and performance may vary across stakeholders and situations.

The implementation of adaptive plans involves both preparatory and contingency actions. Preparatory actions are taken in advance to improve readiness and support the transition from one action to another within the adaptive pathway (Haasnoot et al., 2019). This requires the organisation to anticipate flexibility in terms of timing, scope, and cost, since each option in the pathway may demand a different type of response. As a result, it becomes difficult to rely on a single fixed plan. Many institutions may struggle with this need for flexible upfront planning, as their structures are often not designed to accommodate such flexibility.

In addition to preparatory actions, contingency actions are necessary to ensure a timely and effective response when conditions deteriorate or when unexpected changes arise (Haasnoot et al., 2013). In the context of ageing bridges, this can be particularly challenging because it depends on signal detection, which may take time to identify and evaluate as a valid trigger for further measures. If the assessment determines that the signals require large and costly actions, additional time is needed to prepare and implement the response. This extended lead time increases the risk of reaching a tipping point before actions can be executed, which may render the planned responses ineffective or obsolete.

While the preparatory actions reflect the ”leading” behaviour of adaptive planning, as described by de Roo et al. (2021), by proactively creating conditions for change before external pressures arise, the contingency actions demonstrate the ”following” characteristic, which involves responding to changes as they occur. In this approach, decisions regarding actions are shaped by actual events or triggers rather than initial assumptions. This is consistent with the concept of adaptive management, which focuses on managing responses to inevitable changes and surprises in the process (Pahl-Wostl, 2006).

9.1.4. Life Cycle Management

Life cycle management (LCM) oversees an asset or asset system throughout its entire life cycle, aiming to achieve an optimal balance between performance, cost, and risk (Fuchs et al., 2014). While traditional service agreements often prioritise short-term factors such as cost, schedule, and quality, the integration of LCM indicators is intended to highlight the long-term implications for assets and systems, helping to prevent short-term decision-making. Adaptive pathways complement the LCM principle by treating asset measures not as isolated solutions but as part of an integrated sequence of actions. This approach focuses on long-term planning while incorporating short-term measures as part of a broader strategy. The adaptation pathways map provides a roadmap of possible routes an asset can take over its lifecycle, allowing organisations to anticipate and plan for a range of long-term options in managing the asset over time.

Life cycle management (LCM) highlights the importance of managing the interfaces between life cycle stages, where each phase is expected to provide input for the next (Fuchs et al., 2014). The implementation of adaptive pathways aligns with this principle by recognising the impacts generated by sequences of actions, including path dependency, timing, switching costs, and regret potential. By anticipating the impact of entire pathways rather than an individual action, the transition between life cycle stages can be managed more effectively to support the long-term objectives of the asset.

Life cycle management also emphasises the importance of flexibility in assets to adapt to changes over time, enabling them to accommodate future developments and evolving requirements (Fuchs et al., 2014). The range of pathway options provided in the adaptation pathways map supports this flexibility by enabling transitions from one action to another as conditions evolve. Preparatory and contingency actions, which are integrated into the implementation of adaptive pathways, further support this flexibility by facilitating smoother transitions when changes are required.

9.2. Contributions of the Research

9.2.1. Theory Contributions

This study offers a theoretical contribution that enhances the understanding of how to respond to uncertainty in the renewal and renovation of ageing bridges, as outlined below:

- This study presents an alternative perspective on addressing uncertainty in the context of ageing bridges, moving beyond the deterministic approach that focuses on predicting possible future outcomes. It introduces adaptive approaches that emphasise flexibility and responsiveness, allowing for adjustments as conditions change.
- This study broadens the understanding of capacity within the implementation of adaptive pathways. In many Dynamic Adaptive Policy Pathways (DAPP) approaches, capacity is typically understood as object-related, focusing on whether the system or asset can continue to meet its objectives as defined by the adaptation tipping point. This study introduces the concept of process-related capacity, which refers to the organisational ability to provide and implement actions in response to identified tipping points. Process-related capacity acts as a boundary condition in shaping the development of adaptive approaches.
- The proposed process design introduces a portfolio-level implementation of adaptive approaches, enabling inter-project learning and the sharing of capacity. This expands on the current application of the DAPP approach, which is typically limited to the level of individual projects.

9.2.2. Practical Contribution

- The proposed process design provides a systematic approach that addresses both uncertainty and the limited capacity faced in the renewal and renovation of ageing bridges. It offers a guiding framework for programming the sequence of actions while allowing flexibility to adjust those actions when conditions change or new knowledge becomes available during the process.
- The proposed design also recognises the importance of flexible upfront planning to enable adjustments when future developments deviate from the initial plan by accommodating different options in the planning. In addition, the design encourages a learning process that supports the R&R program in optimising the selection of available actions and enhancing the program's overall capacity.
- The proposed design supports the implementation of life cycle management by enabling oversight of the possible measures of the asset throughout its entire lifecycle and facilitating the integration of interfaces between different measures applied to the asset.

9.3. Research Limitation

The study presents the following limitations associated with its methodological aspects:

- **Case Study:** This research focuses on the renewal and renovation of ageing bridges in the Netherlands under the responsibility of Rijkswaterstaat. The applicability of the findings and the proposed process design to renewal and renovation efforts managed by other organisations, such as municipalities or private parties, remains to be explored and requires further investigation.
- **Number of Interviewees in Case Studies:** Due to the broad scope of this study, interview topics were tailored to match the specific expertise of each respondent. However, this approach led to a limited number of responses on certain topics, which may introduce bias by over-representing particular viewpoints or interpretations.

- **Demonstration:** The demonstration relies on a fictional case rather than a real-world example, which may limit its ability to capture the full complexity of ageing bridge scenarios. In addition, the assumptions made within the fictional context may oversimplify the actual conditions and challenges faced in practice.
- **Validation:** Due to time constraints, the findings and the proposed process design have not undergone expert evaluation or validation. Therefore, their reliability and practical applicability still require further validation.
- **Implementations:** The proposed design is currently limited to a conceptual process framework. To enhance its applicability in practice, the development of a more detailed and technically grounded process framework is necessary.

10 Conclusion

In this chapter, the findings of this research are summarised. The first section provides the answers to the research question, which is followed by recommendations for future research.

The aim of this research is to explore the applicability of adaptive pathways as a planning approach to manage deep uncertainty in the renewal and renovation of ageing infrastructure in the Netherlands. For this research objective, the following main research question is formulated.

" How can adaptive pathways be applied to address deep uncertainty in the renewal and renovation of ageing bridges in the Netherlands?"

To address the main research question, sub-questions were formulated and answered individually. The findings from each sub-question were then synthesised to construct a comprehensive answer to the main research question.

10.1. Answering Questions

10.1.1. Research Questions

RQ1: What types of uncertainty influence the renewal and renovation of ageing bridges in the Netherlands?

The renewal and renovation of ageing bridges in the Netherlands are influenced by the following types of uncertainty:

- **Structural Uncertainty:**

  Structural uncertainty arises from limited information on historical conditions, such as past loads, which are essential for accurately assessing deterioration. It also stems from incorrect or incomplete assumptions about the current state of ageing bridges. This type of uncertainty challenges the effectiveness of existing approaches that rely on forecasting and modelling, as these methods may result in inaccurate assumptions. This potentially increases the risk of unforeseen outcomes, including under- or over-budgeting and unexpected bridge failures.
- **Scenario Uncertainty:**

  Scenario uncertainty arises from the difficulty in predicting future network demand, including possible increases in traffic volume or shifts in transport modes that influence the functional requirements of bridges. It also stems from uncertainty about broader future developments that may affect bridge design standards, such as the emergence of new construction materials or innovations in transportation technology.
- **Social and Stakeholder Uncertainty:**

This uncertainty arises from the relative importance or acceptance that society and relevant stakeholders place on the criteria used for renewing and renovating ageing bridges. These differing perspectives affect how the R&R program is structured, especially in determining priorities and allocating budgets.

These uncertainties create a condition of deep uncertainty in the renewal and renovation of ageing bridges. This is reflected in the limited and fragmented knowledge caused by structural uncertainty, the inability to assign reliable probabilities to future developments due to scenario uncertainty, and the existence of competing values and perspectives stemming from social and stakeholder uncertainty. This context highlights the importance of adopting an adaptive approach that can respond flexibly and effectively to the challenges posed by deep uncertainty.

RQ2: What is the gap between the identified uncertainties and the existing approaches in Rijkswaterstaat to manage them in the renewal and renovation of ageing bridges?

The existing approaches in Rijkswaterstaat already recognise the presence of uncertainty in the planning and decision-making process. However, these approaches still face limitations in effectively managing and responding to that uncertainty. The current strategies used by Rijkswaterstaat to address uncertainty include the following:

- The existing approach relies heavily on forecasting and modelling as the basis for reserving budgets and preparing for future uncertainty. However, structural uncertainty poses a challenge to this approach, as there is insufficient knowledge about the appropriate model structure to accurately represent the system. In response to this, Rijkswaterstaat is making efforts to promote cross-project learning within its renewal and renovation activities to improve understanding and reduce the structural uncertainty. Nevertheless, the mechanism to support this learning process is still in development and has not yet been fully implemented.
- In response to scenario uncertainty, Rijkswaterstaat allocates cost surcharges to prepare for unforeseen future conditions. However, these surcharges are typically based on statistical variation, which may not be effective in addressing nonlinear developments or extreme scenarios. Managing scenario uncertainty effectively requires the development of multiple alternative options to accommodate a range of possible futures. In practice, however, Rijkswaterstaat's approach is often limited by a tendency to seek a single optimal solution from the available choices, rather than keeping multiple options open for future planning.
- Rijkswaterstaat involves experts in various aspects of renewal and renovation, including assessing the technical condition of infrastructure. In the later stage, Rijkswaterstaat allows for stakeholder participation, including citizen involvement through city councils. However, due to limited capacity, not all demands of society can be accommodated, which underscores the need for prioritisation. However, social and stakeholder uncertainty lead to varying perceptions of urgency, making it challenging to develop a clear prioritisation mechanism. This complicates the process of determining which infrastructure projects should be prioritised under the condition of limited capacity.

The remaining gap between the existing approach of Rijkswaterstaat in responding to the uncertainty becomes the basis for developing a more adaptive approach, which is through using the adaptive pathways.

RQ3: How do adaptive pathways support planning under uncertainty in the context of renewal and renovation of ageing bridges?

Utilising adaptive pathways in the renewal and renovation of ageing bridges enables more flexible planning by allowing adjustments to the sequence of actions when future conditions deviate from the initial plan. These pathways also provide a set of options or alternative action sequences to anticipate potential changes. By identifying these options in advance, the possible impacts of each can be assessed early on, which supports the allocation of upfront budget reserves to better respond to those impacts.

Adaptive pathways can also support the prioritisation of bridges that require urgent attention when capacity is limited. The adaptation pathways map outlines feasible routes of action that each bridge can take, allowing for adjustments based on available capacity. This approach helps in identifying alternative pathways that enable delaying important but less urgent actions, ensuring that the limited capacity to conduct the important actions is directed to the most critical needs first.

By implementing adaptive pathways at the portfolio level, it becomes possible to plan action sequences that facilitate cross-project learning and enable knowledge transfer from earlier projects. The insights gained through this process are expected to help reduce and manage uncertainty across the portfolio. This approach supports more informed decision-making, improves the assessment of available options, and improves the overall capacity of the portfolio.

RQ4: To what extent can adaptive pathways be implemented in the renewal and renovation of ageing bridges to address deep uncertainty?

While adaptive pathways present a promising approach to managing uncertainty, their successful implementation relies on the organisation's readiness to accommodate timely transitions from one action to another. This requires not only institutional flexibility but also a well-developed system for monitoring and detecting signals that indicate when a change is necessary. In the context of ageing bridges, such signals are derived from multiple indicators, including cost, performance, and risk. The involvement of these diverse indicators adds complexity to the process of identifying clear and timely triggers for action, making the monitoring process more challenging.

In addition, the implementation of adaptive pathways requires preparatory actions to enhance readiness and support flexible planning. However, not all institutions are structured to accommodate this level of flexibility in advance. Effective implementation of adaptive pathways also depends on a proper contingency plan in place to enable timely and effective responses when conditions worsen or unexpected changes occur. In the context of ageing bridges, this becomes particularly challenging, as it relies on signal detection, which may take time to identify and validate as a legitimate trigger for action. If the identified signals point to the need for costly or complex interventions, additional preparation time may be required. This extended lead time increases the risk of reaching a tipping point before actions can be carried out, potentially making the planned responses ineffective or obsolete.

In general, adaptive pathways have the potential to be applied in the renewal and renovation of ageing bridges. However, broader implementation requires institutional readiness to support the flexibility needed for adaptation, as well as the development of supporting tools to effectively identify and respond to triggers for changes in actions.

10.1.2. Main Research Question

The answers to the sub-research questions reveal that the renewal and renovation of ageing bridges in the Netherlands are subject to various types of uncertainty, which pose challenges for the existing approaches in addressing the drivers and overcoming the barriers.

Even though the current approaches of the Rijkswaterstaat already acknowledge the presence of uncertainty in its planning approaches, it is still dominated by deterministic approaches in efforts to predict the outcomes and anticipate potential variation in the planning. However, such approaches fall short in addressing key limitations: the risk of relying on incorrect assumptions due to structural uncertainty; the wide range of plausible future developments posed by scenario uncertainty; and the potential for conflicting perceptions regarding the importance of certain measures, as seen in social and stakeholder uncertainty.

In response to these conditions, adopting more adaptive approaches that address various types of uncertainty becomes increasingly important. Implementing adaptive pathways provides a promising strategy by mapping out multiple options and allowing for the adjustment of actions when conditions change. Given that the concept of adaptive pathways is still relatively new in the context of ageing bridges, the following main research question arose to investigate the applicability of this approach:

" How can adaptive pathways be applied to address deep uncertainty in the renewal and renovation of ageing bridges in the Netherlands?"

In response to the main research question, the proposed process design demonstrates that adaptive pathways can support flexible planning by enabling adjustments to the sequence of actions when future conditions diverge from the original plan. The approach also aids in prioritising bridges that require urgent attention when capacity is constrained. Furthermore, applying adaptive pathways at the portfolio level allows for coordinated sequencing of actions, facilitating cross-project learning and enabling the knowledge transfer from earlier projects.

However, the implementation of adaptive pathways does not fully bridge the gap between existing approaches and the diverse types of uncertainty. Uncertainty is likely to persist due to the complex and interrelated factors that vary across individual cases of ageing bridges. A complete understanding of the condition of each bridge remains unattainable, as both technical states and contextual factors may evolve over time in unpredictable ways. Similarly, future demands and stakeholder or societal preferences are subject to change and cannot be precisely estimated.

The goal of implementing adaptive pathways is not to eliminate uncertainty, but to create room for responding to multiple plausible conditions that cannot be fully predicted or controlled in advance. This approach recognises the changes brought by uncertainty as both challenges and opportunities. To address challenges, adaptive pathways provide predefined options that can be activated when existing conditions become unfeasible. At the same time, they support the adjustment of actions to capture new opportunities that emerge as knowledge develops over time.

The implementation of adaptive pathways to incorporate flexibility for adjustment can present several challenges. Infrastructure planning and delivery often require long lead times, making it essential for organisations to establish robust signal detection and monitoring systems to ensure that measures are implemented before they become ineffective. Additionally, organisations must have the capacity to undertake preparatory and contingency actions. However, not all organisations are structured or equipped to support these requirements.

Rijkswaterstaat demonstrates potential for implementing the adaptive pathways concept. The organisation already acknowledges the influence of uncertainty, as evidenced by its efforts to monitor the development of key life cycle indicators such as cost, risk, and performance over time. Additionally, Rijkswaterstaat also possesses the capacity to undertake preparatory and contingency actions. By integrating the monitoring of these life cycle indicators with systematic planning for preparatory and contingency measures, the implementation of adaptive pathways within Rijkswaterstaat can be a feasible and practical approach.

With the current emphasis on asset management, Rijkswaterstaat is well-positioned to adopt adaptive pathways as a means to enhance the renewal and renovation process for ageing bridges in the Netherlands. Integrating adaptive pathways into asset management practices enables the R&R program to be more adaptive towards the condition of deep uncertainty that often becomes an obstacle to the process. As the number of ageing bridges continues to grow, the implementation of adaptive pathways can strengthen asset management's role as a key enabler, supporting more responsive planning towards the drivers and contributing to increased organisational capacity to overcome existing barriers.

10.2. Recommendations

10.2.1. Practical Recommendation

Based on the results of this research, several recommendations can be made for practices, as follows:

- Although uncertainty may challenge the reliability of forecasting and assumptions made by Rijkswaterstaat, this does not imply that forecasting should be entirely disregarded in the planning process. Rather than serving as a means of control, forecasting can be repurposed to estimate thresholds that signal the need for further action. These threshold-based forecasts can be used to develop several actions based on multiple scenarios related to the threshold, for instance, identifying appropriate actions when the threshold is met, not met, or shifts over time.
- The implementation of the adaptive pathways can start with categorising the bridges to develop the potential portfolio combinations to support shared capacity and cross-project learning. Instead of categorising the project based on the time horizon of when the technical life of the bridges ends, it should be categorised based on the similarity of the challenges faced by the bridges to accommodate cross-project learning. Including bridges with varying time frames in a single portfolio not only helps to distribute capacity more evenly over time but also enables knowledge

transfer from earlier projects to subsequent ones.

- It is important to explore the level of acceptance of Rijkswaterstaat toward the development of cost, risk, and performance of the bridge as integrated indicators. This also includes examining the conditions under which one indicator may be prioritised over the others. Gaining such insights can help reduce ambiguity in identifying situations that require further action and prevent delays in the decision-making process.
- In developing a budget reserve that accommodates flexibility, Rijkswaterstaat can begin by analysing the cost implications of factors such as path dependency, timing, switching costs, and regret potential associated with various pathway options. This approach enables the preparation of multiple types of budget reserves tailored to different plausible future conditions, rather than relying solely on the statistical variation of a single estimation.

10.2.2. Recommendation for Future Research

Considering the limitations of this study, several avenues for future research are suggested to further complement and extend its findings, as outlined below:

Case Study Using Real Case of Ageing Bridges

As this study uses fictional cases to explore the feasibility of implementing adaptive pathways, future research involving real ageing bridge case studies is necessary to examine the practical application and effectiveness of the approach in dealing with real-life complexity.

Case Study in Other Organisation

As this study focuses on ageing bridges managed by Rijkswaterstaat, further research on bridges managed by other parties, such as municipalities and private entities in the Netherlands, can provide more holistic insights into the renewal and renovation of ageing infrastructure across different governance contexts.

Portfolio Approach for Ageing Bridges

Future research can explore the basis for organising ageing bridges into portfolios, such as grouping by similar objectives, technical conditions, or stakeholder involvement. These arrangements may help accommodate adjustments, enable shared use of capacity, and support learning through adaptive pathways. Additionally, further investigation is needed into how action sequences are structured within the portfolio to facilitate cross-project learning, which is an area that remains underexplored in the current study.

Integrated Trigger Identification for Ageing Bridges

The triggers for actions in ageing bridges involve multiple indicators, such as cost, risk, and performance, with the interpretation of acceptable thresholds varying among stakeholders. Future research could focus on developing an integrated approach to identify triggers that considers these multiple indicators. This includes determining threshold levels at which certain measures for ageing bridges are no longer acceptable.

Valuing Options in Adaptive Pathways

Future research can explore the possibility of quantifying the value of the options derived from the adaptation pathways map, as illustrated in Figure 6.7. This may include interpreting these options as real options, such as the option to defer, expand, switch, or abandon. Quantifying a real option involves estimating the value of flexibility in investment decisions under uncertainty (Greden et al., 2005). Quantifying these options can support decision-makers in objectively assessing the potential impact of each pathway and provide a stronger basis for justifying upfront budget allocations for the available alternatives and deciding which pathways to implement under certain conditions.

Form of Collaboration with Market Parties

The adoption of adaptive pathways is likely to influence the form of collaboration or contracting with other parties. Future research can examine how this shift impacts the expected outcomes of collaboration, which may move from delivering a single end solution to managing a sequence of actions over time. This change may require a long-term collaboration model. Additionally, further study is needed to explore how the flexibility inherent in adaptive pathways can be integrated into contractual arrangements and collaboration forms.

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A

Question List

A.1. Case Study Interview

A.1.1. Topic 1: Bridge Adaptability

General Question

1. Could you explain your background and experience in bridge renovation and replacement projects?

Change in external forces

2. Based on your experience, which changes in external conditions (e.g. increased traffic, increased load, climate change, transportation mode shifting, etc.) have the dominant impact on the bridges in the Netherlands?
3. Has the change occurred gradually or significantly lately?
4. What are the impacts of the changing conditions on the physical condition of the existing bridges in the Netherlands?

   Follow-up Questions:

   - Are the physical impacts noticeable?
   - How do you notice the physical impacts?
   - Will the impacts occur immediately or suddenly create major physical failure?
   - Have the impacts already been anticipated before?
   - What are the measures by the organisation to anticipate the impacts?
5. What do you think are the impacts of the changing conditions on the performance of the bridges in the Netherlands regarding their availability and accessibility?

   Follow-up Questions:

   - Has it already significantly impacted the availability and accessibility of the existing bridges in the Netherlands?
   - Have the impacts on the availability and accessibility of the bridges already been anticipated before?
   - What are the measures by the organisation to anticipate the impacts?
6. Do you think the speed of the changing conditions will get faster, slower, or the same as the current condition? And why do you think so?
7. Do you think the scale of the impacts will get smaller, bigger, or the same as the current condition? And why do you think so?

Bridge Adaptability

8. What kind of bridge materials are adaptable to changing conditions?
9. What kind of bridge design (geometry, structure, etc.) is adaptable to changing conditions?
10. What kind of operation and maintenance measures are needed by the bridge in response to the changing conditions?

State of the Bridges

11. Do you think the state of existing bridges in the Netherlands, especially bridges that reach their physical end of life, will be able to withstand the changing conditions? And why do you think so?
12. How to make the existing bridges more adaptable to changing conditions?

Response to Changing Conditions

13. Looking at the existing practices in the Rijkswaterstaat, what are the dominant measures taken in response to the impacts of changing conditions on the bridges, reactive or proactive? Under what conditions are certain measures taken?
14. What is the focus of the current response to the impacts of the changing condition by the Rijkswaterstaat?
15. Is the response of the Rijkswaterstaat dominantly accommodated through short-term actions or long-term planning?
16. Are the current responses taken by Rijkswaterstaat effective enough? And why do you think so?

Expected Outcomes

17. Considering the changing conditions, what should be the focus of the bridge's renovation and replacement projects? And why do you think so?
18. What are the challenges to achieving that?
19. What measures should be taken to achieve that?

A.1.2. Topic 2: Renovation and Replacement Decision-making

Background

1. Could you explain your background and experience in renovation and replacement projects?

Decision-making Process

2. At which stage is your involvement in the VenR process chain (e.g. in OIB (Objecten in beeld), RA (Regioanlyse), or PH (Planfase))? What is your involvement?
3. What are the expected decision outcomes at that stage?
4. What are the essential aspects to consider in that stage?
5. What data is required to make decisions at that stage?
6. What are the data availability and certainty levels required to make decisions at that stage?
7. How does Rijkswaterstaat deal with limited data availability and certainty levels in renovation and replacement decision-making?

Objectives and Value

8. What should be the objectives of renovation and replacement decisions?
9. Have renovation and replacement objectives changed during the decision-making process?
10. How important are sustainability and social values in renovation and replacement decision-making?

Stakeholders

11. Who are the important stakeholders in renovation and replacement decisions?
12. What are the stakeholders' interests in renovation and replacement decisions?

Renovation and Replacement

13. What are the triggers for the process of renovation and replacement decisions?
14. What conditions are certain assets encouraged to be renovated or replaced?
15. How does the asset's economic, functional, and technical life determine the renovation and replacement decision?
16. What measures are renovation preferred over replacement?
17. What measures are replacement preferred over renovation?

Delay in the Decision-making Process

18. How long does the renovation and replacement decision-making process usually take?
19. What determines the length of the decision-making process?
20. Does Rijkswaterstaat ever experience delays in renovation and replacement decision-making processes? If yes, what causes the delay?

    Follow-up Questions:

    - How long does the delay impact the timeline of the decision-making process?
    - How will the delay impact the direction of the decision?

Decision Implementation

21. How long should the decision be realised after the final renovation and replacement decision?
22. Should the decision be implemented radically in a short time or gradually in small steps over a longer time?

A.1.3. Topic 3: Adaptation Signals Monitoring

Background

1. Can you tell me about your background?
2. From these aspects -cost, risk, and performance- which one are you involved in monitoring?

Monitoring

3. What is the purpose of monitoring?
4. Why do these aspects need to be monitored?
5. How are the aspects monitored?
6. What are the types of monitoring plans of the organisation? (Proactive or reactive)
7. How long does the process to monitor the aspects take?

Monitoring Findings

8. How to identify the signals for further measures from the monitoring findings?
9. Are there any categorisations of the monitoring findings?
10. Do the findings categorisations become the trigger for further measures?
11. Who will use the findings from the monitoring?
12. What to do with the findings from the monitoring?
13. What are the next steps to follow up on the findings from the monitoring?

14. How long does it take for further measures to be taken after the signals for further measures are identified?

Challanges

15. What is the current level of data availability and certainty that you use to monitor these aspects? Do you think it is reliable enough to identify the signals for further measures?
16. What is the level of data availability and certainty that you need to monitor these aspects?
17. How to deal with the limited data availability and uncertainty?
18. Do you think the current monitoring regime is effective enough to identify the signals for further measures?
19. What are the challenges in monitoring and identifying the signals for further measures from these aspects?
20. How to improve the current monitoring regime in the organisation?

A.2. Expert Semi-quantitative Interview

A.2.1. Questionnaire

Respondent Profile

1. Professional role
   - Contractor
   - Consultant
   - Engineer
   - Planner
   - Other
2. Experience with Infrastructure Projects
   - <5 years
   - <5-10 years
   - 11-20 years
   - >20 years
3. Familiarity with Bridge Projects
   - Not Familiar
   - Some Experience
   - Frequent Involvement

Action Assessment: Preservation

This section focuses on the preservation measures for ageing bridges. In this section, you will be asked to score the preservation measure toward certain parameters based on your knowledge or experience.

Notes: In this questionnaire, preservation is defined as the measure to slow or counteract the ageing process. Technical objects are maintained above the minimum quality level necessary to ensure the required performance.

5. Considering its life cycle cost, the preservation measure for the ageing bridge in general is....

   Score Guide:

   - 0-2= More expensive than the cost to renew
   - 3-5= Costly over time
   - 6-8= Moderate cost efficient

- 9-10= Very cost efficient

6. After preservation is conducted on the ageing bridge, the risk of disruption, failure, or unintended consequences becomes ....

   Score Guide:

   - 0-2= High and difficult to predict
   - 3-5= Significant
   - 6-8= Acceptable/manageable
   - 9-10= Very low

7. In terms of performance achievement (availability, capacity, reliability, etc), the preservation measure makes the ageing bridge...

   Score Guide:

   - 0-2= Rarely achieved the expected performance
   - 3-5= Have the performance quickly declined
   - 6-8= Works well for a limited period
   - 9-10= Consistently maintains the initial expected performance

Action Assessment: Mitigating

This section focuses on mitigating measures for ageing bridges. In this section, you will be asked to score the mitigating measure toward certain parameters based on your knowledge or experience.

Notes: In this questionnaire, a mitigating measure is defined as modifying functional requirements by making interventions elsewhere in the system, without altering the asset (for example, re-routing). This measure fulfils the functional needs differently from its initial functional requirement.

8. Considering its life cycle cost, the mitigating measure for the ageing bridge in general is....

   Score Guide:

   - 0-2= More expensive than the cost to renew
   - 3-5= Costly in hidden ways
   - 6-8= Moderately cost-efficient
   - 9-10= Very cost efficient

9. After the mitigating measure is conducted on the ageing bridge, the risk of disruption, failure, or unintended consequences becomes ....

   Score Guide:

   - 0-2= High and difficult to predict
   - 3-5= Significant
   - 6-8= Acceptable/manageable
   - 9-10= Very low

10. For sustaining the performance levels, the mitigating measure in the ageing bridge usually…

    Score Guide:

    - 0-2= Often fails to meet expectations
    - 3-5= Has noticeable compromises
    - 6-8= Meets basic needs
    - 9-10= Fully satisfies requirements

Action Assessment: Downgrading

11. Over its lifecycle cost, the downgrading measure for the ageing bridge is generally ...

    Score Guide:

    - 0-2= Hidden and cumulative
    - 3-5= Often underestimated
    - 6-8= Reasonable
    - 9-10= Very low

12. After the downgrading measure is conducted, the ageing bridge's performance typically…

    Score Guide:

    - 0-2= Unsuitable
    - 3-5= Poor for future usage
    - 6-8= Works under constraints
    - 9-10= Still meets most needs

13. When the downgrading measure for the ageing bridge is conducted, the risk of long-term failure or user dissatisfaction becomes ...

    Score Guide:

    - 0-2= Immediate and significant
    - 3-5= High in long run
    - 6-8= Acceptable
    - 9-10= Minimal

Action Assessment: Renovation

This section focuses on renovation measures for ageing bridges. In this section, you will be asked to score the renovation measure toward certain parameters based on your knowledge or experience.

Notes: In this questionnaire, the renovation measure is defined as enhancing an asset's functional performance by upgrading or adding existing structures, and sometimes, involves demolishing part of the existing structure. The improvement measure includes increasing the utility value of the infrastructure.

14. The renovation measures for the ageing bridge usually make the life cycle cost become...

    Score Guide:

    - 0-2= High due to surprises
    - 3-5= Often underestimated
    - 6-8= Reasonable with some risks
    - 9-10= Predictable and efficient

15. During and after the renovation measure is conducted on the ageing bridge, the risk of disruption, failure, or unintended consequences becomes ...

    Score Guide:

    - 0-2= High and recurring
    - 3-5= Significant
    - 6-8= Manageable
    - 9-10= Low

16. After the renovation is conducted on the ageing bridge, the performance of the asset typically ...

    Score Guide:

- 0-2= Remains vulnerable
- 3-5= Requires compromise
- 6-8= Is strong but limited in a certain timespan
- 9-10= As good as the new asset

Action Assessment: Renewal

This section focuses on renewal measures for ageing bridges. In this section, you will be asked to score the renewal measure toward certain parameters based on your knowledge or experience.

Notes: In this questionnaire, the renewal measure is defined as complete replacement, when a new object replaces the ageing one. It marks the start of a new lifespan of the object.

17. Over the long term, the cost of renewal for the ageing bridge is…

    Score Guide:

    - 0-2= Not cost effective
    - 3-5= High but justified
    - 6-8= Balanced by performance gains
    - 9-10= Worth the investment

18. Renewal for the ageing bridge introduces risk that is…

    Score Guide:

    - 0-2= High
    - 3-5= Moderate but known
    - 6-8= Limited
    - 9-10= Low and manageable

19. The performance of the ageing bridge after renewal becomes ...

    Score Guide:

    - 0-2= Still limited in some ways
    - 3-5= Comparable to renovation
    - 6-8= Meet high standards
    - 9-10= Significantly improved

A.2.2. Scorecard Derived from Questionnaire

After the questionnaire is completed, the scores are entered into a scorecard to enable comparison between the different actions. If the expert finds that the initial scores do not accurately reflect the relative effectiveness of the actions, it is allowed to adjust the scores within the scorecard to better represent their assessment.

Indicators	Cost	Risk	Performance
Preservation	9	9	8
Mitigating	8	7	4
Downgrading	8	3	5
Renovation	5	6	8
Renewal	8	9	10

Table A.1: Score Card Derived from Semi-quantitative Interview

B

Network Analysis

This appendix presents the network analysis created using Atlas.ti, based on the codes identified from document analysis, interviews, and relevant theoretical frameworks. The networks illustrate the relationships between key concepts and support the interpretation of findings in the study.

B.1. Key Factors

B.1.1. Drivers

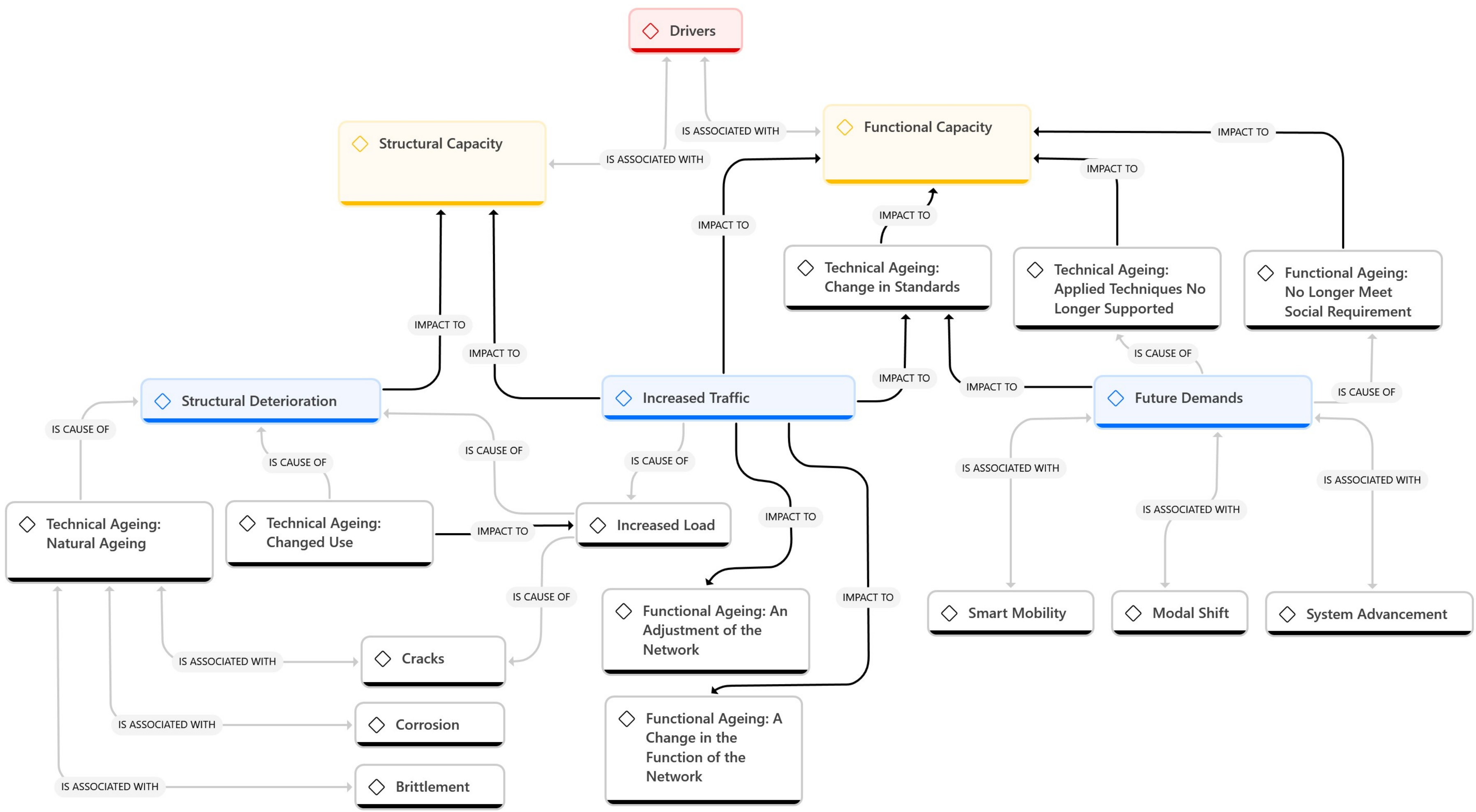

Figure B.1: Drivers for Renewal and Renovation of Ageing Bridges

B.1.2. Enablers

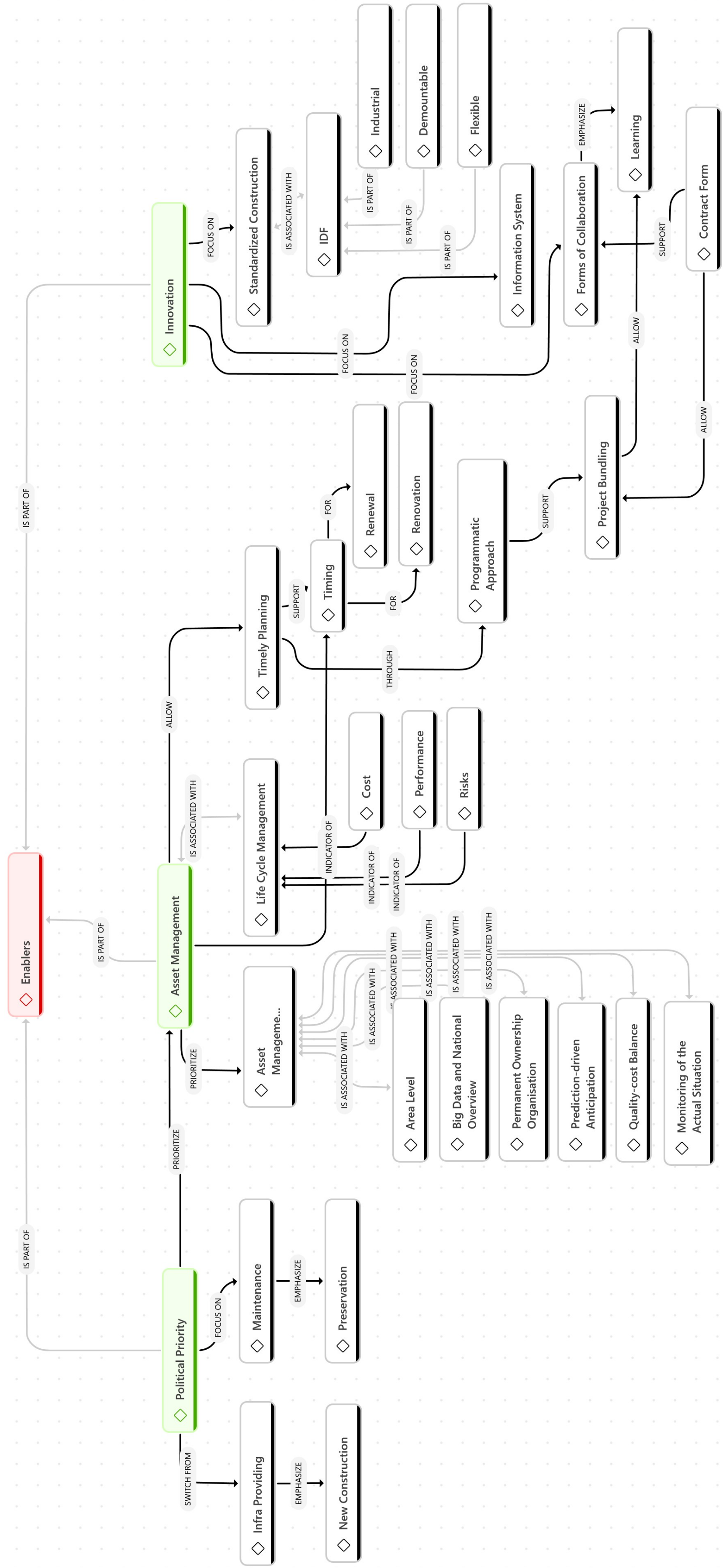

Figure B.2: Enablers for Renewal and Renovation of Ageing Bridges

B.1.3. Barriers

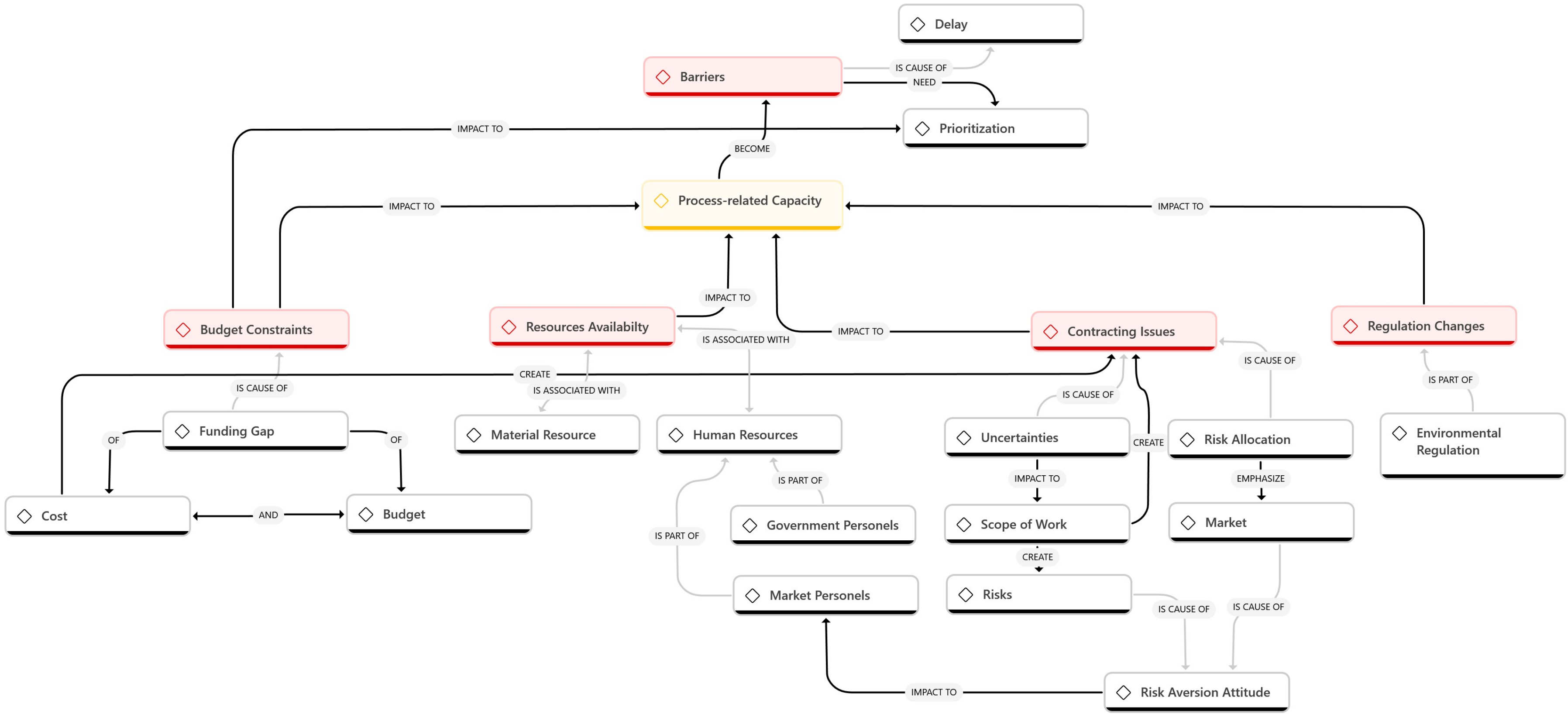

Figure B.3: Barriers for Renewal and Renovation of Ageing Bridges

B.2. Uncertainty

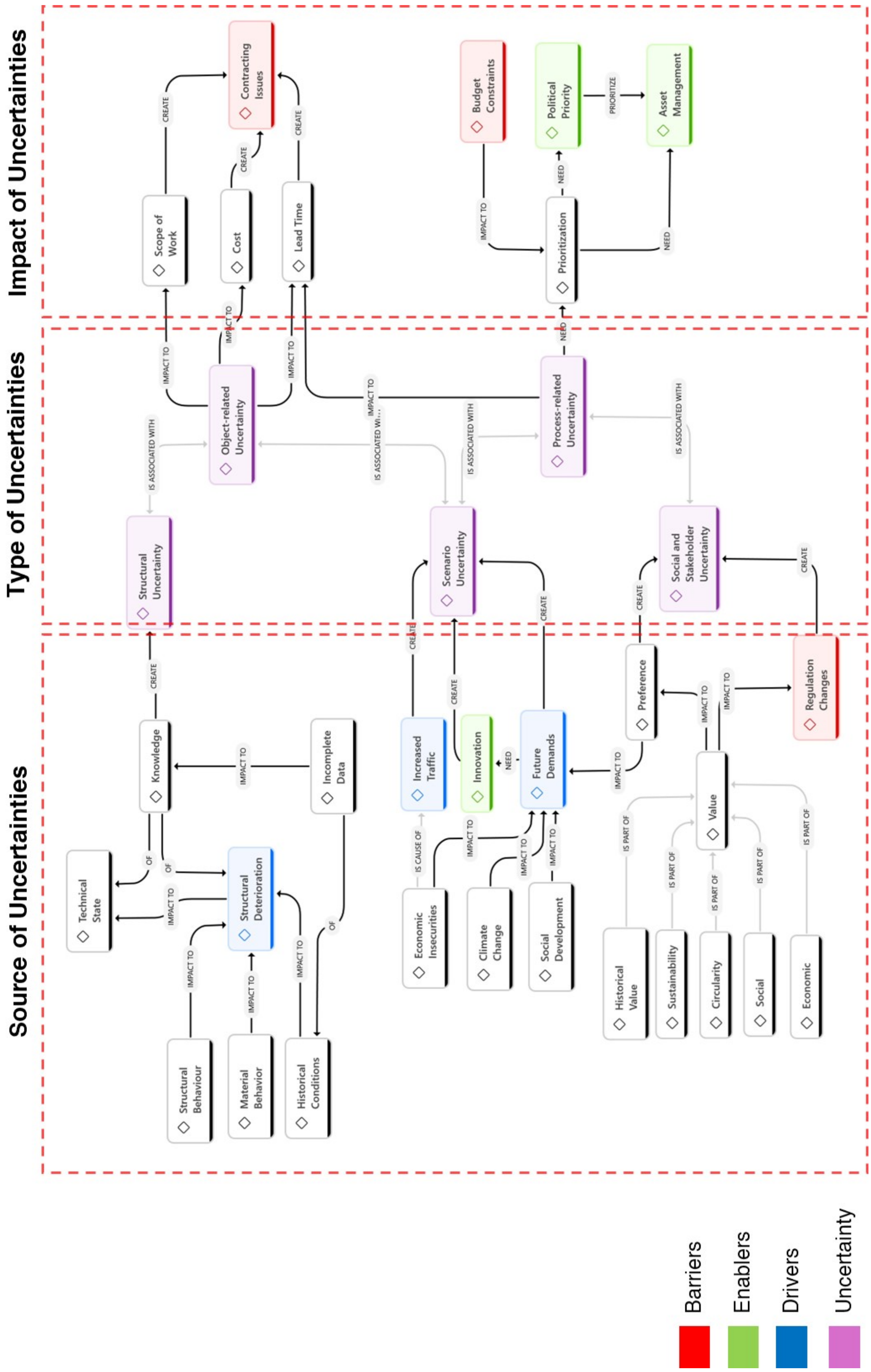

Figure B.4: Uncertainty

B.3. Spectrum of Adaptive Approach

B.3.1. Involvement in Planning

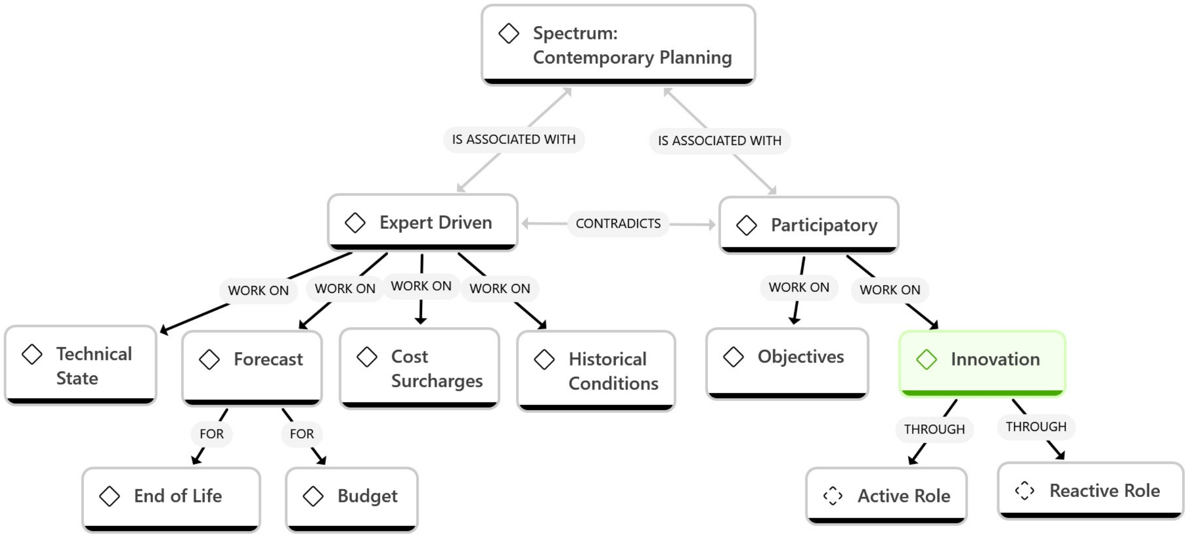

Figure B.5: Spectrum: Involvment in Planning

B.3.2. Conditioning the Possibility of Change

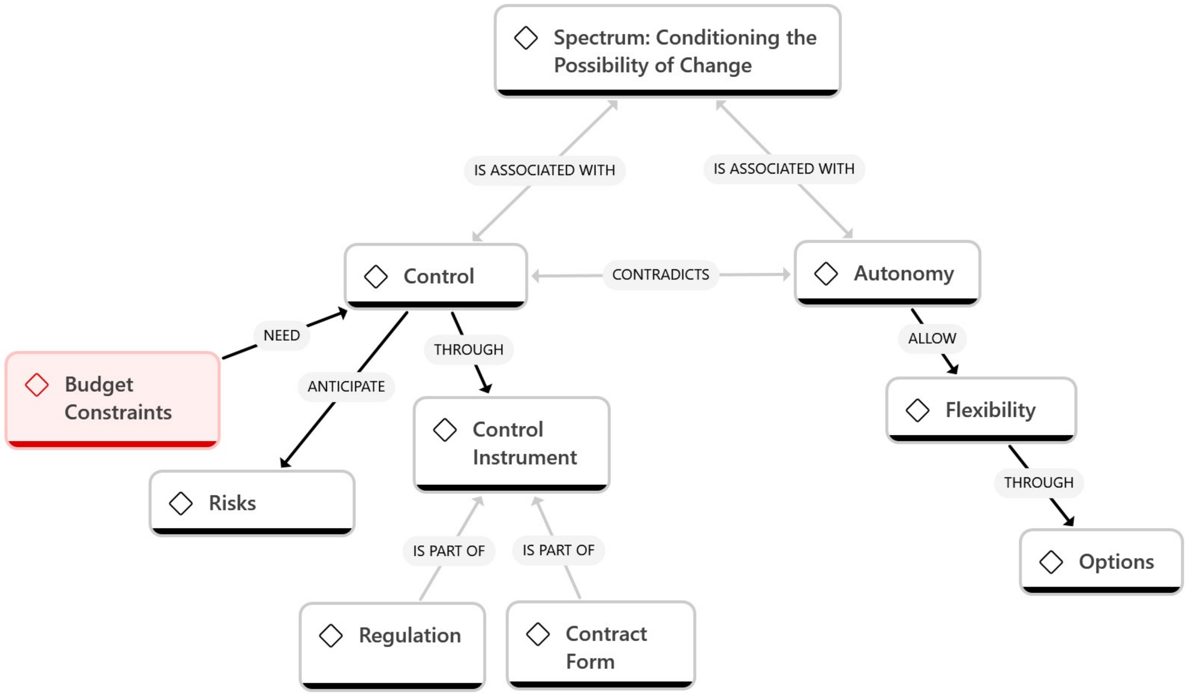

Figure B.6: Spectrum: Conditioning the Possibility of Change

B.3.3. Acting in Response to Change

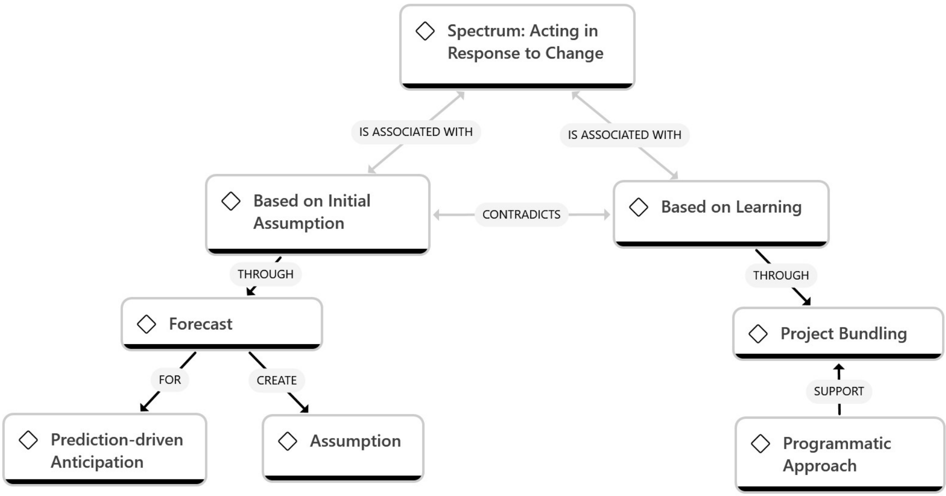

Figure B.7: Spectrum: Acting in Response to Change

B.3.4. The Need for Capacity to Change

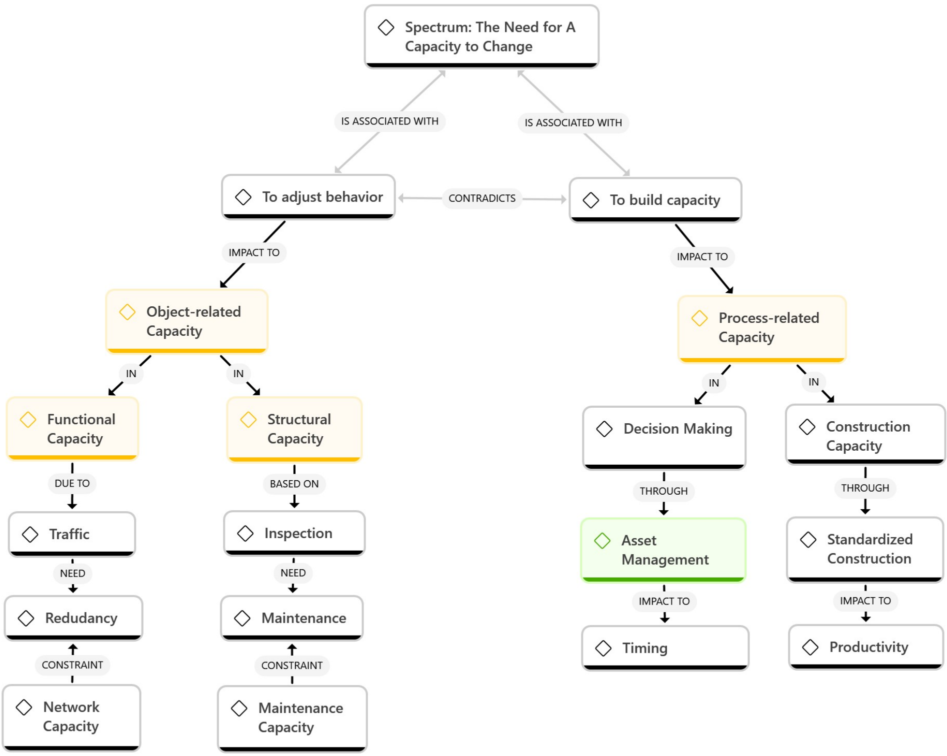

Figure B.8: The Need for A Capacity to Change

B.4. Problem Identification

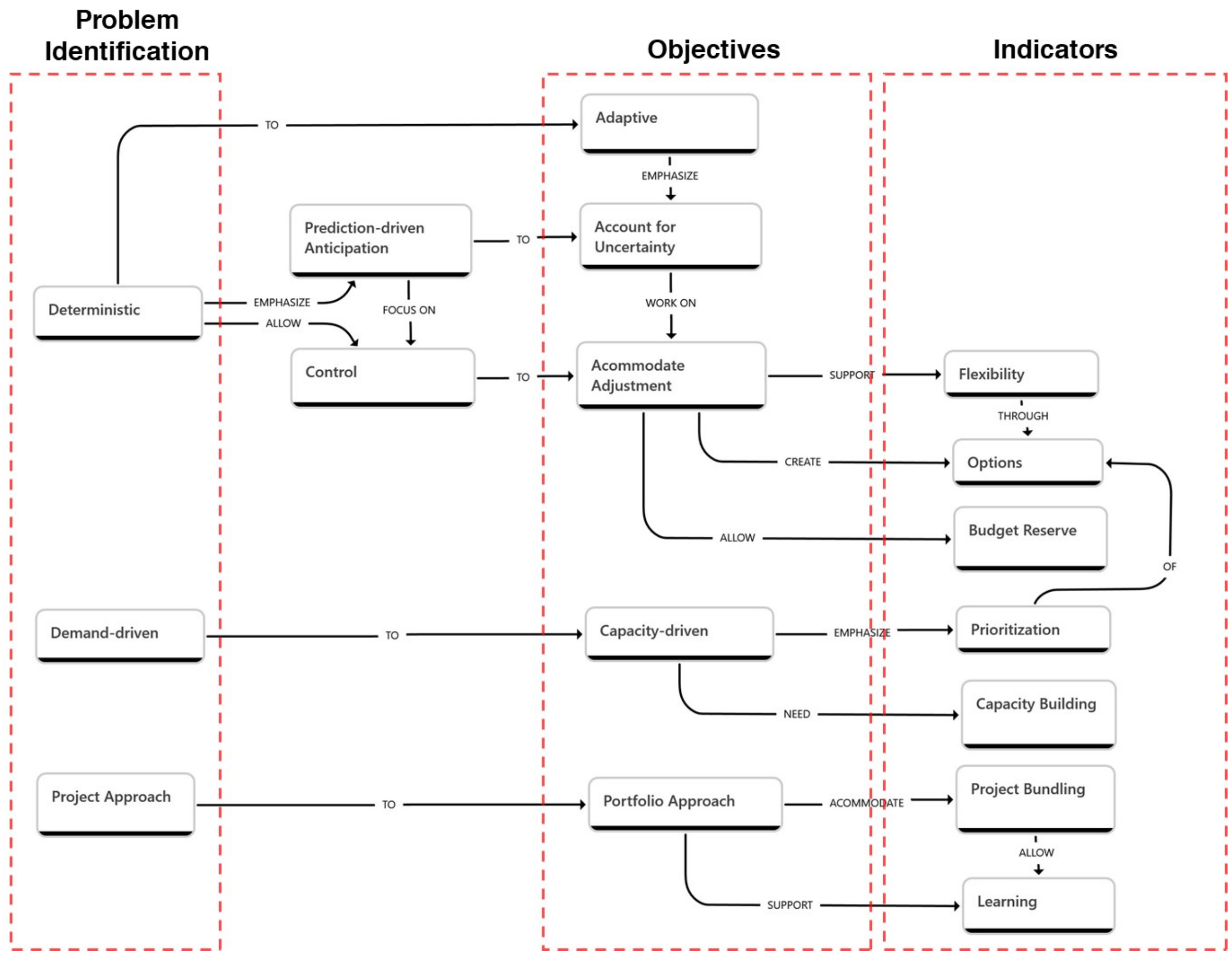

Figure B.9: Problem Identification