A. L. Ordóñez Llancce

Towards Climate-Resilient Infrastructures through an Integrated Infrastructure Design Approach

Master Thesis

Towards Climate-Resilient Infrastructures through an Integrated Infrastructure Design Approach

By

A. L. Ordóñez Llancce

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Colophon

Author

Name	Angela Lisset Ordóñez Llancce
Student Number	5337003

Graduation Thesis

University	Delft University of Technology
Faculty	Faculty of Civil Engineering and Geosciences (CiTG) Stevinweg 1 2628 CN Delft
Master	Construction Management & Engineering

Graduation Committee

Chairman	Prof. Dr. Johan Ninan Faculty of CiTG
First Supervisor	Dr. Yirang Lim Faculty of CiTG
Second Supervisor	Dr. Audrey Esteban Faculty of Architecture
External Supervisor	Joep van Leeuwen Rotterdam Municipality

In Collaboration with

Rotterdam Municipality
Wihelminakade 179
3072 AP Rotterdam

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Preface

The culmination of my study program in Construction Management and Engineering at Delft University of Technology is embodied in this thesis entitled "Towards Climate-Resilient Infrastructures Through An Integrated Infrastructure Design Approach." Throughout the development of my thesis, numerous unforeseen challenges emerged, rigorously testing my personal resilience. The innovative nature of my research topic brought both excitement and uncertainties, coupled with personal doubts about my capability to delve into this new area of investigation. Initially, my instinct was to maintain control over every aspect of the project, but I soon realized this approach was neither possible nor practical. Instead, I learned to accept the inherent uncertainties of future challenges, preparing myself mentally to face them, and thus, to keep progressing.

One of the main challenges that persisted throughout my entire writing journey was encapsulating my thoughts and perspectives into words. The complexity of the topic underscored the necessity of finding simple yet effective ways to communicate the importance of Integrated Infrastructure Design Approach (IIDA) and its role in enhancing climate resilience. During the validation phase, an enlightening analogy occurred to me while discussing with an expert: understanding IIDA is like relearning how to cook after moving abroad. I adore Peruvian food; however, when living far from home, it's not always feasible to stick to traditional recipes. Attempting to do so requires significant time and effort to find the same ingredients, which are often too expensive. This inconvenience is not unique to me but has been a longstanding issue faced by migrants. Their solution? Fusion cuisine. They begin with an understanding of the core characteristics of the dishes they wish to recreate, then explore the ingredients available in their new location, followed by trial and error until they devise new recipes. This knowledge is eventually shared with others, reinforcing the idea that cooking is not merely about replicating existing recipes; it's about exploration and learning.

Similarly, as people adapt their cooking techniques under new circumstances, local infrastructure authorities, such as municipalities, can no longer adhere to old pratical process when planning and designing local infrastructure projects. Just as a cook begins by understanding the fundamental characteristics of the dishes they aim to recreate, municipalities must clearly define their goals for enhancing climate resilience within their infrastructure. Next, akin to a cook exploring new ingredients available in their new location, municipalities must assess and adapt to new environmental conditions, recognizing unforeseen climate variations and integrating (perhaps new) various variables into their projects—these are the implementation lenses.

Following this, just as cooks engage in trial and error to perfect new recipes, municipalities should enact policies that enable internal actors to execute pilot projects, exploring different implementation lenses to find what works best in their specific context. Finally, mirroring how culinary knowledge is shared and recipes are spread, municipalities must gather and institutionalize new knowledge, continuously updating their design criteria to keep pace with best practices related to climate resilience.

Integrated Infrastructure Design Approach ensures that infrastructure planning and design are not only responsive to current challenges but are also adaptive and innovative, drawing on new insights and experiences to meet the demands of a changing world.

Angela Ordóñez Llancce
Delft, May 2024

Executive Summary

➢ Introduction

This research emphasizes the critical need for climate-resilient infrastructure (CRI) in the face of increasing urban population density and consequent environmental stresses (Short & Farmer, 2021), such as rising global temperatures and severe climate events like droughts and heavy rainfall as IPCC (2022) is forecasting. These stresses underscore the importance of developing infrastructure that can withstand climate variability and minimize CO2 emissions (Shakou et al, 2019). The role of CRI is vital as it not only enhances the robustness of local infrastructure against climate disruptions but also reduces the financial burdens of repairs and additional protective measures (OECD, 2018). Moreover, it is necessary alongside mitigation strategies to address both immediate and long-term climate challenges (Short & Farmer, 2021), which municipalities play a pivotal role in enhancing climate resilience.

Municipalities have a direct engagement with urban planning and policy implementation related to public transit, land use, and urban design (Eidelman et al., 2022). Furtheremore, their close connection with local communities places them in a strategic position to drive initiatives that improve resilience at a local level (Den Exter et al., 2015), thus mitigating economic losses and protecting against fatalities caused by climate events. An integrated infrastructure design approach (IIDA) is advocated to account for interdependencies among various urban systems (Grafius et al., 2020), promoting a collaborative and multifunctional approach (Hertogh et al., 2018a) that optimizes resource allocation (Araya & Vasquez, 2022) and fulfills broader sustainable development goals, making it crucial for effective climate adaptation in densely populated cities.

➢ Problem statement

The problem statement highlights the need for a shift from a siloed to an integrated design approach in urban infrastructure to address the interactions (French, 2014) and interdependencies between different infrastructure systems that are crucial for enhancing climate resilience. The current siloed approach fails to consider these interactions, potentially leading to unforeseen vulnerabilities (Carhart & Rosenberg, 2017) and negative cumulative impacts such as increased solid waste, atmospheric pollution, and higher consumption of resources (Enshassi et al., 2014) in cities like Rotterdam. A siloed approach undermines the efficacy of municipalities' climate adaptation and other mitigation strategies, such as mobility and energy transitions. Therefore, recognizing the absence of guidelines for implementing an effective Integrated Infrastructure Design Approach (IIDA), the research aims to develop a strategic roadmap to guide municipalities in this implementation, focusing on the practical implications and the roles of various actors involved in the process.

➢ Research objective and main question and sub-questions

The research aims to answer how an integrated infrastructure design approach can be implemented by municipalities to enhance climate resilience in local infrastructures. To dissect this main question, the research is structured around four sub-questions, each aimed at exploring different aspects. The first two sub-questions, addressed through literature reviews, focus on identifying the characteristics that define climate-resilient infrastructure and understanding how an integrated design approach is conceptualized and applied in local infrastructure development. The third sub-question investigates how municipalities, such as Rotterdam Municipality (RM), are applying these concepts in real-world projects through a document review. Finally, the fourth sub-question, through thematic analysis of interviews with internal municipal actors, aims to identify the factors influencing the effectiveness of these integrated approaches in enhancing climate resilience. The outcomes of these inquiries aim to provide a solid foundation for the main research question, linking theoretical insights with practical outcomes.

➢ Research Methodology

The research adopts a pragmatic paradigm, emphasizing practical applications and real-world relevance, aimed at enhancing the climate resilience of municipal infrastructures through an integrated design approach. This orientation informs the research design, focusing on actionable recommendations and effectiveness in real settings, and is divided into three sequential parts: literature review, case study, and roadmap development. The literature review addresses foundational concepts regarding climate-resilient infrastructures and integrated approaches, setting the stage for a focused research into how these concepts are applied in practice. The second part, the case study, examines RM implementation of IIDA through document reviews and interviews, providing a detailed perspective on local practices. From the interviews with municipal actors, a thematic analysis uncovered influencing factors. This detailed examination helps bridge theoretical insights with practical outcomes, informing a roadmap for broader application. The final part of the research involves developing a strategic roadmap, validated by experts, aimed at guiding municipalities in effectively implementing IIDA. This roadmap is intended to be adaptable, with insights potentially applicable to other Dutch municipalities and beyond, ensuring that the findings contribute significantly to both academic literature and practical municipal management.

➢ Final Strategic Roadmap

The final strategic roadmap consists in five steps, see Figure I.

Step 1: Organising a Multi-disciplinary Strategic Collaboration Team

The first step involves creating a multi-disciplinary team within the municipality to address various critical dimensions like human capacity, organizational culture, governance, and others since no single department can implement alone IIDA effectively. This team includes urban designers, the head manager of local infrastructure, process managers, financial managers, human resources and climate resilience policy advisors, and information managers. Each member is tasked with specific roles such as assessing internal and external actors, financial planning, and managing information.

Step 2: Identify Municipality's Critical Dimensions

In the second step, the team conducts surveys to identify and prioritize the critical dimensions, mentioned in the previous step, affecting the effectiveness of IIDA. The prioritisation will help in selecting the necessary assessments of the next step.

Step 3: Assessing the Needed Dimension Baseline

The third step aims to establish a baseline for the needed dimensions. This involves various assessments to understand the municipality and city's needs comprehensively, encompassing internal and external actors' assessments, current existence policies, infrastructure, financial capabilities, project development processes, and information management.

Step 4: Selecting Action Flows

Step four ensures the alignment of selected action flows with the previously identified needs and priorities, optimizing the impact of municipal efforts. Actions include external work agreements, financial negotiations, engaging citizens, developing internal collaboration policies, development of pilot projects policy and execution, institutionalizing best practices, and disseminating information and knowledge.

Step 5: Consolidating and Scaling-Up

The final step involves consolidating the previous actions flow to align integration in the three management levels. This step is crucial for planning projects in an integrated manner, facilitating the execution of integrated pilot projects and programs, ensuring that each component aligns with the municipality's overall strategic goals and infrastructure needs.

➢ Limitations

The research has certain limitations primarily due to its focused scope and specific context. The study, concentrating on a single city, may not offer broad generalizability across different urban areas due to varying climate impacts and infrastructure priorities. Additionally, the experts validating the study's roadmap are from Dutch municipalities, which may not represent challenges faced by municipalities outside the Netherlands, potentially necessitating further modifications to the roadmap. Lastly, the roadmap's development within the context of Rotterdam's organizational culture, which supports bottom-up initiatives due to its horizontal hierarchy, may limit its applicability in municipalities with a vertical hierarchy, where top-down decisions predominate.

➢ Conclusions

The research presents a strategic roadmap designed to help municipalities effectively implement an Integrated Infrastructure Design Approach (IIDA) to enhance Climate-Resilient Infrastructures (CRI). This roadmap was develop following a comprehensive literature review that spotlighted key characteristics of CRI and the implementation lenses of IIDA. The identified characteristics of CRI include adaptable and integrated design, sustainable and robust construction, flexibility within local infrastructure authorities, as well as heightened awareness and collaboration within municipalities. Furthermore, the IIDA implementation lenses identified include functional, transdisciplinary, synergistic, intervention scale, technological, time, and financial aspects. Practical examples from the Rotterdam Municipality, including projects like Water Plazas, Green-Blue Schoolyards, and the integration of heating networks with sewer renewal, illustrate the application of the IIDA lenses. These initiatives demonstrate how IIDA, along with strategic interventions at various scales, lead to effective outcomes in enhancing climate resilience.

Moreover, through thematic analysis, the study identified nineteen factors grouped into six dimensions that affect the effectiveness of municipalities in implementing IIDA. These dimensions include human capacity, organisational culture, governance, information and knowledge, project development process, and finance. Each dimension highlights critical areas such as the importance of cross-disciplinary collaboration, internal actors' soft skills and knowledge, the integration of environmental, social, and technical aspects in project development and innovation thorugh pilot projects. Therefore, the strategic roadmap emphasises the necessity of collaborative governance and the engagement of various actors to ensure comprehensive climate resilience. This involves not only internal actors within the municipalities but also local infrastructure authorities, citizens, and other external actors.

In conclusion, the research stresses the importance of developing municipal capabilities in various key areas to support the enhancement of climate-resilient infrastructure. These include fostering soft skills among municipal actors, enhancing support departments like information and technology to manage data effectively, ensuring easy access to updated internal information, and facilitating the integration and scaling of projects. These strategies aim to create a municipal environment conducive to innovative, resilient infrastructure development, thus enabling municipalities to better respond to the challenges posed by climate change.

➢ Recommendations

The recommendations for Rotterdam Municipality to scale up the implementation of IIDA focus on enhancing human capacity, governance, information management, and financial planning. Workshops are proposed to develop managerial skills and awareness about the role of management roles in climate resilience, alongside the introduction of a standardized policy for pilot projects. Enhancements to digital platforms are suggested to improve accessibility to information and thus facilitate better communication and decision-making within the municipality. Additionally, it is advised to collect and analyze financial data from pilot projects to more accurately forecast budgets for future integrated designs, thus improving the effectiveness of budget allocation.

For other municipalities, adopting the strategic roadmap developed in this research is encouraged to increase awareness and implementation of actions necessary for enhancing climate-resilient infrastructure. The roadmap provides a comprehensive framework that includes strategic actions suitable for various municipal contexts, highlighting the importance of collaboration among municipal actors, private companies, and academic institutions. Recommendations also stress the importance of engaging with local infrastructure entities and research institutions to share financial responsibilities and acquire critical data for planning and training purposes, especially for municipalities with limited resources.

Future research directions identified in the study include exploring integration within program management, to improve decision-making processes related to project scope and budget. There is a call for studies to align municipal budgeting processes with integrated design approaches, ensuring resources are adequately allocated to support climate-resilient infrastructure while balancing other essential public services. Further investigation is also suggested to understand the roles and impacts of external actors, such as local infrastructure authorities and private companies, in the integration process, as well as examining how these factors influence the success of projects before they go to tender.

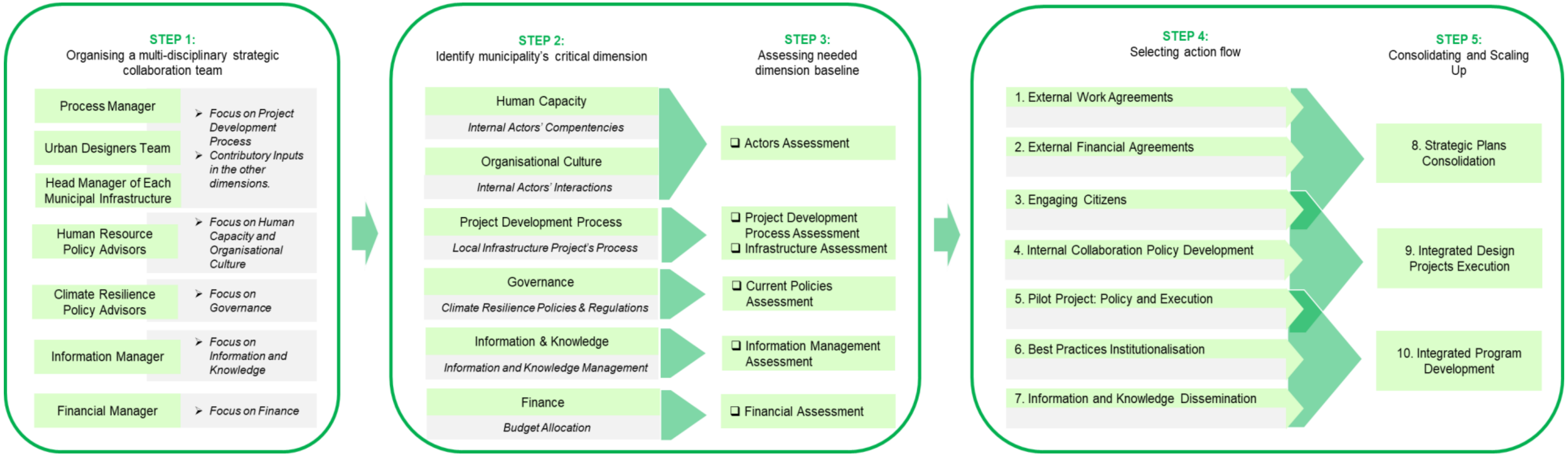


Figure I: Final Strategic Roadmap for Municipalities to Effective Implement an Integrated Infrastructure Design Approach to Enhance Climate-Resilient Infrastructures

Samenvatting

➢ Introductie

Dit onderzoek benadrukt de kritieke behoefte aan klimaatbestendige infrastructuur (KBI) in het licht van toenemende stedelijke bevolkingsdichtheid en de daaruit voortvloeiende milieuspanningen (Short & Farmer, 2021), zoals stijgende wereldtemperaturen en ernstige klimaatevenementen zoals droogtes en hevige regenval zoals voorspeld door het IPCC (2022). Deze spanningen onderstrepen het belang van het ontwikkelen van infrastructuur die klimaatvariaties kan weerstaan en CO2-uitstoot kan minimaliseren (Shakou et al., 2019). De rol van CRI is essentieel omdat het niet alleen de robuustheid van lokale infrastructuur tegen klimaatgerelateerde verstoringen verbetert, maar ook de financiële lasten van reparaties en extra beschermende maatregelen vermindert (OECD, 2018). Bovendien wordt het als noodzakelijk beschouwd naast mitigatiestrategieën om zowel onmiddellijke als langetermijn klimaatuitdagingen aan te pakken (Short & Farmer, 2021), waarbij gemeenten een cruciale rol spelen in het versterken van klimaatbestendigheid.

Gemeenten zijn direct betrokken bij stadsplanning en beleidsimplementatie gerelateerd aan openbaar vervoer, grondgebruik en stadsontwerp (Eidelman et al., 2022). Verder is hun nauwe verbinding met lokale gemeenschappen hen in een strategische positie om initiatieven te bevorderen die de veerkracht op lokaal niveau verbeteren (Den Exter et al., 2015), waardoor economische verliezen worden geminimaliseerd en bescherming tegen dodelijke slachtoffers door klimaatevenementen wordt geboden. Een integraal infrastructuurontwerpbenadering (IIOB) wordt bepleit om rekening te houden met de onderlinge afhankelijkheden tussen verschillende stedelijke systemen (Grafius et al., 2020), wat een collaboratieve en multifunctionele benadering bevordert (Hertogh et al., 2018a) die de toewijzing van middelen optimaliseert (Araya & Vasquez, 2022) en bredere duurzame ontwikkelingsdoelen vervult, essentieel voor effectieve klimaatadaptatie in dichtbevolkte steden.

➢ Probleemstelling

De probleemstelling benadrukt de noodzaak van een verschuiving van een geïsoleerde naar een geïntegreerde ontwerpbenadering in stedelijke infrastructuur om de interacties (French, 2014) en onderlinge afhankelijkheden tussen verschillende infrastructuursystemen aan te pakken die cruciaal zijn voor het versterken van klimaatbestendigheid. De huidige geïsoleerde benadering houdt geen rekening met deze interacties, wat kan leiden tot onvoorziene kwetsbaarheden (Carhart & Rosenberg, 2017) en negatieve cumulatieve effecten zoals toegenomen vast afval, atmosferische vervuiling en hoger verbruik van middelen (Enshassi et al., 2014) in steden zoals Rotterdam. Een geïsoleerde benadering ondermijnt de doeltreffendheid van klimaatadaptatie van gemeenten en andere mitigatiestrategieën, zoals mobiliteit en energietransities. Daarom wordt, gezien het ontbreken van richtlijnen voor het implementeren van een effectieve IIOB, het onderzoek gericht op het ontwikkelen van een strategische routekaart om gemeenten te begeleiden bij deze implementatie, met de nadruk op de praktische implicaties en de rollen van verschillende betrokken actoren.

➢ Onderzoeksdoel, hoofdvraag en deelvragen

Het onderzoek is gericht op het beantwoorden van de vraag hoe een geïntegreerde infrastructuurontwerpbenadering door gemeenten geïmplementeerd kan worden om de klimaatbestendigheid van lokale infrastructuren te verbeteren. Om deze hoofdvraag te ontleden, is het onderzoek gestructureerd rond vier deelvragen, elk gericht op het verkennen van verschillende aspecten. De eerste twee deelvragen, behandeld via literatuurstudies, richten zich op het identificeren van de kenmerken die klimaatbestendige infrastructuur definiëren en begrijpen hoe een geïntegreerde ontwerpbenadering wordt geconceptualiseerd en toegepast in lokale infrastructuurontwikkeling. De derde deelvraag onderzoekt hoe gemeenten, zoals de Gemeente Rotterdam (GR), deze concepten toepassen in echte projecten via documentenonderzoek. Ten slotte, de vierde deelvraag, door thematische analyse van interviews met interne gemeentelijke actoren, streeft naar het identificeren van de factoren die de effectiviteit van deze geïntegreerde benaderingen bij het versterken van klimaatbestendigheid beïnvloeden. De uitkomsten van deze onderzoeken beogen een solide basis te bieden voor de hoofdvraag, waarbij theoretische inzichten worden gekoppeld aan praktische uitkomsten.

➢ Onderzoeksmethodologie

Het onderzoek hanteert een pragmatisch paradigma, gericht op praktische toepassingen en relevantie in de echte wereld, gericht op het verbeteren van de klimaatbestendigheid van gemeentelijke infrastructuren door middel van een geïntegreerde ontwerpbenadering. Deze oriëntatie informeert het onderzoeksontwerp, gericht op actiegerichte aanbevelingen en effectiviteit in echte settings, en is verdeeld in drie opeenvolgende delen: literatuuronderzoek, casestudy en routekaartontwikkeling. Het literatuuronderzoek behandelt fundamentele concepten met betrekking tot klimaatbestendige infrastructuren en geïntegreerde benaderingen, en legt de basis voor een gericht onderzoek naar hoe deze concepten in de praktijk worden toegepast. Het tweede deel, de casestudie, onderzoekt de implementatie van IIOB door GR door middel van documentenonderzoek en interviews, en biedt een gedetailleerd perspectief op lokale praktijken. Uit de interviews met gemeentelijke actoren kwam een thematische analyse naar voren die beïnvloedende factoren blootlegt. Dit gedetailleerde onderzoek helpt theoretische inzichten te overbruggen met praktische uitkomsten, en informeert een routekaart voor bredere toepassing. Het laatste deel van het onderzoek omvat de ontwikkeling van een strategische routekaart, gevalideerd door experts, gericht op het begeleiden van gemeenten bij de effectieve implementatie van IIOB. Deze routekaart is bedoeld om aanpasbaar te zijn, met inzichten die mogelijk toepasbaar zijn op andere Nederlandse gemeenten en daarbuiten, en zorgt ervoor dat de bevindingen aanzienlijk bijdragen aan zowel de academische literatuur als het praktische gemeentebeheer.

➢ Definitieve Strategische Routekaart

De definitieve strategische routekaart bestaat uit vijf stappen, zie Figuur I.

Stap 1: Organiseren van een multidisciplinair strategisch samenwerkingsteam
De eerste stap omvat het creëren van een multidisciplinair team binnen de gemeente om verschillende kritieke dimensies aan te pakken zoals menselijke capaciteit, organisatiecultuur, governance en andere, aangezien geen enkele afdeling alleen IIOB effectief kan implementeren. Dit team bestaat uit stedenbouwkundigen, de hoofdmanager van lokale infrastructuur, procesmanagers, financiële managers, personeelszaken en beleidsadviseurs voor klimaatbestendigheid en informatiemanagers. Elk lid heeft specifieke taken zoals het beoordelen van interne en externe actoren, financiële planning en informatiebeheer.

Stap 2: Identificeren van kritieke dimensies van de gemeente
In de tweede stap voert het team enquêtes uit om de kritieke dimensies te identificeren en te prioriteren, zoals genoemd in de vorige stap, die de effectiviteit van IIOB beïnvloeden. De prioriteitstelling helpt bij het selecteren van de noodzakelijke beoordelingen voor de volgende stap.

Stap 3: Beoordelen van de benodigde basislijn van dimensies
De derde stap is gericht op het vaststellen van een basislijn voor de benodigde dimensies. Dit omvat verschillende beoordelingen om de behoeften van de gemeente en stad volledig te

begrijpen, inclusief beoordelingen van interne en externe actoren, bestaande beleidsmaatregelen, infrastructuur, financiële capaciteiten, projectontwikkelingsprocessen en informatiemanagement.

Stap 4: Selecteren van actiestromen

Stap vier zorgt voor de afstemming van geselecteerde actiestromen met de eerder geïdentificeerde behoeften en prioriteiten, om de impact van de gemeentelijke inspanningen te optimaliseren. Acties omvatten externe werkovereenkomsten, financiële onderhandelingen, betrokkenheid van burgers, ontwikkeling van intern samenwerkingsbeleid, ontwikkeling en uitvoering van pilotprojectbeleid, institutionaliseren van beste praktijken en verspreiding van informatie en kennis.

Stap 5: Consolideren en opschalen

De laatste stap omvat het consolideren van de voorgaande actiestromen om integratie in de drie managementniveaus af te stemmen. Deze stap is cruciaal voor het plannen van projecten op een geïntegreerde manier, het faciliteren van de uitvoering van geïntegreerde pilotprojecten en programma's, en zorgen dat elk onderdeel in lijn is met de algemene strategische doelen en infrastructuurbehoeften van de gemeente.

➢ Beperkingen

Het onderzoek kent bepaalde beperkingen, voornamelijk vanwege de gefocuste reikwijdte en specifieke context. De studie, die zich concentreert op één enkele stad, biedt mogelijk geen brede toepasbaarheid in verschillende stedelijke gebieden vanwege variërende klimaateffecten en prioriteiten in infrastructuur. Bovendien komen de experts die de routekaart van de studie valideren uit Nederlandse gemeenten, wat mogelijk niet de uitdagingen vertegenwoordigt waarmee gemeenten buiten Nederland worden geconfronteerd, wat verdere aanpassingen aan de routekaart noodzakelijk kan maken. Tot slot kan de ontwikkeling van de routekaart binnen de context van de organisatiecultuur van Rotterdam, die bottom-up initiatieven ondersteunt vanwege haar horizontale hiërarchie, de toepasbaarheid beperken in gemeenten met een verticale hiërarchie, waar beslissingen van bovenaf overheersen.

➢ Conclusies

Het onderzoek presenteert een strategische routekaart ontworpen om gemeenten effectief te helpen bij het implementeren van IIOB ter verbetering van Klimaatbestendige Infrastructuur (KBI). Deze routekaart is ontwikkeld na een uitgebreid literatuuroverzicht dat de sleutelkenmerken van CRI en de implementatielenzen van IIOB belichtte. De geïdentificeerde kenmerken van KBI omvatten aanpasbaar en geïntegreerd ontwerp, duurzame en robuuste constructie, flexibiliteit binnen lokale infrastructuurautoriteiten, evenals verhoogd bewustzijn en samenwerking binnen gemeenten. Verder omvatten de geïdentificeerde implementatielenzen van IIOB functionele, transdisciplinaire, synergetische, interventieschaal, technologische, tijds- en financiële aspecten. Praktijkvoorbeelden uit de gemeente Rotterdam, waaronder projecten zoals Waterpleinen, Groen-Blauwe Schoolpleinen, en de integratie van verwarmingsnetwerken met rioolvernieuwing, illustreren de toepassing van de IIOB -lenzen. Deze initiatieven tonen aan hoe IIOB, samen met strategische interventies op verschillende schalen, leidt tot effectieve resultaten in het versterken van klimaatbestendigheid.

Bovendien identificeerde de studie door middel van thematische analyse negentien factoren, gegroepeerd in zes dimensies, die de effectiviteit van gemeenten bij het implementeren van IIOB beïnvloeden. Deze dimensies omvatten menselijke capaciteit, organisatiecultuur, bestuur, informatie en kennis, projectontwikkelingsproces en financiën. Elke dimensie benadrukt kritieke gebieden zoals het belang van interdisciplinaire samenwerking, zachte vaardigheden en kennis van interne actoren, de integratie van milieu-, sociale en technische aspecten in projectontwikkeling en innovatie door middel van proefprojecten. Daarom benadrukt de strategische routekaart de noodzaak van collaboratief bestuur en de betrokkenheid van verschillende actoren om een omvattende klimaatbestendigheid te waarborgen. Dit betreft niet alleen interne actoren binnen de gemeenten, maar ook lokale infrastructuurautoriteiten, burgers en andere externe actoren.

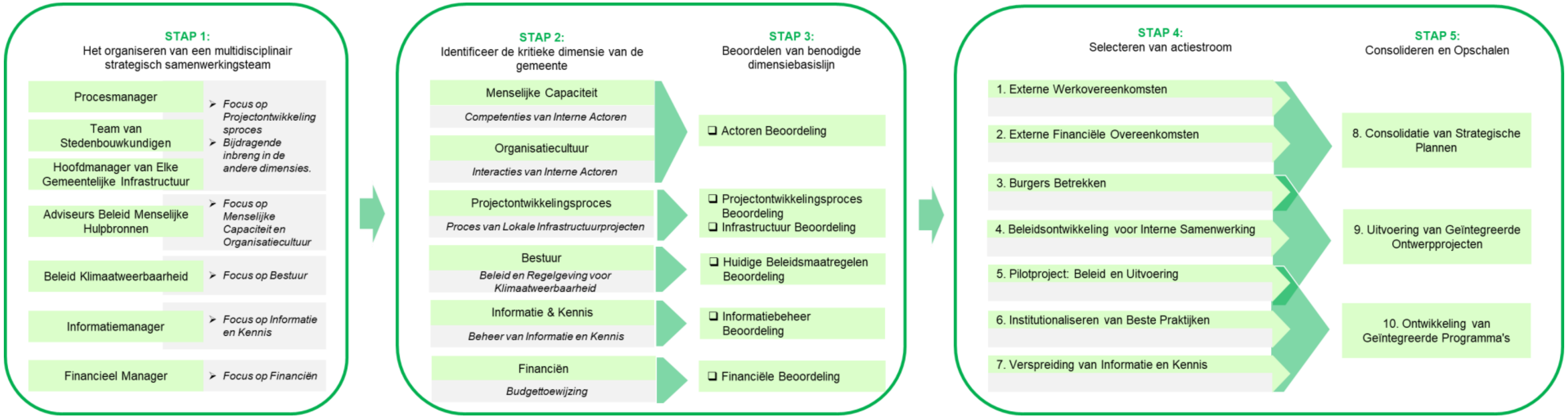
Tot slot benadrukt het onderzoek het belang van het ontwikkelen van gemeentelijke capaciteiten op verschillende sleutelgebieden om de verbetering van klimaatbestendige infrastructuur te ondersteunen. Deze omvatten het bevorderen van zachte vaardigheden onder gemeentelijke actoren, het verbeteren van ondersteuningsafdelingen zoals informatie en technologie om gegevens effectief te beheren, het garanderen van gemakkelijke toegang tot bijgewerkte interne informatie en het faciliteren van de integratie en opschaling van projecten. Deze strategieën zijn gericht op het creëren van een gemeentelijke omgeving die bevorderlijk is voor innovatieve, veerkrachtige infrastructuurontwikkeling, waardoor gemeenten beter kunnen reageren op de uitdagingen die de klimaatverandering met zich meebrengt.

➢ Aanbevelingen

De aanbevelingen voor de GR om de implementatie van IIOB op te schalen, zijn gericht op het verbeteren van menselijke capaciteit, bestuur, informatiebeheer en financiële planning. Er worden workshops voorgesteld om managementvaardigheden en bewustzijn over de rol van managementfuncties in klimaatbestendigheid te ontwikkelen, naast de introductie van een gestandaardiseerd beleid voor proefprojecten. Verbeteringen aan digitale platforms worden gesuggereerd om de toegankelijkheid van informatie te verbeteren en zo betere communicatie en besluitvorming binnen de gemeente te vergemakkelijken. Daarnaast wordt geadviseerd om financiële gegevens van proefprojecten te verzamelen en te analyseren om toekomstige geïntegreerde ontwerpbudgetten nauwkeuriger te kunnen voorspellen, waardoor de effectiviteit van budgettoewijzing wordt verbeterd.

Voor andere gemeenten wordt aangemoedigd de in dit onderzoek ontwikkelde strategische routekaart over te nemen om het bewustzijn en de uitvoering van acties die nodig zijn voor het verbeteren van klimaatbestendige infrastructuur te vergroten. De routekaart biedt een uitgebreid raamwerk dat strategische acties bevat die geschikt zijn voor verschillende gemeentelijke contexten, waarbij het belang van samenwerking tussen gemeentelijke actoren, private bedrijven en academische instellingen wordt benadrukt. Aanbevelingen benadrukken ook het belang van samenwerking met lokale infrastructuurentiteiten en onderzoeksinstellingen om financiële verantwoordelijkheden te delen en cruciale gegevens te verwerven voor plannings- en trainingsdoeleinden, vooral voor gemeenten met beperkte middelen.

Toekomstige onderzoeksrichtingen die in de studie zijn geïdentificeerd, omvatten het verkennen van integratie binnen programmabeheer, om besluitvormingsprocessen gerelateerd aan projectomvang en budget te verbeteren. Er is een oproep voor studies om gemeentelijke budgetteringsprocessen af te stemmen op geïntegreerde ontwerpbenaderingen, waarbij ervoor wordt gezorgd dat middelen adequaat worden toegewezen ter ondersteuning van klimaatbestendige infrastructuur en tegelijkertijd andere essentiële openbare diensten in evenwicht worden gehouden. Verder onderzoek wordt ook voorgesteld om de rollen en impact van externe actoren, zoals lokale infrastructuurautoriteiten en private bedrijven, in het integratieproces te begrijpen, evenals het onderzoeken hoe deze factoren de succes van projecten beïnvloeden voordat ze aanbesteed worden.



Figuur I: Definitieve Strategische Routekaart voor Gemeenten voor de Effectieve Implementatie van een Geïntegreerde Infrastructuurontwerpbenadering om Klimaatbestendige Infrastructuren te Versterken

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List of Acronyms

CRI Climate-Resilient Infrastuctures

IIDA Integrated Infrastructure Design Approach

RM Rotterdam Municipality

MSP Municipal Sewerage Plan 2021-2025

EV Expert Validation

Introduction

Chapter 1: Introduction

This chapter presents the research topic of obtaining a master's degree in Construction Management and Engineering. Section 1.1 explains the background that frames this study. This section highlights the importance of climate-resilient infrastructure in facing the effects of climate variations due to climate change, the role of municipalities, and why an integrated infrastructure design approach can be used to enhance climate-resilient infrastructure. Section 1.2 describes the problem statement and the reasoning behind selecting the research topic. Section 1.3 explains the knowledge gap this research aims to reduce academically and practically. Section 1.4 describes the research objective, question, and sub-questions this study seeks to answer to reduce the knowledge gap. Section 1.5 frames the scope of the research, and the selected research method is explained and described in section 1.6.

1.1. Background

This section explains the background context that frames this research. First, it introduces the need to enhance climate resilience in local infrastructures. Next, it describes municipalities' critical role in making this happen compared to other governance levels. Lastly, it presents an integrated infrastructure design approach for municipalities to enhance climate-resilient infrastructure.

1.1.1 The Importance of Climate-Resilient Infrastructure

The exponential increase in urban population density translates into rising energy demand, leading to greenhouse gas emissions, thus exacerbating environmental alterations and magnifying the effects of climate change (Short & Farmer, 2021). The main alteration is the global temperature increase, which the Intergovernmental Panel on Climate Change (IPCC, 2022) forecasts could reach a critical threshold of 1.5°C between 2030 and 2052. This temperature change will trigger considerable climate risks of a magnitude, such as heavy precipitations and drought in different regions (IPCC, 2022), negatively impacting urban infrastructures globally. Therefore, 193 countries and the European Union signed the Paris Agreement in 2015, aiming to limit global warming and reduce greenhouse gas emissions long-term (United Nations, n.d.). However, adaptation strategies are also needed to face climate change because, while mitigation strategies have a long-term focus, adaptation strategies focus on the short- and medium-term (Short & Farmer, 2021). Therefore, according to Shakou et al. (2019), urban infrastructure needs to be climate-resilient (CRI) since this infrastructure is designed to face the effects of climate variations. At the same time, they are designed and built in a way that minimises CO2. Both strategies will be implemented to enhance this type of infrastructure. Furthermore, CRI reduces the need for users to invest in backup measures and reduces the costs of repairs after a disruptive event occurs (OECD, 2018).

1.1.2 Municipalities' Role in the Need of Climate-Resilient Infrastructure

To enhance climate resilience, the role of municipalities is becoming increasingly pivotal. This recognition is attributed to their direct involvement in formulating and implementing policies about public transit, urban design, and land-use planning (Eidelman et al., 2022). These policy arenas afford municipalities significant leverage in mitigating climate change impacts within urban environments. Through strategic urban planning and design, municipalities are positioned to enact measures that enhance the resilience of urban open spaces to the effects of climate variations.

Further underpinning the critical role of municipalities in climate resilience is their proximal relationship with citizens. Compared to higher levels of governance, municipalities wield a more immediate influence on the population, facilitating a direct conduit for disseminating and implementing climate resilience initiatives (Den Exter et al., 2015). This direct line of communication and influence is instrumental in mobilising community engagement and participation in resilience-building activities. For that reason, municipalities urgently need to enhance climate-resilient infrastructure (CRI) to face the escalating impacts of climate change, characterised by fatalities and substantial economic losses. For example, the European Environment Agency (2023) reported that member states of the European Union sustained economic losses to the tune of €111.7 billion over the years 2021 and 2022 alone, underscoring the economic imperative of enhancing climate resilience at the municipal level.

While cross-government collaboration is indispensable in fostering a holistic approach to climate resilience (Gregory & Mehrotra, 2024), municipalities remain distinctly significant. Their responsibilities in planning, designing, constructing, and maintaining local infrastructure place them at the forefront of physical adaptation to climate change. This dual role of policy formulation and infrastructure development positions municipalities as critical actors in the broader climate resilience framework, anchoring climate resilience at the local level.

1.1.3 Integrated Design Approach as a Means for Municipalities

According to French (2014), infrastructures are managed with a siloed approach, which means that infrastructures are planned, designed and maintained only by actors in their sector. For example, road and sewer departments will plan and design their infrastructure separately. However, Shen (2019) explains how this approach is becoming less effective in achieving CRI since urban infrastructures are physically clustered and functionally integrated. Thus, while each infrastructure system is linked, actions in one area can have ripple effects in others, making integrated planning and execution crucial (Araya & Vasquez, 2022).

On the other hand, an integrated infrastructure design approach (IIDA) can anticipate these interdependencies and turn them into an opportunity to improve the system's overall resilience, as Grafius et al. (2020) mentioned. This leads to a minimisation of service interruptions and a reduction in the scope and cost of rehabilitation works. Efficient resource allocation is another crucial benefit which closely aligns with sustainable urban development goals (Jayasinghe et al., 2023). Moreover, implementing this approach results in multifunctional infrastructures, benefiting different stakeholders. As Hertogh et al. (2018a) mentioned, this type of infrastructure satisfies a more comprehensive number of stakeholders, and the cost is divided among several parties. The authors also consider that this type of infrastructure is suitable when space and resources are scarce and there is a need to improve the spatial quality. Thus, IIDA presents compelling benefits for municipalities since it aligns with the current need to create an adaptable, robust and sustainable urban environment, especially in dense cities.

1.2. Problem Statement

The theoretical findings suggest a necessary shift from a siloed approach to an integrated one in urban infrastructure projects since the first one ignores the interactions between infrastructure systems (French, 2014). Those interactions, also known as interdependencies, play an essential role in enhancing climate resilience in infrastructure since they bring more visibility to unforeseen vulnerabilities (Carhart & Rosenberg, 2017). However, besides climate adaptation projects, municipalities like Rotterdam Municipality (RM) also go through different transitions, such as mobility and energy, due to their mitigation strategies. To anchor these transitions in practice will demand multiple interventions in the urban sphere if these interventions are done through a siloed approach, see Figure 1.

Figure 1: Representation of Siloed Approach Projects

Different actors within RM have recognised the rise of these interventions and the potential generation of cumulative impacts in the city, such as the generation of solid waste, atmospheric pollution, and an increase in the consumption of energy, materials and water (Enshassi et al., 2014), that will negatively impact the economy and the citizens. From initial discussions, it was concluded that there was an absence of guidelines for municipalities to implement IIDA effectively. Therefore, this study seeks to develop a strategic roadmap to contribute to the theoretical understanding of integrated infrastructure development to enhance climate-resilient infrastructures. By doing so, the research addresses the practical aspect of applying IIDA within a municipal context, particularly emphasising the actors involved and their impact on the process.

1.3. Research Gap

In the past decade, the Integrated Infrastructure Design Approach (IIDA) has increased attention due to the growing complexity and uncertainty in infrastructure projects (IID, 2013). From the literature review was found that this shift from a siloed to an integrated approach was initially advocated by French (2014) and Verheijen (2015). They emphasized the need for a change in design processes. Building on this foundation, Vooredent (2017), Zeiler (2019), and Keusters et al. (2021) further explored the integrated design process, identifying problem definition as a critical phase. Voorendet (2017) and Visser (2020) expanded the discussion by examining various interpretations (or lenses) of integration within design contexts, while Brand and Hertogh (2021) investigated strategic approaches to integration in the design process. Most recently, Warbroek et al. (2022) highlighted institutional barriers such as sectoral budgets and divergent organizational goals, which impede operational integration.

Despite these advancements, a significant gap remains in the application of these theories from municipal perspective and in the context of climate resilience. Although Shakou et al. (2019) proposed a framework to enhance climate-resilient infrastructure, their work largely focuses on theoretical and macro-level strategies without delving into the practical implications for municipal operations. This oversight in literature reveals a lack of further exploration into how municipalities can specifically use an integrated infrastructure design approach to enhance climate resilience effectively. Thus, this study aims to explore the implementation of an integrated infrastructure design approach by municipalities as a practical means to enhance climate resilience.

In this study, the Rotterdam Municipality (RM) serves as a case study through which the implementation of IIDA is examined. The research assesses and analyzes climate resilience policies, actions, and projects executed by RM, focusing on their integration with IIDA. Additionally, it explores the influential factors that RM encounters while using this approach. The insights derived from this research are essential, providing a foundation for all actors involved directly and indirectly in local infrastructure projects to assess, reflect upon, and realign their standard practices with the principles of IIDA. Ultimately, the study underscores the potential benefits of IIDA for local infrastructure authorities and private operators, highlighting their role in enhancing climate resilience within urban infrastructures.

1.4. Research Objective

The research aims to analyse the implementation of an integrated infrastructure design approach in municipalities to enhance climate resilience in local infrastructures. The thesis results in a framework to effectively implement this approach, thus contributing to the literature on urban infrastructure project management and organisation adaptation. Consequently, the research focuses on exploring the notion of climate-resilient infrastructure from a municipal perspective.

To achieve the objective of the research, the main research question (RQ) is:

"How can municipalities enhance climate-resilient infrastructures by effectively implementing an integrated design approach?"

The research question is divided into four sub-questions (SQ) to facilitate a comprehensive analysis.

SQ1: What are the characteristics of climate-resilient infrastructure?

This sub-question was formulated to be answered through a literature review and aims to acknowledge the main characteristics that make an urban infrastructure climate-resilient. To answer this sub-question, its evolution, definition, and the key components of climate resilience in urban infrastructure were explored, as well as the changes in urban infrastructures' life cycles due to the effects of climate variations. Moreover, it explores the literature on how climate resilience has been anchored to the municipal level and the challenges to developing climate-resilient infrastructures.

SQ2: How is an integrated design approach applied to local infrastructure?

This sub-question is formulated to be explored through a comprehensive literature review, aiming to examine how an integrated design approach is applied to the development of local infrastructure projects. The review will detail the conceptualisation of integrated infrastructure design approach, and discuss the implementation of this approach through various lenses, analyzing how it is adapted to local infrastructure contexts.

Moreover, the practical component of the research, from the case study, provided empirical feedback. This feedback refined the structure of the implementation lenses from a municipal perspective, ensuring that the theoretical insights from the literature review are grounded in real-world application. This is further explained in section 1.6.

SQ3: How are municipalities implementing an integrated infrastructure design approach to enhance climate-resilient infrastructure?

This sub-question was formulated to be answered through a document review to examine RM's actions and projects to enhance climate-resilient infrastructure through an integrated design approach. This analysis focuses on qualitative aspects of enhancement in local infrastructure, taking Water Plazas, Green-Blue Schoolyards and the Sewer System Renewal as examples. It explores how these projects have contributed to enhancing climate resilience in the infrastructure involved while also exploring the application of IIDA. Therefore, this answer aims to bridge theoretical insights from SQ1 and SQ2 with practical outcomes.

SQ4: What factors influence municipalities' effectiveness in using an integrated design approach to enhance climate-resilient infrastructures?

This sub-question was formulated to be answered through a thematic analysis based on interviewing internal actors of the municipality of the case study. These interviews will explore the influential factors that impact a municipality's effectiveness when using an integrated design approach to enhance climate resilience. The outcome of this analysis will provide a holistic perspective for municipalities to identify critical areas that they should pay attention to in order to implement this approach effectively in their organisation.

In conclusion, as SQ1 and SQ2 are answered from the literature review, these answers are used as a foundation to give context to answers SQ3, SQ4 and RQ. Figure 2 shows the framework of this research.

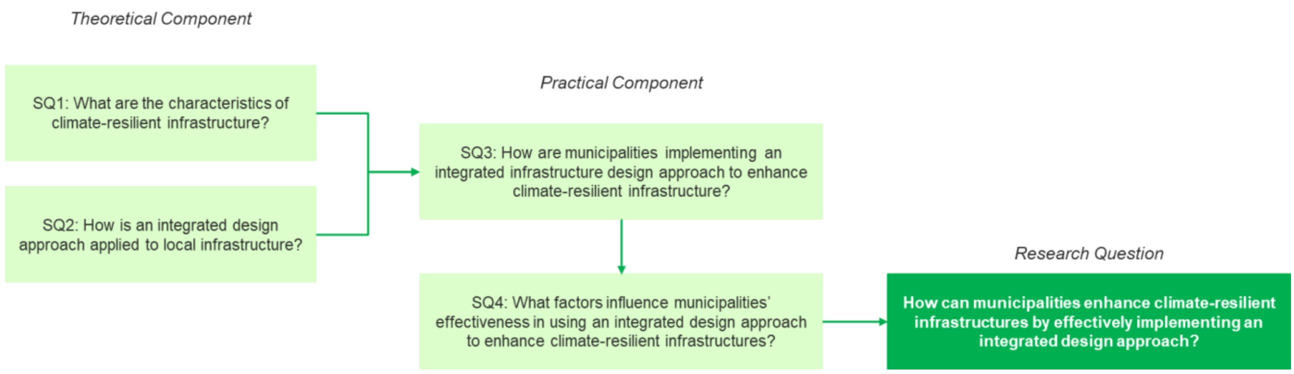

Figure 2: Research Framework

1.5. Scope

This research focuses on the Netherlands, a nation characterised by its predominant geographic location below sea level, which puts them in a risk situation due to probabilities of growth in flowing (Climate Adaptation Services, n.d). Furthermore, the country has been experiencing changes in its climate as the increase in extreme precipitation, more extensive periods of drought, and warmer summers increase the probability of heatwaves (Climate Adaptation Services, n.d). Moreover, Dutch cities' urban challenges are amplified by the intersection of various systemic transitions:

- Transition towards Circularity: Under the Circular Construction Economy Transition Agenda 2018, the Dutch government has proposed an ambitious goal: a 50% reduction in CO_2 emissions by 2030 and the total elimination of such emissions in the construction sector by 2050 (Consumer Goods Transition Team, 2018).

- Energy Transition: The Dutch government's efforts to incorporate more extensive renewable energy sources, such as geothermal energy, require a new heating network infrastructure. This process increases the number of projects under municipal jurisdiction and requires efficient use of underground space, an already scarce resource in several cities, such as Amsterdam (City of Amsterdam, 2020).

- Renewal of Existing Infrastructure: The country's infrastructures are facing the functional end of its technical and economic lifecycle (Hertogh et al., 2018b), which entails a growing need for replacements and renewal projects at the urban level.

On the other hand, although transdisciplinarity and intersectoral collaboration are essential to achieve climate resilience in cities, municipalities remain decisive entities for citizens to ensure climate-resilient infrastructures. Likewise, the research conducted by Patnaik et al. (2022) highlights problems arising from internal organisational structure's interactions between organisations and private companies. Thus, the research focuses on the predominant role that municipal governments play in integrating local infrastructure to enhance climate resilience. With special consideration of those primary infrastructures such as sewage systems, open public spaces (greenery and street roads), and heating networks, their management is usually the municipalities' direct responsibility in the conception and execution stages. This research does not consider bridges, tunnels, and highways because of special maintenance requirements.

1.6. Research Design and Method

The research paradigm adopted for this study is pragmatism, which adheres to a philosophical worldview emphasising the practical implications and real-world applications of research findings (Morgan, 2014). This pragmatic orientation profoundly shapes the formulation and execution of the research design plan, ensuring that the methodologies are directly aligned with the practical needs of the field. The pragmatic approach is precious as it directly addresses real-world challenges and produces actionable recommendations that can be implemented in natural settings (Creswell, 2009). Therefore, sub-questions 3 and 4 are formulated with practical orientations to explore current effective practices in implementing an integrated design approach and to understand the factors influencing their outcomes, both positively and negatively.

Moreover, pragmatism supports a reflective and iterative research process (Morgan, 2014), which is crucial for this study due to its exploratory nature and the goal of profoundly understanding municipal perspectives on climate-resilient infrastructure. Figure 3 provides a visual representation of the research process, which is divided into three parts: literature review, case study and roadmap development. The research process integrates theoretical insights with practical applications facilitated through continuous expert validation (EV) to develop the final roadmap.

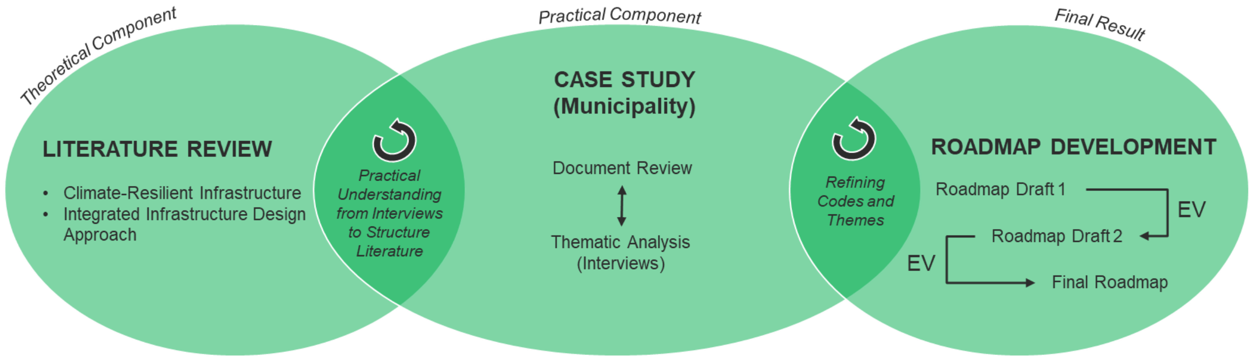

Figure 3: Research Process

As Figure 3 illustrates, each part provides insight into the other. The case study, more specifically the interviews, helped to structure the literature review section. This ensures that the findings follow the municipal perspective. On the other hand, as the roadmap was developed, it was noticed that some codes and themes needed to be refined to improve the presentation of the findings to the readers.

1.6.1 Part I: Literature Review

This part is organised in two chapters in the following order: Climate-Resilient Infrastructures (CRI), Chapter 2, and Integrated Infrastructure Design Approach (IIDA), Chapter 3. This structure is deliberately designed to prioritise a foundational understanding of the environmental context before integrating this knowledge into the infrastructure design, as suggested by Keusters et al. (2021). Thus, the literature review is framed first to establish a solid grounding in climate resilience within local infrastructures, which serves as the essential foundation for the entire framework. This approach is illustrated in Figure 4, where CRI, detailed in Chapter 2, forms the base layer. On the other hand, the downward arrows emphasizes that the theories developed in Chapter 3 do not stand in isolation but are directly anchored into the reality of municipal needs and rooted in fundamental environmental understandings.

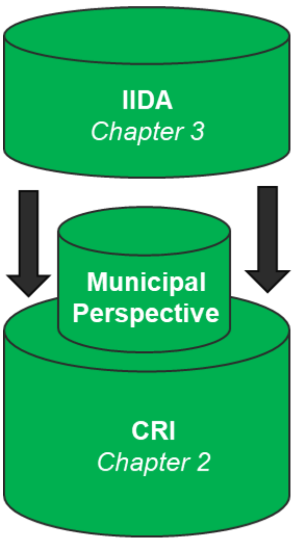

Figure 4: Literature Review Framework

This part of the research aims to answer the SQ1 and SQ2 through a comprehensive literature review. This was conducted through Google Scholar, TU Delft Worldcat Library, and the TU Delft repository searches. For this, keywords in different languages (English and Dutch) were used to ensure extensive and relevant coverage of the topi. Some selected words were: 'urban infrastructure', 'urban resilience', 'climate resilience', 'climate-resilient infrastructure', 'project integration', 'integrated infrastructure design' and 'integrated design'. Furthermore, other words were added to deepen the research in the specific sections, such as 'climate resilience + municipal policies'. In the case of Dutch, words such as *'integral ontwerp+ gebiedsaanpak'* (integrated design + area approach) were used.

1.6.2 Part II: Case Study – Rotterdam Municipality

This part is organised in two chapters in the following order: Document Review, Chapter 4, and Interviews, Chapter 5. This part of the research aims to answer the SQ3 and SQ4 through a case study. Choosing a case study as a field research method allows for collecting various sources, such as direct observation, interviews, and documents (Fidel, 1984). Due to the importance of a holistic perspective to study climate-resilient infrastructure and an integrated design approach, the research focused only on one municipality. Moreover, focusing on one municipality will provide a detailed overview of Dutch municipal practices to inform and guide similar urban practices in different international contexts, recognising the particularities and limitations inherent to the extrapolation of the results.

The selection of the municipality depended not only on their interests in climate resilience but also on their experience using IIDA and their urgency to implement it effectively. Under this criteria, Rotterdam has been undertaking climate change adaptation actions since 2008, guided by a strategic vision and water management plans (Rotterdam Municipality, 2019a). It has been developing pilot projects like Water Plazas and Green-Blue Schoolyard. The interest of Rotterdam Municipality (RM) in this topic allowed us to do this research as a graduation project, facilitating access to data and getting in contact with its internal actors.

Rotterdam Municipality is responsible for the Netherlands' second-largest city and the largest port in Europe. The city was destroyed at the beginning of WWII but was rebuilt and horizontally expanded from this historical event. However, most of their local infrastructures are at the end of their functional and technical capacity, raising different infrastructure projects such as renewing the sewerage system. On the other hand, the city is going through an energy transition, such as the shift from gas to sustainable sources and the need to implement climate adaptation strategies. Therefore, RM must implement IIDA effectively to extend the use of this approach across the municipality.

Document Review

The document review provides context about RM's practical implementation. The reviewed documents are collected through RM's organisation levels to find how climate resilience is currently anchored through its organisation to develop urban infrastructure project design and how they have been using IIDA. Table 1 shows the list of documents reviewed by RM based on their type. All internal documents open to the public are referred to as public, while the ones are not as private. Due to confidentiality, all private documents have been anonymised and referenced through assigned codes. The letters RM assigned these codes, referring to Rotterdam Municipality and a number.

Table 1: Overview of the Reviewed Documents from Rotterdam Municipality

No.	Type of Documents	Availability	Document Name/ Anonymised Name
1	Strategies	Public	1. Rotterdam Weerwoord 2. Vision Public Space 2019-2020 Rotterdam 3. Rotterdam Adaptation Strategy 4. The Rotterdam Heat Transition Vision 5. Rotterdams "Values Wheel"
2	Organisational charts and work procedure	Public and Private	1. Municipality's Organisational Structure (RM1) 2. Tasks and actions of RM's programs 3. Explanation of work procedure at project level (RM2) 4. Municipal Sewerage Plan 2021-2025
3	Pilot/ Executed Projects Reports	Private	1. Internal document on Blue-Green Schoolyard Project (RM3) 2. Internal document of Water Plaza Project (RM4)

Thematic Analysis - Interviews

Interviews provide a deep understanding of the challenges, barriers, and enablers faced by different strategic, program, and project internal actors while using IIDA. The aim is to examine the influential factors that RM face from a holistic view. In this manner, practical experience can be translated into academic knowledge to help other municipalities implement IIDA in their organisations. A thematic analysis was chosen to analyse the data collected since it facilitates the identification of key themes, providing a comprehensive view of the issues (Lochmiller, 2021). Further explanation of the interview procedure, data collection and analysis can be found in Chapter 5.

1.6.3 Part III: Roadmap Development

This part is organised in three chapters: Roadmap Development and Expert Validation, Chapter 6; Discussion and Limitatiation, Chapter 7; and Conclusion and Recommendations, Chapter 8. This part aims to answer the research question and validate the final results through experts on climate resilience and integrated design. Some experts were related to the case study, and others were from other Dutch municipalities to ensure the roadmap's flexibility outside Rotterdam Municipality. Further explanation of the roadmap development and its validation can be found in Chapter 6.

1.6.4 Thesis Structure

The structure of this thesis is designed to address the established subquestions sequentially, thus building a solid foundation to answer the central question of this research, see Figure 5.

Chapter 1 lays the foundations of the research, articulating the problem and breaking down the research method adopted in this study to answer the research question.

Chapters 2 and 3 explain the theoretical pillars supporting this study: climate resilience in local infrastructures and an integrated design approach. These two pillars are connected under the municipal perspective. These chapters provide the foundation for the interview, as per the interview protocol.

Chapter 4 provides a detailed description of the document review to help readers understand RM's organisational dynamic and work procedure regarding IIDA. Chapter 5 focuses on analysing the data collected from the interviews.

Chapter 6 is dedicated to developing and validating a practical roadmap to guide municipalities in implementing an integrated infrastructure design approach to enhance climate-resilient infrastructure. This roadmap will be helpful for municipalities beginning and seeking to expand the implementation of these practices across their organisation. Subsequently, Chapter 7 includes a discussion of the research's results and its limitations. Lastly, Chapter 8 presents the research's conclusions and recommendations for Rotterdam Municipality and general municipalities. This final chapter also seeks to open future research paths.

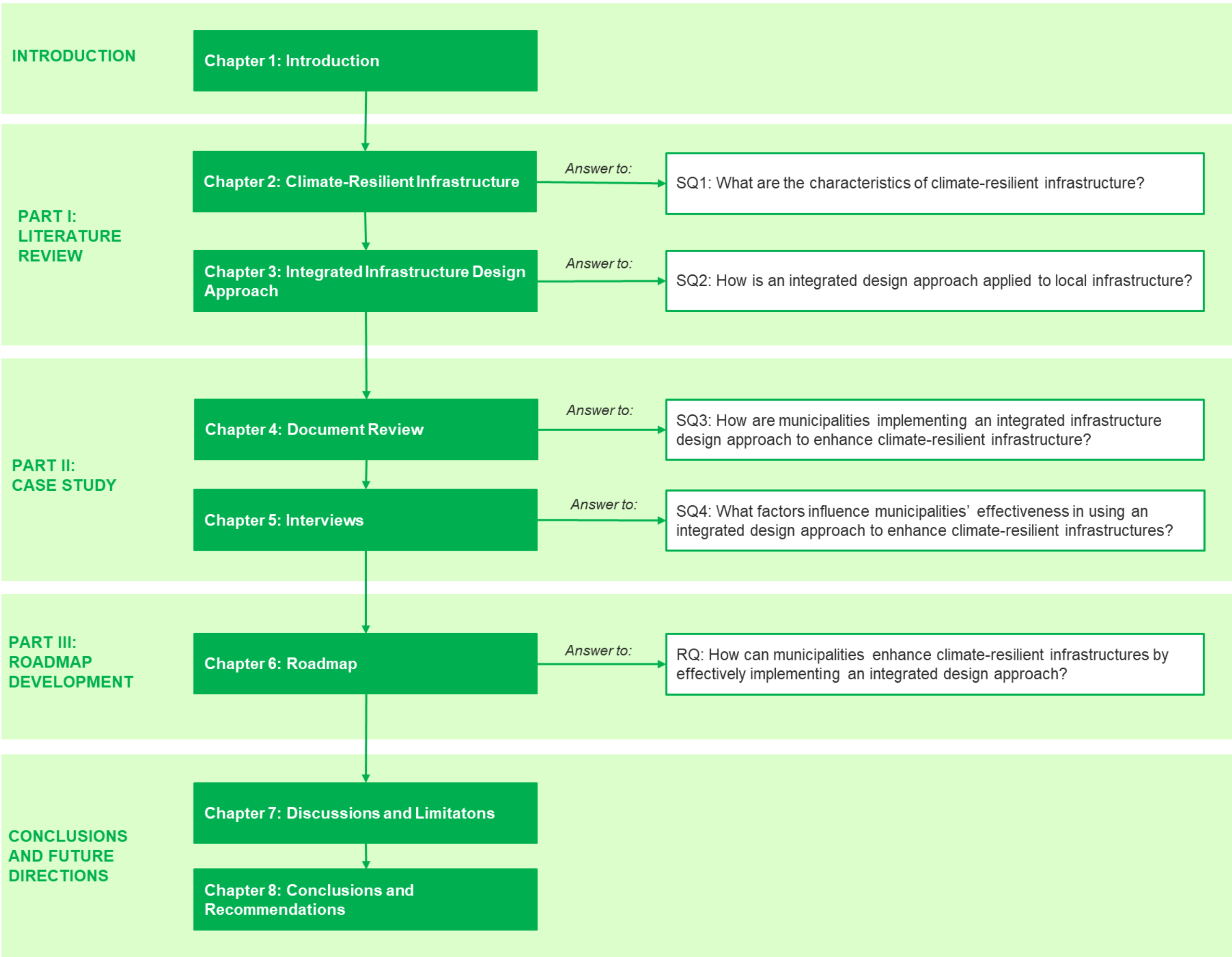

Figure 5: Thesis Structure

PART I
Literature Review

This first part aims to give a theoretical foundation to the case study by addressing the two main concepts of the research: climate-resilient infrastructures (CRI) in Chapter 2 and integrated infrastructure design approach (IIDA) in Chapter 3. Both chapters are explored and described from the municipal perspective.

Chapter 2: Climate-Resilient Infrastructures

The 'city' manifests as a dynamic and multifaceted system within the urban setting, a conglomerate of physical, sociocultural, environmental, economic and institutional subsystems that coexist and co-evolve within the urban space (Abdrabo & Hassaan, 2015). In this complex urban framework, infrastructure emerges as a crucial component since networks such as roads and sewer system have been constructed to make the terrirtory accessible and usable (Meyer et al., 2020). Roads are use to connect different locations while the sewer system keep areas flood-free. Furthermore, Desouza and Flanery (2013) and Chester et al. (2019) agree that urban infrastructure plays a role in responding to climate change, acting as a first line of defence and protection.

This section addresses the research sub-question *'SQ1: What are the characteristics of climate-resilient infrastructure?'* and is structured into six sections. It begins with section 2.1, which provides an overview of resilience's evolution in the infrastructure context and concludes with the definition of climate-resilient infrastructure. Section 2.2 explains each phase of the climate resilience cycle, while section 2.3 describes how it is the life cycle of climate-resilient infrastructures. Then, section 2.4 describes how climate resilience is anchored from the national to municipal level, and section 2.5 explains the challenges for municipalities to enhance climate resilience. Finally, section 2.6 concludes this chapter by answering the sub-question.

2.1. Resilience Evolution in Infrastructures

Initially conceptualised regarding the physical attributes of infrastructure, resilience has progressively transformed into a more comprehensive and dynamic approach (Rehak et al., 2018; Shen, 2019). Historically, specific vulnerabilities have been sought to be mitigated within established risk thresholds, adopting what could be described as a defensive posture or a 'fail-safe approach'. This traditional approach, founded on risk management principles, prioritised physical protection and structural strength (Coaffee & Clarke, 2017; Chester et al., 2019). However, the emergence of climate change, with its inherent uncertainties regarding the frequency and intensity of extreme events, has highlighted the limitations of such an approach. The assumption of stability and predictability is no longer sustainable and feasible, revealing the need for infrastructures that are not only robust but also adaptable and flexible (Miller et al., 2018). Consequently, the narrative has evolved towards a design that allows infrastructure to fail and organisations to be prepared to manage the consequences of it, which Miller et al. (2018) identify as a 'safe-to-fail approach'.

Hallegatte et al. (2019) expand on this idea, suggesting that infrastructure resilience should be understood across three interconnected levels, see Figure 6. At the first level, the focus is on the individual physical asset, where resilience translates into a reduction in the life cycle costs of the asset. The second level looks at the resilience of infrastructure services, the network as a whole and its ability to provide continuous and reliable services Here, the concept of infrastructure evolves from individual assets to infrastructure systems, encompassing other critical elements such as human capacity and operational facilities essential for service delivery. Proag (2021) defines infrastructure systems as a collection and interconnection of physical and human systems coordinated to provide a specific service. Additionally, Meyer et al. (2020) highlight the significant role these infrastructure system play in shaping the occupational patterns of an area.

The third and final level that Hallegatte et al. (2019) focus on is resilience from the perspective of infrastructure users. At this level, Hallegatte et al. (2019) highlight that the accurate measure of resilience lies in the ability to mitigate the full impacts on communities and ensure their well-being following disruptive events. Miller et al. (2018) also support this broader view and consider it essential to pay attention to those who provide infrastructure services, as they are the ones whose demands and social values change with time.

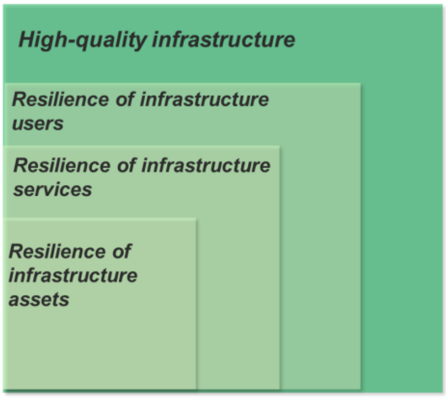

Figure 6: Resilience Infrastructure Levels by Hallegatte et al. (2019)

While Hallegatte et al. (2019) brought attention to the well-being of the users, the OECD (2018) highlighted the importance of how the infrastructures are planned, designed and managed. In that context, Shakou et al. (2019) consider that CRI should also be designed and built in a way that minimises CO2 emissions. However, considering the variations in climate conditions, resilience is no longer a static design and construction measure but a cyclical process of continuous improvement through the life cycle of the infrastructure (OECD, 2018). This perspective is also supported by Rehak et al. (2018), who emphasise that resilience should not be seen as a way to return to the “initial” state of the infrastructure but rather as an evolutive process through time. In each cycle -prevention, absorption, recovery and adaptation- actions must be improved (Rehak et al., 2018).

In conclusion, the concept of infrastructure resilience in the context of climate change is resized to encompass beyond the physical integrity of the infrastructure itself. Resilience broadens from technical to organisational and societal resilience (Boone, 2012, cited in Trucco & Petrenj, 2017). Thus, climate-resilient infrastructure can be defined as any infrastructure planned, designed, and built to minimise CO2 emission while continually adapting through its life cycle to ensure its services' continuity after climate variations.

2.2. Climate Resilience Cycle

This section explains the cyclic process of climate resilience in infrastructures, divided into four phases: prevention, absorption, recovery and adaptation, see Figure 7. Proag (2021) mentions that the analysis of climate resilience in infrastructures is oriented towards a 'system of systems' perspective. Under this perspective, the characteristics that enhance climate resilience in local infrastructures extend beyond the physical asset, as explained below in each phase's description.

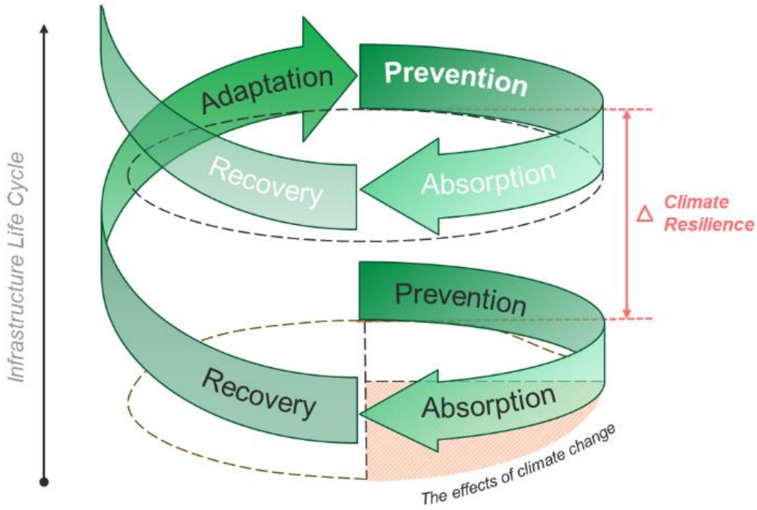

Figure 7: Climate Resilience Cycle adapted from Rekat et al. (2018)

2.2.1 Prevention Phase

This phase aims to ensure that the infrastructure system is less vulnerable to disruption events due to climate change (Rehak et al., 2018). In this phase, Masood et al. (2016) recommend establishing criteria and goals to assess climate resilience during the whole life cycle of the infrastructure and addressing the stakeholder requirements. Furthermore, Trump et al. (2017) also point out the role of the communities in this phase, as their interests and actions can mitigate or exacerbate the disruptions. For example, they block sewer entrances with garbage or demand more parking in areas needing more greenery.

The main component in this phase is awareness, which determines the organisation and stakeholders' ability to understand climate change's impact on infrastructures and recognise how existing interdependencies between the different domains of urban infrastructure, such as public services and open spaces, can influence climate resilience. According to Pederson et al. (2006, cited in Reed & Wang, 2019), these interdependencies can be defined as the multidirectional relationship between assets, systems or networks that require inputs or interactions from various sources for their optimal functioning. These interdependencies can be recognised through the checklist that Carhart and Rosenberg (2017) developed, see Table 2.

Such interdependencies, although vital, increase susceptibility to cascading effects, also known as 'domino effects' (Vallejo & Mullan, 2017), exacerbating the vulnerability of critical infrastructure when failures occur (Shen, 2019). Thus, considering interdependencies in the design can significantly improve the resilience and efficiency of urban infrastructure by bringing more visibility to unforeseen vulnerabilities (Carhart & Rosenberg, 2017). Moreover, being aware of interdependencies and managing them appropriately in the preparation phase and adaptation phase can present opportunities to strengthen climate resilience, such as increasing communication, collaboration, strategic communication (Grafius et al., 2020), and stakeholder engagement (Iturriza et al., 2020). Thus, the analysis of climate resilience in infrastructures is oriented towards a 'system of systems' perspective, according to Proag (2021). Under this perspective, the components that strengthen the resilience of infrastructures extend beyond the physical asset itself, requiring infrastructures to be designed in an integrated and systemic manner.

Table 2: Infrastructure Interdependency Characterisation Checklist by Carhart & Rosenberg (2017)

Category	Description	Type
Directionality	Whether the reliance of one element on another is mutual	Bi-directional
		Non-reciprocal
Order	Whether the relationship is direct or via an intermediary.	First order
		Second order
		Higher order
Coupling	Whether the effects of the relationship are felt closely in time and space.	Loose
		Tight
Location	Whether the element of interest provides or receives a resource.	Upstream
		Downstream
Type	The nature of the relationship, spatially or in terms of resource flow.	Physical
		Digital
		Geographic
		Organisational
Interaction Type	The degree of cooperation and structure of the relationship.	Competition
		Symbiosis
		Integration
		Spillover
Functionality	Whether the relationship is an integral part of the function of the elements or not.	Functional
		Non-functional
Necessity	Whether the relationship is unavoidable or required or whether there is flexibility.	Necessary
		Optional
Outcome	Whether the effect of the relationship on the element of interest is positive or negative.	Benefit
		Dis-benefit
Life-cycle impact stage	The phase of the project during which the effects of the relationship are relevant.	Planning
		Construction
		Operation
		End of life
		Scenario
Geographic scale	The spatial distribution of the relationship or its effects.	Project
		Local
		National
		International
Sectoral scale	Whether the relationship is contained within one infrastructure sector or not.	Intra-sector
		Inter-sector

2.2.2 Absorption Phase

Rehak et al. (2018) describe that the Absorption Phase starts when the effects of an event impact the infrastructure, and the duration of the phase is determined by its robustness. Desouza and Flanery (2013) describe three different outcomes that these stressors could cause: destruction, decline and disruption. They describe the first one as the permanent loss of infrastructure, such as the collapse of a dike due to the rise of sea level or sewerage due to flooding. The second one is the gradual loss of its functions, and the last is the temporary unavailability of its functions. Furthermore, this phase is characterised by the robustness of the infrastructure, which determines the ability of the infrastructure to absorb the effects of the disruptive event without losing its function (Snelde et al., 2012; Nagumey & Qiang, 2007; cited in Twumasi-Boayke & Sobanjo, 2018;

Shakou et al., 2019); giving rise to the absorption phase, see Figure 6. Rehak et al. (2018) mention that robustness is determined through the structural properties of the infrastructure and the implemented security measures. This means that the infrastructure's capacity of robustness will depend on the organisational decisions on how infrastructure systems are designed and built.

2.2.3 Recovery Phase

This phase starts when the effects of the disruptive event are gone. According to Mulowayi (2017), assessing the performance of urban infrastructures' interdependencies and preventing the escalation of the damages during the absorption phase hinder the recovery efforts, highlighting the importance of this phase's technical aspect. However, the technical aspect is determined by financial and qualified human resources (Rehak et al., 2018) and the availability of the correct information and guidance for recovery efforts (Mulowayi (2017), underlying the importance of the economic and organisational aspects. Moreover, it is necessary to remember that the primary goal of this phase should benefit the citizens (Amaratunga & Haigh, 2011; Labadie, 2008; Sulliva, 2003, cited in (Mulowayi, 2017). Thus, the social aspect has also to be considered in this phase.

On the other hand, this phase is determined by the ability of the infrastructure to recover its function once the effects of the disruptive event end, giving rise to the recovery phase. This component depends mainly on the availability of different resources, such as material and financial, for the infrastructure to be repaired or replaced (Rehak et al., 2018). Therefore, this ability is also linked to the organisation's planning and management of resources.

2.2.4 Adaptation Phase

In this phase, organisations learn from disruptive events and determine and develop processes to strengthen resilience (Rehak et al., 2018). In other words, the Absorption phase's outcomes reflect the actions taken during the preparation phase. Therefore, Masood et al. (2016) encourage feedback loops between operators/maintainers, planners, and designers to increase the knowledge of design improvement decisions. The authors also suggest considering the socioeconomic impacts of these decisions.

The main characteristic in this phase is the ability of the organisation to adapt the infrastructure to the necessary changes required in the long term (Rehak et al., 2018). The authors also mention that organisations must innovate their processes and educate themselves to create the right conditions to enhance climate resilience and adaptability. On the other hand, Sánchez-Silva and Calderón-Guevara (2022) focus on this ability in the infrastructure itself, mentioning that the asset should have a flexible design to accommodate unexpected changes. This infrastructure's ability is commonly linked with flexibility since both relate to changes.

2.3. Life Cycle of Climate-Resilient Infrastructure

According to the asset life cycle illustrated by Silvius et al. (2012 cited in Silvius Gilbert, 2018), the phases of infrastructure are detailed design, construction, operation and decommissioning, see Figure 8. However, considering the climate resilience cycle described in the previous sub-section, additional phases must be included to represent the life cycle of a climate-resilient infrastructure visually. This expanded representation is necessary to raise awareness when creating business cases for infrastructures, as mentioned by Masood et al., 2016, which underlines the importance of considering the whole life cycle to enhance climate resilience. Therefore, Figure 9 illustrates how the asset life cycle varies considering climate resilience.

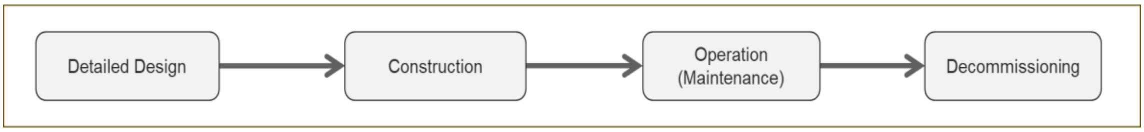

Figure 8: Asset Life Cycle illustrated by Silvius et al. (2012 cited in Silvius Gilbert, 2018)

The lifecycle of infrastructure designed to incorporate climate resilience typically commences with detailed design and construction phases. These initial stages, along with the operational (maintenance) phase, form part of the Prevention Phase as outlined in subsection 2.2.1. To infuse climate resilience during the planning and design stages, modifications to building codes and related standards are recommended (Proag, 2021). Furthermore, Trump et al. (2017) emphasize the crucial role of stakeholder engagement in the use and management of infrastructure services, which can significantly affect the ease of recovery from climate impacts.

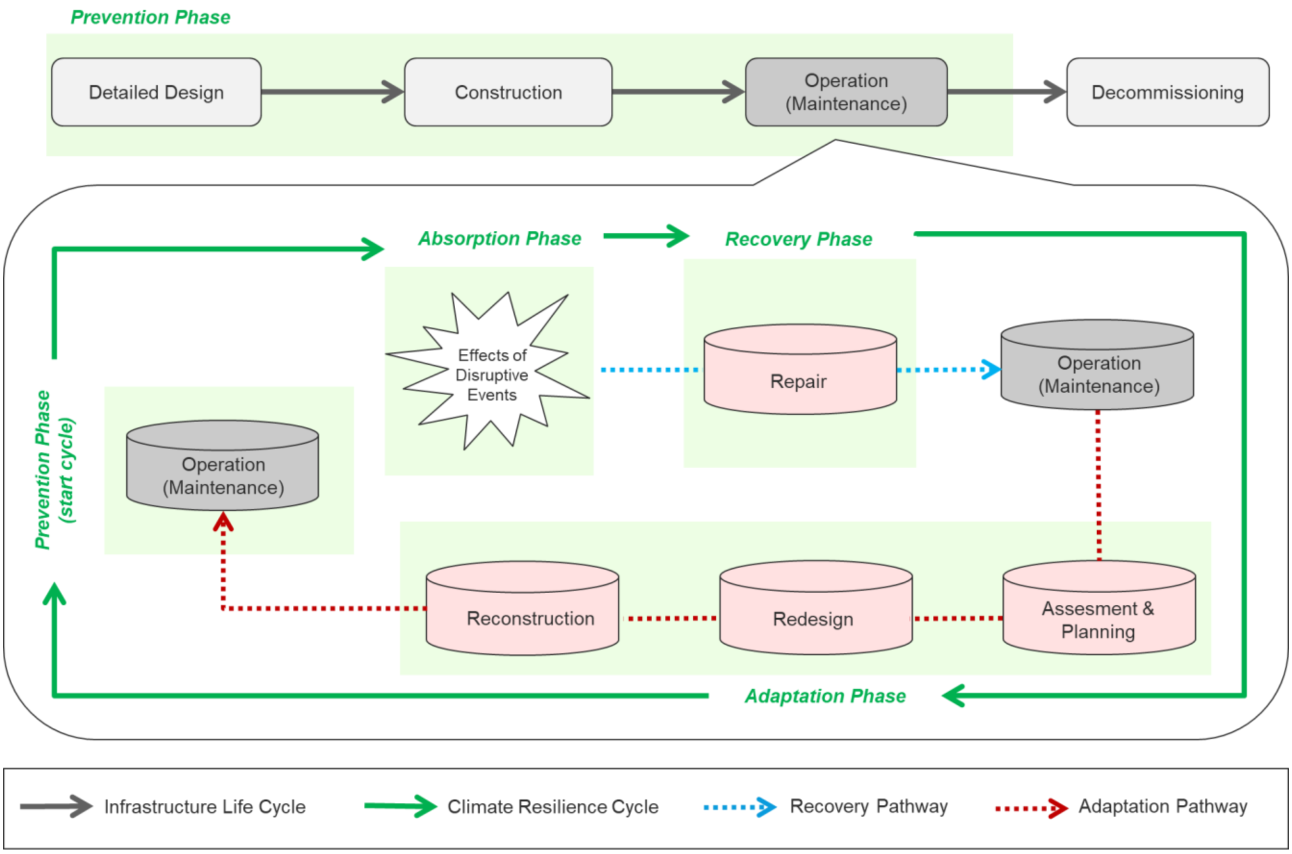

Figure 9: Incorporating Climate Resilience Cycle in Infrastructure Life Cycle developed from the concepts of Mulowayi (2017), Rehak et al., 2018) and Proag (2021)

Figure 9 primarily addresses the negative outcomes that follow when infrastructure is impacted by the effects of climate variations during the operational phase. After the immediate disruptive effects have subsided, the Recovery Phase begins. According to Mulowayi (2017), this is a short-term phase aimed at restoring infrastructure functionality to a basic operational level. The recovery pathway (indicated by the light blue arrow) leads back to the operational phase. It is important to note, however, that the operational phase post-recovery is not considered a distinct phase in the climate resilience lifecycle because the infrastructure remains susceptible to future disruptive events due to unchanged design characterstics.

Consequently, the Adaptation Phase (marked by the red arrow) is initiated by assessing the outcomes from the Absorption Phase to understand the reasons behind the infrastructure's disruption. This phase progresses through planning and redesigning stages aimed at reconstructing the infrastructure with enhanced resilience. While Mulowayi (2017) may classify reconstruction as part of the recovery phase, it is essential to recognize that this phase specifically aims to enhance climate resilience, thereby necessitating innovative approaches and the development of new knowledge (Rehak et al., 2018) based on insights gained from prior experiences. Following reconstruction, the infrastructure re-enters the operational phase, now with improved resilience characteristics.

2.4. Anchoring Climate Resilience from National to Municipal Level

At the global level, the Netherlands has signed several international agreements to address climate change: the Framework Convention on Climate Change in 1997, the Kyoto Protocol in 2017, and the Paris Agreement in 2015. These agreements form the basis for their national frameworks to reduce greenhouse gas emissions (Ministry of Economic Affairs and Climate, 2020). These national policies are later translated into mitigation and adaptation plans and integrated into the strategic level, as Den Exter et al. (2015) described. However, effective integration of these policies necessitates establishing both vertical and horizontal linkages across various organizational levels (Den Exter et al., 2015; Warbroek et al., 2023). Den Exter et al. (2015) define vertical linkages as interactions with higher levels of government, while Warbroek et al. (2023) describe horizontal linkages as interactions among different departments within the same hierarchical level. In this context, the role of managers and a steering committee is critical in steering these linkages, ensuring comprehensive understanding and commitment to these policies across the municipality (Den Exter et al., 2015). Additionally, policies focused on information dissemination are crucial to keeping all stakeholders well-informed and engaged (Proag, 2021).

The effectiveness of climate policies varies depending on the phase of the climate's life cycle, requiring specific strategies at different stages. During the Prevention Phase, regulatory-based policies play a pivotal role. For instance, Vallejo & Mullan (2017) highlight the importance of incorporating environmental impact assessments into spatial planning. This ensures that environmental aspects are considered from the beginning in the design process. Additionally, policies that ensure safety in the design, construction, and maintenance of infrastructure are critical (Labaka et al., 2016). Furthermore, public procurement policies should emphasise climate resilience by evaluating the long-term costs associated with an asset across various future scenarios, as suggested by the OECD (2018). These measures are crucial for minimizing the future impact of climate change and enhancing overall CRI.

2.5. Climate-Resilient Infrastructure Challenges

The challenges to planning and designing CRI are climate change uncertainties, fragmented institutions, balancing priorities, political instability, and lack of local power.

- Uncertainties. Since infrastructures have a long lifetime, there is higher exposure to climate change and less certainty of how, when and with what intensity they will be impacted (Giordano, 2012). However, since few cities have direct experience with significant impacts, the knowledge is limited, making it harder for planners to prepare infrastructures for those failures (Monstadt & Schmidt, 2019).

- Fragmented institutions.- The management of interdependencies between different infrastructure systems becomes more complex in a fragmented institutional landscape where each entity has distinct structures, knowledge bases, and interests (Monstadt and Schmidt, 2019). This fragmentation hinders effective information exchange, essential for coordinated planning and resilience building (Monstadt & Schmidt, 2019). A unified database system, as suggested by Roy (2019), could mitigate these issues by facilitating more integrated planning across different organizations.

- Balancing Priorities.- Organizations often struggle to address both immediate crises and long-term resilience strategies. For example, the COVID-19 pandemic highlighted how emergency responses can divert attention and resources from longer-term climate resilience initiatives (Mehryar et al., 2022).

- Short-Term vs Long-Term Focus.- Infrastructure operators frequently focus on immediate outcomes due to short-term financial pressures, overshadowing the long-term benefits of investments in climate resilience (OECD, 2018). This is compounded by the tendency of companies to accept losses from supply disruptions rather than invest in preventative measures without regulatory obligations (Monstadt & Schmidt, 2019).

- Political instability.- Political shifts can lead to the reallocation of municipal resources away from community-focused climate resilience projects towards short-term political gains (Mehryar et al., 2022).

- Lack of local power.- In countries with centralized governments, local authorities often lack the power necessary to effectively allocate resources towards climate change mitigation and adaptation strategies. Empowering local entities is crucial for effective resource allocation and action on climate resilience (Mehryar et al., 2022).

2.6. Conclusions

This chapter answered the sub-question “SQ1: What are the characteristics of climate-resilient infrastructure?” through a literature review. To find the answer to this question, a synthesis of the collected literature directly connected climate resilience and the infrastructure life cycle. Through this analysis, it can be concluded that a climate-resilient infrastructure (CRI) has the following characteristics:

- **Adaptable and integrated design.** CRI's design is adaptable, allowing users to continue using its service despite the effects of climate variations. CRI is also integrated, thus reducing the unforeseen uncertainties from interdependencies with other local infrastructures.

- **Sustainable and robust construction.** CRI is built in a way that does not enhance CO2 emissions and can still absorb the effects of climate variations without being destroyed.

- **Adaptable maintenance authorities**. The authorities responsible for the maintenance phase must be adaptable since redesign and rebuild are needed to enhance climate resilience. Therefore, the responsibilities must be adapted to fulfil these new tasks successfully.

- **Organisational and stakeholder awareness.** CRIs responsible must be aware of how existing interdependencies between local infrastructure can negatively influence infrastructure’s climate resilience and, therefore, include them in the design phase.

- **Collobarative governance.** CRI requires cross-government collaboration at different levels to ensure that climate resilience anchors from the national to municipal level. Furthermore, in collaborative governance, information sharing is enhanced, keeping all stakeholders informed of new policies related to climate resilience.

Chapter 3: Integrated Infrastructure Design Approach

This section is structured into four sub-sections to answer the sub-question, “SQ2: How is an integrated design approach applied to local infrastructure?” It begins with an overview of the concept of integration in the context of urban infrastructure design, presented in section 3.1. Subsequently, in section 3.2, the various lenses through which infrastructure integration can be analysed are explored and described. Next, section 3.3 describes the integrated design process, and section 3.4 explains different ways of implementing IIDA. Lastly, section 3.5 concludes by answering the sub-question.

3.1. Integration Design Approach

Traditionally, infrastructure systems have been planned and designed separately without considering how their performance impacts each other (French, 2014). However, enhancing climate resilience in urban infrastructures requires to shift from a silo approach, as this is no longer effective (Johnston, 2022). In response to this need, integration in the design context has gained relevance in urban infrastructure. The concept of integration can be categorized into two types, as described by Jagger (2009). The first type is internal integration, which occurs within a single sector. An example of this is the integration of road and railway systems, both of which are components of the transportation sector. The second type is external integration, which happens between different sectors. An example is the case of combining a geothermal network from the energy sector with the sewerage system from the water system sector.

However, Verheijen (2015) advocates that integrated infrastructure design involves multiple angles and perspectives, seeking a comprehensive understanding and achieving holistic solutions in analysis and design. Years later, the concept of 'integration' in the design field is extended by Visser (2020), concluding that integration refers to the interrelation of various lenses when addressing a problem, see Figure 10.

On the other hand, IIDA requires active collaboration between various disciplines and functionalities throughout the design process (Hertogh et al., 2018a), enriching the project's sociological, cultural, ecological and economic value (Verheijen, 2015). However, to achieve an integrated design, Voorendt (2017) expands on this idea, pointing out that multi-discipline collaboration means working together on one design activity since the goal is to achieve a thinking process across the different boundaries of each discipline. Thus, IIDA transcends the simplification of infrastructure design to single and sectoral objectives with monofunctional solutions (Brand & Hertogh, 2021). It incorporates considerations of decentralisation in urban infrastructure systems, which are essential to achieve more resilient cities (Derrible, 2017). Consequently, adopting this approach leads to focusing not only on the physical and technical aspects but also on effectively integrating various disciplinary knowledge and practices.

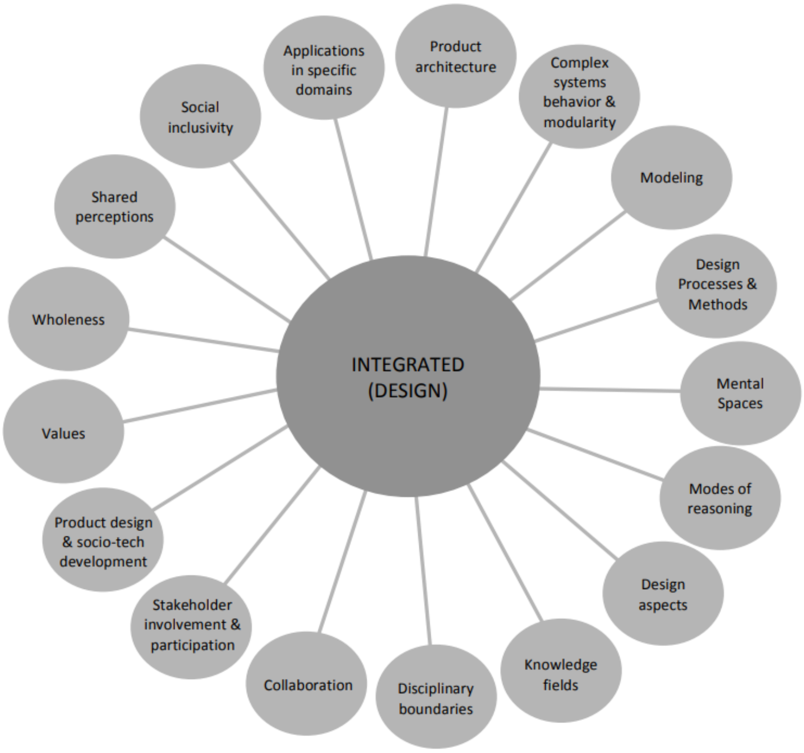

Figure 10: Different Interpretations of Integration by Visser (2020)

3.2. Integrated Infrastructure Design Approach: Implementation Lenses

Drawing on the theoretical frameworks of Visser (2020) and Voorendt (2017), this study proposes specific 'integration lenses' from the context of municipal implementation: Functional, Transdisciplinary, Synergistic, Intervention Scale and Technological. These lenses focus on the different perspectives of the IIDA implementation, which categorisation came through the literature review on the topic.

3.2.1 Functional Lens

This lens considers integrating different urban infrastructures' purposes by sharing space (Voorendt, 2017) and developing in a single project. Each infrastructure has its purpose, in other words, each primary function for which it has been built. For example, the road network's primary function is to connect point A to point B, allowing users to move along, while the water system's primary function is to treat and distribute drinking water to their users. Therefore, a multifunctionality infrastructure can be defined as one that performs several functions/purposes and provides several benefits, according to EC DG Environment[1] (2012, cited in Siehr et al., 2022).

One example of multifunctional infrastructure is the integration of blue-green infrastructures with grey infrastructures, bringing the following functions: detention of stormwater, water storage, water filtration, erosion reduction, cooling urban heat, smog reduction, increase property value, stress and noise reduction, and increase social gathering and recreation access (Siehr et al., 2022). Another example is the multifunctional flood defence, which combines flood defence with functions fulfilled by hydraulic and road infrastructure and buildings (Voorendt, 2017). The integration of

[1] EC DG Environment is the Directorate-General for Environment, which is a branch of the European Commission responsible for EU policy on the environment.

functionalities can be implemented for new infrastructures, as well as existing ones. For example, a road is upgraded when green infrastructure is added simultaneously (Derrible, 2017).

3.2.2 Transdisciplinary Lens

This lens focuses on integrating skills and experience from different stakeholders and disciplines throughout collaboration to generate holistic solutions that contribute to and benefit all involved actors. Keusters et al. (2021) mention two types of integrations from the participant's perspective: stakeholder integration, which happens more at the system level, and discipline integration, which happens more at a component level. In stakeholder integration, Mitsova (2021) point out the value of community involvement for the projects as they help with priority setting and scenario planning. Moreover, the author concluded that this collaboration also benefits communities as they can have more political and financial resources needed to strengthen the protection of infrastructures. In discipline integration, Ahern (2013) highlights that planners and designers should not substitute collaborations with other disciplines by trying to "apply their knowledge", as each stakeholder has their research skills, culture, and resources to create alternative solutions.

Furthermore, Keusters et al. (2021) point out that an IIDA refers to integrating both levels. Schoulund et al. (2021), with a case study in Argentina, is an example of how the authors link both levels through a participatory design. In that country, there has been a separation tendency between technical aspects of spatial design in urban infrastructure projects, impacting the infrastructure quality and the users' quality of life. The authors set a participatory design for replacing an old bridge to increase the business development between the two sides. They gathered engineering disciplines with project managers, architects, landscape architects, politicians and historians to collaborate in the definition phase, mentioning that the coordination at the municipal level was crucial. The authors conclude that shifting the perception of infrastructure from an asset to a medium that links the city is necessary.

3.2.3 Synergistic Lens

This lens integrates objectives of transition solutions such as mobility, energy, circularity, smart technology and climate adaptations that are spatially interconnected. The IPCC (2022) highlights the necessity of implementing transition pathways such as energy, urban and infrastructure systems to limit global warming and reduce emissions. Thus, infrastructure projects where these transitions are integrated provide synergies and reduce their adverse effects (Warbroek et al., 2023). This type of project is called a "blended infrastructure project" since social, economic, environmental and technological dimensions are implemented (Cucuzella & Goubran, 2018).

One example of the implementation of this lens is the installation of heat grids, which is part of the energy transition, and the installation of water retention areas, which is part of the climate adaptation in Overijssel. In this case, both transition solutions lacked policy instruments to integrate both measures at the operational level, thus allowing the continuity of a siloed approach despite the involved actors being aware of the co-benefits from implementing this lens (Warbroek et al., 2023). Another example is the proposed waterful station, where water management with generating energy is implemented in a bus station (Cucuzella & Goubran., 2019).

Understanding this lens will help specialists be aware of the multiple new combinations of transition solutions they have yet to do before in a single project. These combinations also consider the existing requirements, conditions, restrictions, and limitations that each transition solution could bring into the project. For example, Warbroek et al. (2023) mention financial flow barriers because municipalities sectorise their budgets.

3.2.4 Intervention Scale Lens

This lens determines the scale level of urban infrastructure integration. This could be at a small local level, known as the small wins approach or, on a bigger scale, as the area-oriented approach. Termeer and Dewulf (2019, cited in Ersoy et al., 2020) believe the first one might be a feasible strategy to implement urban infrastructure integration, as small wins focus on increasing local gradual change achievements that have lasting impacts (Ersoy et al. (2020). On the other hand, V&W et al. (2008, cited in Jager, 2009) consider an area-oriented approach suitable for large, complicated projects with considerable environmental impacts and several parties and sectors play a role in the project.

3.2.5 Technological Lens

This lens focuses on the integration of digital technologies and data. Argyroudis et al. (2022) point out the need for integration approaches for such tools since they have the potential to enhance climate resilience in infrastructures, see Figure 11. The authors give examples of how digital technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), Machine Learning (ML), Building Information Modelling (BIM), Digital Twin (DT) and Agent-based modelling (ABM) can be used to increase climate resilience through infrastructure life-cycle. IoT can be used for data collection and input for technical designs, while BIM helps with data visualisation and rapid data sharing. Acknowledging this lens in the planning can help foresee barriers during IIDA implementation. For example, in the case of technological lense, Rekola et al. (2011) mention that the main barrier at the beginning of the use of BIM was software originated.

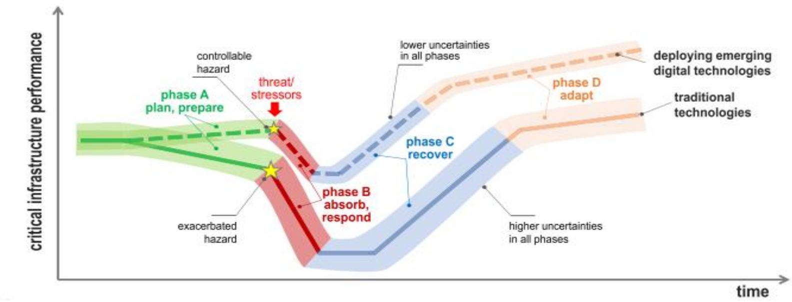

Figure 11: Climate-Resilient Infrastructure enhanced by emerging digital technologies vs traditional technologies by Argyroudis et al. (2022)

3.3. Integrated Infrastructure Design Approach: Process

The design phase of urban infrastructure projects is an essential factor for their performance since it defines the project scope, which determines cost estimation, stakeholder management, and risk management (Keusters et al., 2021). Voorendt (2017) described an integrated design process that requires the integration of system thinking, which is the analysis of actual needs. This idea is also supported by Keusters et al. (2021), who recognise the importance of understanding the environmental background to define the problem.

As Figure 12 shows, Voorendt (2017) explains that the design phase starts with exploring the problem, which will have as products an inventory of environmental elements, actors involved (interests), and the project's goal that will be useful to determine the primary function and its specifications. The criteria, boundary conditions and requirements are formulated from the functional specifications. Verheijen (2015) states that the wishes, desires and expectations should not be part of the requirements, as social added value can be discouraged. Lastly, Voorendt (2017) also describes the necessity of life cycle thinking during the design phase and structural thinking to gather all the information from the integrated disciplines.

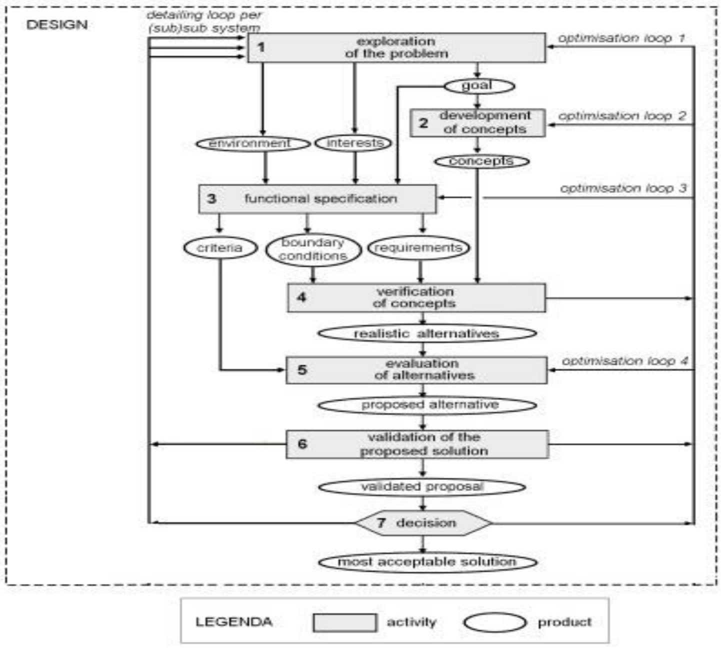

Figure 12: Design Phase from the Integrated Desing Process by Voorendt (2017)

During the application of the integrated design process for multifunctional flood defence, Voorendt (2017) considers climate change in the following way:

- Exploration of the problem.- In this step, the author is aware that the area where the infrastructure is located gets impacted by storms and has the knowledge that the current infrastructure is not prepared for future climate conditions. Therefore, exploring the problem requires two main things: gathering information about the effects of climate variation on infrastructure in a determined area and assessing the infrastructure's technical capacity to face those impacts. Lastly, protecting the infrastructure against these impacts should be part of the project's goals.

- Functional specifications.- In this step, climate change effects are considered as boundary conditions. In the case of multifunctional flood defence, hydraulic boundary conditions, such as water level, wave height, and ground surface level, have been determined to be considered in the structural design of the infrastructure.

3.4. Implementing Integrated Infrastructure Design Approach for Climate-Resilient Infrastructure

Considering that IIDA is still perceived as a novel approach, there are several ways in which municipalities can begin its implementation. Kilbane and Roös (2023) highlight 'charrette', an interactive design method consisting of a series of workshops. This approach brings together key stakeholders and citizens to involve them in project design and planning, which are crucial for creating resilient cities and providing detailed analysis at the local level. Hughes et al. (2020), for their part, propose conducting experimental pilot projects as a means to demonstrate the viability of innovative approaches and to test new ideas on a controllable scale. They emphasise that, for these pilots to expand and transform cities into living laboratories, they must be well designed, demonstrating their success and attracting actors willing to invest and participate in them. On the other side, on a larger scale, Schäfer and Scheele (2017) approach 'living labs' as initiatives aimed at discovering and combining innovative solutions at the local level that support regional plans. They emphasise that adaptation to climate change requires both top-down (top-down) and bottom-up (bottom-up) approaches, with the former identifying physical vulnerabilities in infrastructure systems and the latter focusing on social vulnerabilities. Thus, this is the ultimate scale on which municipalities will obtain the most benefits for CRI.

3.5. Conclusions

This chapter answered the following sub-question: "SQ2: How is an integrated design approach applied to local infrastructure? Through a literature review. To find the answer to this question, a synthesis of the collected literature focused on implementing an integrated design approach in urban infrastructure projects.

Based on the findings, it concludes that IIDA is:

- **Cross-sectoral approach**. An integrated design involves the collaboration of different sectors and disciplines. Since local infrastructure projects can impact other sectors, stakeholders from these sectors must participate in the planning and design process. For example, renovation projects of the sewer system impact the transportation sector (roads) and open space (greenery and public areas). Thus, actors from those sectors will be involved in the planning to reduce intervention conflicts and in the design to analyse the interdependencies between them. Following the same example, the road material's characteristics and the green infrastructure's water absorption capacity should be considered during the sewer's technical design.

- **Holistic approach.** Implementing integrated design requires a holistic view to seek opportunities for incorporating functions and the city's ambitions in the design and at what intervention scale.

- **Encourage innovative solutions**. Diverse disciplines come together in discussion meetings to explore the problem, each bringing their own expertise and knowledge. Fomenting discussions between technical disciplines and designers enhances innovative solutions that would not have been created by working separately.

- **Means to add co-benefits**. This approach's design highlights the importance of understanding the environmental background where local infrastructures are located. In this way, the infrastructure's functional specifications must consider environmental elements and stakeholders' interests. Thus, authorities responsible for local infrastructure can use an integrated design approach to enhance climate resilience.

Lastly, IIDA's implementation in the municipality brings together diverse perspectives (lenses) such as functional, transdisciplinary, synergistic, intervention scale and technological.

- **Functional Lens:** related to the integration of multiple urban infrastructure functionalities within a single project, such as combining road networks with green infrastructure or water systems.

- **Transdisciplinary Lens**: related to the involvement of various stakeholders and disciplines. By bringing together experts from different fields, such as engineers, architects, and community leaders, IIDA promotes holistic solutions that are sensitive to the needs of all parties involved. This integration at both the system and component levels enhances community engagement, which is an important aspect to enhance CRI (user mindset).

- **Synergistic Lens**: related to the integration of objectives from different transition solutions like mobility, energy, and climate adaptation, creating blended infrastructure projects. These projects leverage the co-benefits of combining multiple transition solutions, such as energy grids with water retention areas.

- **Intervention Scale Lens:** related to the determination of the appropriate scale of infrastructure projects, ranging from localized small wins to broader area-oriented approaches. This flexibility allows for tailored solutions that address specific local needs while considering the environmental impacts and the roles of various stakeholders.

- **Technological Lens:** Lastly, this lens is related to the integration of advanced digital tools such as IoT, AI, and BIM. These technologies facilitate the collection, visualization, and sharing of data, improving climate resilience and operational efficiency throughout the infrastructure lifecycle.

PART II
Case Study

This second part aims to study and analyse the practical side of using an integrated design approach by focusing on Rotterdam Municipality as a case study. This analysis is done in two parts: a document review in Chapter 4 and a thematic analysis of interviews in Chapter 5. The outcomes of both analyses are used to develop the roadmap, which is explained in Part III.

Chapter 4: Document Review

This chapter introduces the Rotterdam Municipality (RM) case study through a document review to answer SQ3: “How does an integrated design approach enhance climate resilience in urban infrastructure?” The gathered information is structured in three sections. Section 4.1 describes an overview of how RM develops its local infrastructure projects. Section 4.2 describes RM’s current actions to achieve CRI by implementing IIDA. Section 4.3 describes some pilots the municipality has done, showing how IIDA enhances climate resilience in their infrastructures. Finally, section 4.4 concludes by answering the sub-question.

4.1. Rotterdam Municipality’s Local Infrastructure Project Development

There are five organisational positions of an urban infrastructure project within Dutch municipalities, as Figure 13 shows. This research focuses on projects involving multiple municipal sectors and requires the participation of external stakeholders, who will be at the bottom left.

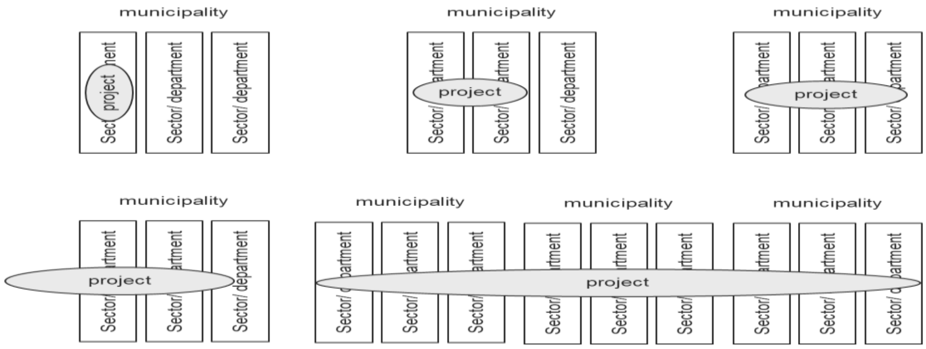

Figure 13: Organisational positions of Dutch municipalities’ project by Karijo (2005)

In this case study, there are two main departments: “Stadsbeheer” (City Management) and “Stadsontwikkeling” (City Development), which are actively involved in the management of the city’s urban infrastructure, see Figure 14. The City Management takes ownership of the city’s infrastructures; thus, it is responsible for operating and maintaining all the existing assets within its jurisdiction. Thus, asset managers and project managers are from this department. To execute their work, the department asks City Development for technical designs and solutions. Thus, disciplines actors such as urban designersa and engineers are from this department. However, project initiation can originate from any of the departments shown in Figure 14, as indicated by the bidirectional arrow.

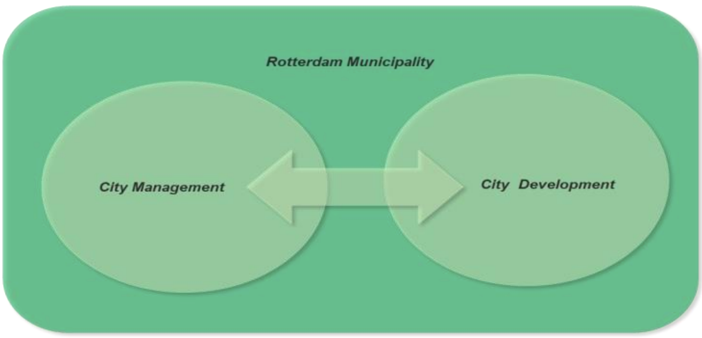

Figure 14: RM’s Main Departments adopted from RM1

Since City Management primarily focuses on the asset itself, this interest often shapes the objectives they set when initiating projects. Consequently, there is a significant risk that local infrastructure projects initiated from this department may only achieve resilience level 1, as described in section 2.1. However, Hallgate et al. (2019) emphasized the importance of focusing on level 3, which pertains to the user mindset, to enhance CRI. Therefore, the objectives of local infrastructure projects will vary depending on the initiating department, influencing the level of resilience achieved.

By implementing IIDA in their projects, RM is currently aligning integration within the three levels of project management: strategic, program, and project and between borh deparment. Figure 15 describes the municipality's integral procedure.

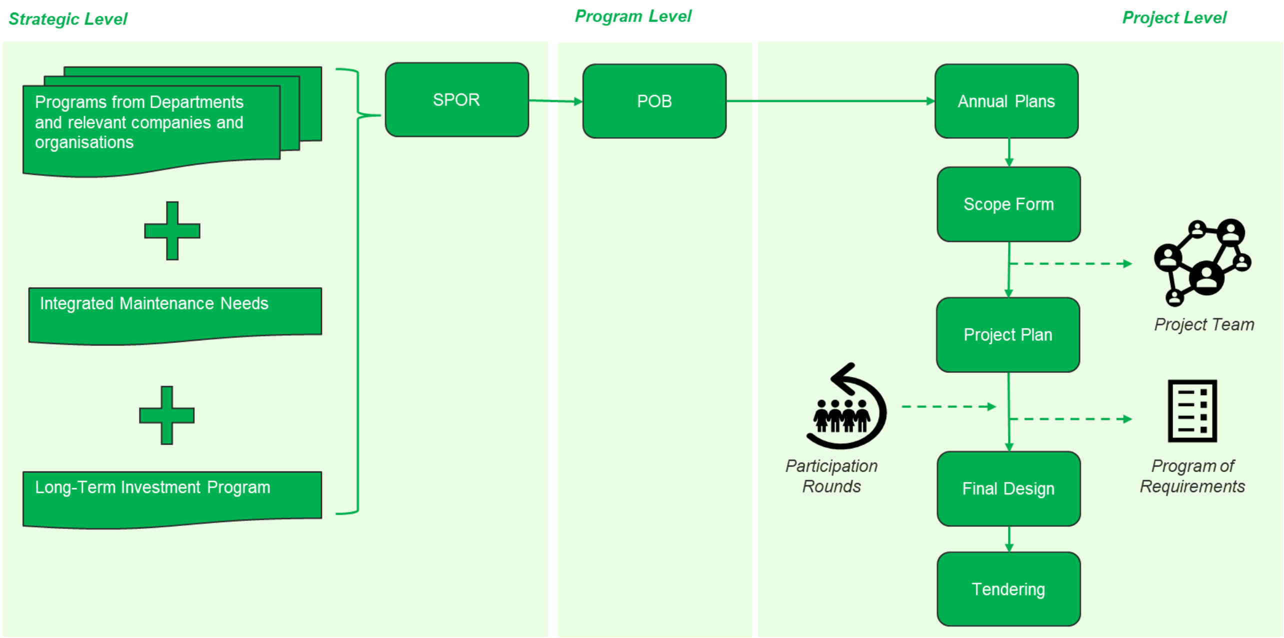

Figure 15: RM's Urban Infrastructure Project Development Procedure adopted from an internal document: RM2

At the strategic level, each department and organisation's programs are integrated into the Urban Programming Public Space (SPOR in Dutch), which describes the strategic tasks for the entire city for four to twenty years. At this level, synergistic and transdisciplinary lenses of IIDA play an important role.

At the program level, policies, financial frameworks and all data related to the infrastructures are aligned in the Program Outdoor Area Consultation (POB in Dutch), in which different stakeholders from relevant sectors per area come together for consultations every six months to determine the scope and the time window for the initiative projects. At this level, the technology lens sets the standard for integrating digital data and technologies from the different stakeholders. These initiatives are later translated to annual plans, the starting point for creating the project plans.

At the project level, the project team is created during the scoping phase and is responsible for developing the project plan. According to the internal document RM2, once the project plan is ready, the requirements program is formulated, and these requirements are established through participation rounds. Thus, the functionality lens must be considered at this level. Moreover, these participation rounds are also used during the design draft until its final version, which relates to the transdisciplinary lens. Lastly, the project is tendered once the technical design is formulated and specification and cost estimations are established.

On the other hand, as mentioned in the Climate Resilience Cycle in Section 2.1.2, the economic aspect is also essential to enhance climate resilience. Although this aspect is more highlighted in the Recovery Phase, all the phases of the CRI Life Cycle, such as (re)design, (re)construction and maintenance related to the Prevention and Adaptation Phase, also require financial resources. Thus, it is important to consider budget distribution when implementing IIDA to achieve CRI.

In this case study, the budget distribution needs to be directly aligned with their urban infrastructure management. The municipality's budget is allocated to eighteen programs, two involving the city's urban infrastructures related to this research: "Beheer van de stad" and Energy Transition (Rotterdam Municipality, 2023). This distribution differs from the previous administration period, where RM managed thirteen programs the last year, each with different tasks, making 75 tasks with specific budgets (Rotterdam Municipality, 2023a). Table 3 mentions the policies and financial framework the city's urban infrastructures follow.

Table 3: Policy and Financial Framework of RM's Urban Infrastructure (Rotterdam Municipality, 2023a) (Rotterdam Municipality, 2019)

Urban Infrastructures under the responsibility of RM	RM's Policy and Financial Framework
Sewerage Replacement	Follow the guidelines of the MSP.
	It is financed by the MSP's investment credit and MSP's credit.
Roads, Bridges, Tunnels Pavement, Street lighting, Greenery and Open Space.	Follow the guidelines of the Note on Maintenance of Capital Goods 2023.
	Financed under "Beheer van de stad."
Streets, gardens and open spaces (which need to be climate-adapted)	Climate Adaptation Administrative Agreement (2018)
	Financed under "Beheer van de stad."

4.2. Rotterdam's Urban Infrastructures

In Rotterdam, urban infrastructures can be grouped in the following ways: urban water system, heating network, open space, roads, bridges, tunnels, electricity network, and IT and telecommunications. The last two infrastructures are outside RM's responsibility; see Table 4.

Table 4: Responsible Actors for the Urban Infrastructures in Rotterdam

		Responsible Actors
Urban Infrastructures	Urban Water System	Water Boards (Surface water), Rotterdam Municipality (sewerage) and Evides (Private company for drinking water)
	Heating Network	Rotterdam Municipality, Vattenfall and Eneco (Private companies)
	Open Space (Greenery and Roads)	Rotterdam Municipality
	Bridges, Tunnels	Rotterdam Municipality
	Electricity Network	Stedin and Eneco (Private companies)
	IT and telecommunication	Several Private Companies

As mentioned in section 1.5, the research will focus on implementing IIDA in the sewerage system, heating network and open space. Next, it will be described in more detail how the urban infrastructures in which RM shares responsibilities with other actors are delimited.

4.2.1. Urban Water System

The Water Act regulates water systems, flood defences, surface water and groundwater bodies in The Netherlands. This law assigns care duties to Water Boards and municipalities, where Water Boards are responsible for purifying urban wastewater (Rijkswaterstaat, n.d-b). In contrast, municipalities are responsible for collecting urban sewage, rainwater and groundwater; these duties are stated in the Municipal Sewerage Plan (Rijkswaterstaat, n.d-c). Figure 16 shows the actors responsible for the urban water system in Rotterdam. Furthermore, according to Article 3.8 of the Water Act, municipalities and Water Boards are obligated to coordinate each other's tasks and powers regarding the wastewater chain (Rijkswaterstaat, n.d-a).

The city's urban water system's drainage structure was built in the nineteenth century and is still mainly used. It is divided into the outdoor space, the wastewater chain and the surface and groundwater system, as Figure 16 shows. The municipal sewage system has been designed to have overflow outlets used during heavy rainfall. Through these overflow outlets, the excess sewer water can be discharged into nearby bodies of water as canals to prevent flooding and water damage to the surrounding areas (Stadsbeheer Rotterdam, 2020).

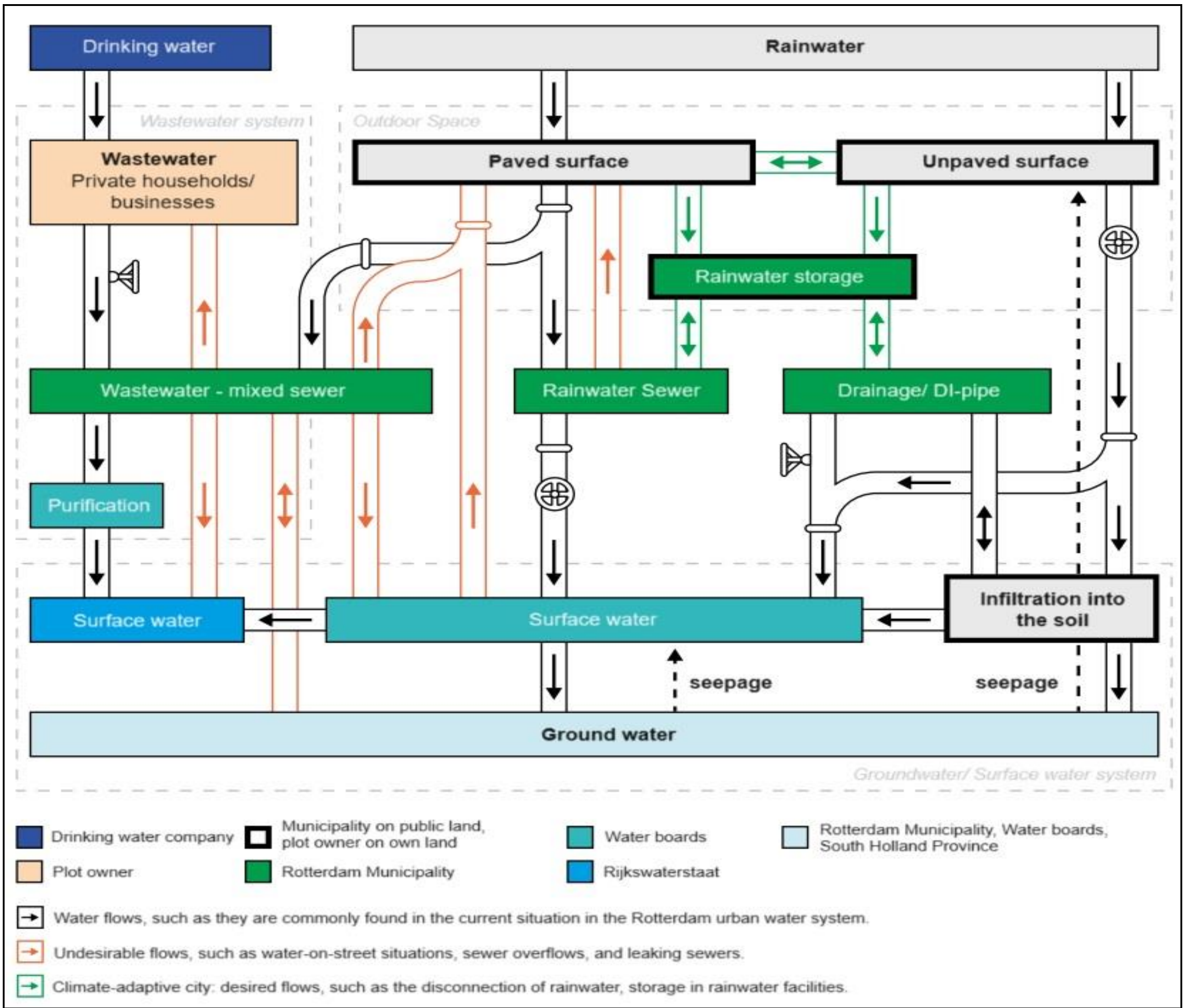

Figure 16: Rotterdam's urban water system and responsabilities by Stadsbeheer Rotterdam (2020)

“Van buis naar buitenruimte – Gemeentelijk Rioleringsplan 2021-2025” (From pipe to outdoor space - Municipal Sewerage Plan 2021-2025) describes the goals, strategies and concrete measures that RM takes to increase climate resilience in the infrastructure. The plan highlights an explicit connection that the sewerage, surface water and outdoor space have with the “Visie Openbare Ruimte 2019-2020 Rotterdam” (Vision Public Space 2019-2020 Rotterdam) and “Rotterdam Weerwoord” (Rotterdam Weather Wise). The Vision Public Space is further described in sub-section 3.1.3, while Rotterdam Weerwoor is explained in section 3.3

4.2.2. Heating System

The National Climate Agreement agrees that municipalities take control of the heat transition of the built environment. Therefore, in 2021, the RM council has adopted “De Rotterdamse Transitievisie Warmte” (The Rotterdam Heat Transition Vision)—this transition consists of making buildings natural gas-free and using other clean energy by 2030 (Rotterdam Municipality, 2022). The main component of this transition is the availability of sustainable heat sources in the city. Rotterdam has the following sources of clean energy: residual heat from industry, geothermal energy, aqua thermal energy and clean electricity from solar and wind (Rotterdam Municipality, 2023a). Furthermore, RM opts for an area-focused approach, allowing them to couple opportunities with other urban infrastructure projects and identify challenges in advance, such as sufficient space for pipe installation to implement the new heat network (Rotterdam Municipality, 2021).

However, the urgency of the transition has brought periods of uncertainty regarding those responsible for the administration and financing of the heating system. Initially, the residual heat was coming from the port of Rotterdam via the heat pipe network called The New Heat Route (DNWW). This was owned by Heat Company Rotterdam (WbR), a public company financed by RM (Rotterdam Municipality, n.d). In 2022, RM sold WbR to Vattenfall, a private company, due to financial issues, with the condition that district heating remained an affordable and reliable alternative to natural gas (Rotterdam Municipality, 2023a). Figure 17 shows the map of the existing heating pipe lines until 2022 and those responsible.

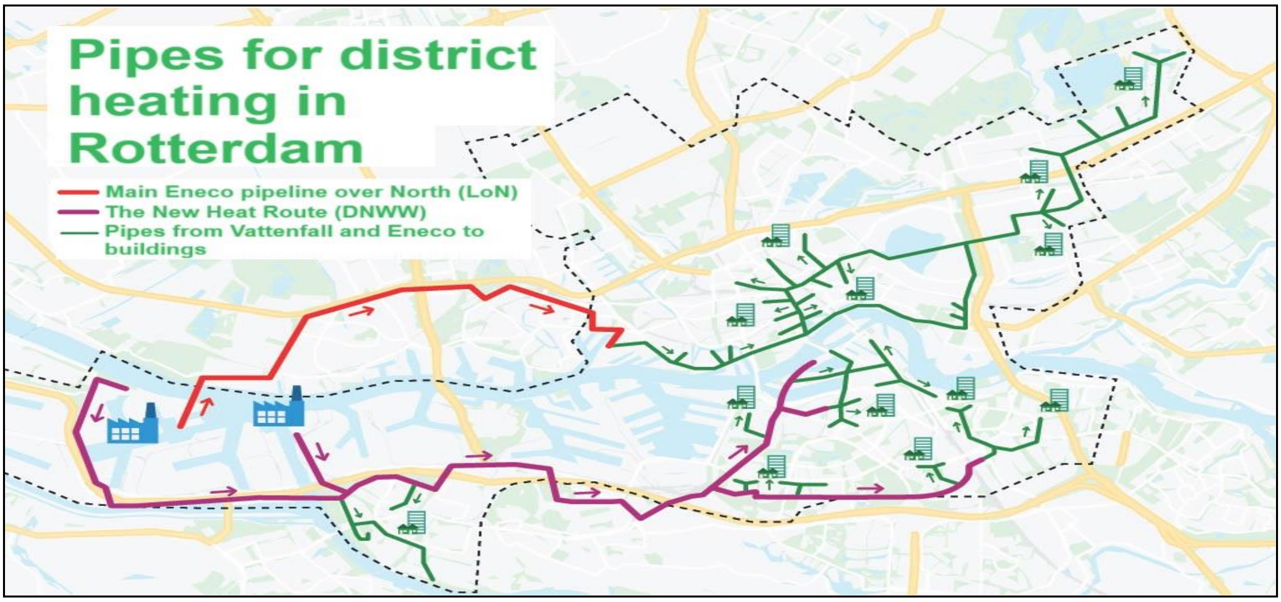

Figure 17: Rotterdam Heating Network Responsible adapted from Rotterdam Municipality (2022a)

On the other hand, the Minister of Climate and Energy recently suggested replacing the current ‘Warmtewet’ (Heat Act) with the ‘Wet Collectieve Warmte’ (Collective Heat Law), giving more public control over the new heat projects and safeguarding public interests. With this law, only heat companies that are public entities and have more than 50% or at least 50% plus one share can participate in the new heat plots (Ministerie van Economische Zaken en Klimaat, 2023). With this law, RM will have a central steering role in the energy transition and be equipped with tools to lead the cost-effective construction of collective heat systems. This will bring opportunities for the municipality to plan and design the building of new heat projects for other urban infrastructure projects. The law is still in process but is expected to be effective next year, 2024.

4.2.3. Open Space

Green areas, such as gardens, parks, sidewalks, and city roads, comprise the Open Space infrastructures. RM’s infrastructure projects follow two primary documents: ‘Visie Openbare Ruimte 2019-2022 Rotterdam’ (Vision Public Space 2019-2022) and ‘Rotterdamse Stijl’ (Rotterdam Style). The Vision Public Space explains RM’s ambition to have a sustainable, green, healthy city by 2030. The ambition desires to move towards an integrated approach and, therefore, links various programs and policy themes, such as replacement programs for sewerage, roads, greenery, ‘Rotterdam Weerwoord’, ‘Rotterdam gaat voor groen’ (Rotterdam goes green), housing construction, energy transition and mobility transition. Following this ambition, whenever streets are opened for maintenance and renewal, it will be done from the property boundary to the property boundary, including renewal of the outdoor space (Stadsbeheer Rotterdam, 2020). The Rotterdam Style is a guideline to unify and maintain the outdoor space’s appearance. It describes the design principles per area, including the characteristics of the materials and objects, the lighting and the planting. Rotterdam Style aims to keep the city attractive and facilitate its maintenance.

In summary, Rotterdam’s urban infrastructures are responsible for the municipality and going through different climate resilience phases. On the one hand, the existing urban infrastructures, such as sewerage systems and open spaces, are phasing the adaptation phase. As mentioned in Figure 8 of Sub-Section 2.1.3., the municipality assesses, plans, redesigns and reconstructs its infrastructure in the Adaptation Phase to increase climate resilience based on the knowledge the municipality learned through the previous phases of the cycle. On the other hand, since the heating infrastructure is currently being designed and built for the first time, this infrastructure system is phasing the Prevention Phase.

4.3. Rotterdam Municipality’s Actions for Climate-Resilient Infrastructure

According to the Municipality of Rotterdam (2019), the city has undertaken climate change adaptation actions since 2008, guided by a strategic vision and water management plans. Efforts began with the implementation of 'Water Plan 2' and progressed with the launch of the 'Rotterdam Climate Proof programme, culminating in formulating the 'Rotterdam Adaptation Strategy' in 2013. The next year, the regional flood risk management was created under the ‘National Delta Programme’, which RM has been working on. Although the ultimate goal is for the country to be climate-resilient and water-robust by 2050, RM aims to achieve this by 2025 due to its geographical characteristics. The city has areas that are below sea level, making the region vulnerable to flooding and reliant on the robustness of their dikes. Therefore, to implement the Spatial Adaptation National Delta Program locally, RM created ‘Rotterdam Weerwoord’, a strategic response that analyses climate change's critical impacts on their infrastructure. Figure 18 describes the implementation of climate resilience at the national, regional and municipal levels, where the last level is the focus of the research.

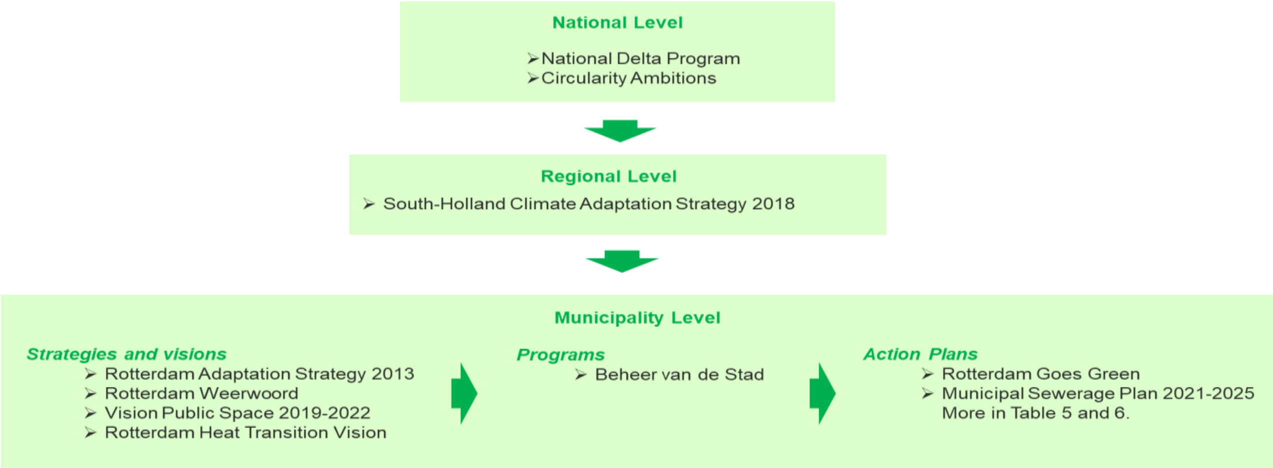

Figure 18: Climate Adaptation Strategies in Rotterdam

At the municipal level, RM has implemented resilience practices into each stage of its infrastructure life cycle. Table 5 provides a breakdown of RM's current actions, mapping each to the corresponding phase of climate resilience linked to the organisation- prevention and adaptation- and to the infrastructure life cycle described in Figure 9, section 2.3.

Table 5: Rotterdam Municipality's Actions: Alignment with Climate Resilience and CRI Life Cycle (Rotterdam Municipality, 2022)

Climate Resilience Phase	Infrastructure Life Cycle	Actions
Prevention	Design	Considering the new heating network in the renewal of the sewerage.
	Construction	Improving the quality of the subsurface.
	Operational	Additional management and maintenance of frequently used walking routes for older adults and people with disabilities.
		Major maintenance on roads (mainly sidewalks and cycle paths) of poor or insufficient quality.
		Areas with an increased risk of groundwater flooding are given priority in the sewer replacement program.
		Conduct a technical inspection of green areas based on the NEN System.
Adaptation	Assessment	"Verordening Beheer Ondergrond Rotterdam" (VBOR) contains regulations for connecting to the municipal sewer. Additionally, 50 mm water storage must be constructed for new site pavings of 500m2 and more.
		Studies into applying and maintaining permeable paving, silent stones and grass paving.
	Planning	Outdoor areas are starting to be considered in the Municipal Sewerage Plan 2021-2025.
	Redesign	Sewer replacement and construction of a separate system.
		The Rainwater Regulation bans draining rainwater into municipal public wastewater sewers. Therefore, plot owners must collect rainwater within their plots. They can connect it to the public rainwater supply if they cannot do so.
		Biodiversity Implementation Agenda, which embeds biodiversity in the city's development during the design and management principles and guidelines.

4.4. Rotterdam Municipality's Application of Integrate Infrastructure Design Approach

According to the Municipal Sewerage Plan, the intervention scale lens that RM has been working on corresponds to the area-oriented approach since their urban infrastructure transcends the district level. Additionally, the plan highlights the necessity of involving residents and other organisations related to the area and the urban infrastructures in their projects, relating to the transdisciplinary lens of IIDA. After exploring the municipality's actions in the context of climate resilience in the previous section, these actions are analysed through the IIDA lenses, showing how RM's organisation actions tackle climate resilience holistically. Table 6 describes some actions RM has taken through IIDA lenses.

Table 6: Rotterdam Municipality's Climate Resilience Actions through IIDA lenses (Rotterdam Municipality, 2022)

IIDA Lenses	Description	Actions
Functional	Integration of different functionalities in a project.	Biodiversity Implementation Agenda, which embeds biodiversity in the city's development during the design and management principles and guidelines.
		Outdoor areas are starting to be considered in the Municipal Sewerage Plan 2021-2025.
Transdisciplinary	Integration of skills and experience from different stakeholders and disciplines throughout collaboration.	Rotterdam Cooperation in the Waste Water Chain (RoSA) is a cooperation agreement signed in 2013 between RM and Water Boards: Hollandse Delta, The Delfland, Schieland and Krimpernerwaard. Together, they are working on agreements to improve their collaboration.
		The initiative project of Stadse Werken Contract Framework is a contract with ten contractors who will pay attention to sustainability, innovation, and communication to replace the sewer system (SEB, 2021).
		Water and Climate consultations with water boards, Capelle and De Ijseel municipality, and private water company Evides.
Technological	Integration of digital technologies and data.	Cross-cluster geo-community increases knowledge shares and inspiration.
		The Basic Subsoil Registration to gain spatial and integral insight into the subsurface.
		Recording and managing 3D object data within the 3D chain.
		The Land Registry provides information about the location of cables and pipelines.
		Workshops will inform the digitalisation and automatisation of the applications and tools available for the workers (Stadsbeheer Rotterdam, 2020).
		Implement the Centralized Automatic Control System (CAS) 2.0 for efficient and automatic system management using process data (Stadsbeheer Rotterdam, 2020).
		The City as a Measurement Network project aims to integrate different measurement networks and move towards a comprehensive system analysis (Stadsbeheer Rotterdam, 2020).
Synergistic	Integration of objectives from diverse critical transitions and ambitions.	Coordinate management and look ahead to future subsurface use, coordinated with above-ground activities and ambitions.
		Creation of the Urban Programming Public Space.

The actions of Table 6 have helped RM develop pilot projects such as Water Plazas and Green-Blue Schoolyards and execute simultaneous sewer renewal projects with new heating networks.

An example is the research and development of maps of the leading climate effects that (will) impact the city, presented in Table 7 by RM, Water Boards and Evides, a private company. Table 7 presents those climate effects in six themes: precipitation, heat, drought, groundwater, flooding and land subsidence (Rotterdam Municipality, 2019a). This action is essential for a better understanding the context problem that local infrastructure projects need to consider to be designed.

Table 7: Local Infrastructures Impacted by Climate Events by Rotterdam Municipality (2019a)

		Climate Events					
		Precipitation	Heat	Drought	Groundwater	Flooding	Land Subsidence
Local Infrastructures	Sewer System	X	X	X		X	X
	Water System	X	X	X		X	
	Open Space	X	X		X		X
	Heating		X			X	X
	Roads	X			X	X	X

The degree of impact has been mapped locally, so depending on the location of the urban infrastructure, some climate events will have a higher or lower impact. These maps can be found in Appendix A. Following, some pilot projects are described as examples on how RM has applied IIDA to enhance CRI. These projects were mentioned by different interviewees during the interview phase.

4.4.1. Water Plazas

Water Plazas are a multifaceted solution that addresses both technical and social needs within urban neighbourhoods, see Figure 19. Technically, they are engineered to store significant volumes of water, which can hold 1.7 million litres of rainwater during wet periods (RM5). When the weather is dry, these spaces are transformed into recreational areas for the community to enjoy. On the social front, Water Plazas contribute to creating a distinct neighbourhood identity, enhancing safety by reducing flooding, and encouraging physical activity through sports and other outdoor activities. However, the outcome might have been vastly different if the municipality had adopted a siloed approach. According to the municipality water expert, the focus would likely have been on traditional infrastructure solutions, such as designing large pipelines to capture stormwater or constructing infiltration crates for rain collection. Alternatively, the creation of urban water buffers might have been considered. These conventional methods, while functional, lack the multifunctional benefits that Water Plazas offer, such as community engagement and recreational value.

Figure 19: Water Plazas from an internal document: RM4

The integrated infrastructure design approach in Water Plazas addresses the practical issue of water management and enhances the quality of urban life. Table 8 describes the implementation of IIDA in this project.

Table 8: Implementation Lenses in Water Plazas from an internal document: RM4

Lens	Description	Explanation
Functional	Integration of different functionalities in a project.	Outdoor space, stormwater storage
Transdisciplinary	Integration of skills and experience from different stakeholders and disciplines throughout collaboration.	Rotterdam Engineering firm, Waterboard Schieland and Krimpenerwaard, residents
Synergistic	Integration of objectives from diverse critical transitions and ambitions.	Climate Adaptation, Renewal Sewerage
Scale of Intervention	Scale level	Local

4.4.2. Green-Blue Schoolyard Project

The pilot project incorporates several technical and social considerations alongside financial planning. From a technical standpoint, it includes the enhancement of greenery to increase shade, surface, and soil infiltration, alongside implementing water storage solutions. The social aspect focuses on creating an outside learning environment for students, fostering a better social climate, promoting physical activities, and aiming to reduce bullying incidents. Figure 20 shows the contrast between a typical schoolyard designed by a siloed approach (left side) and the new design applying an integrated design approach (right side).

Figure 20: Typical Dutch Schoolyard (left) vs Green-Blue Schoolyard (right) from an internal document: RM3

Table 8 describes the implementation of IIDA in this project.

Table 9: Implementation Lenses in Green-Blue Schoolyard from an internal document: RM3

Lens	Description	Explanation
Functional	Integration of different functionalities in a project.	Play and learning landscape, water storage.
Transdisciplinary	Integration of skills and experience from different stakeholders and disciplines throughout collaboration.	Play and learning landscape, water storage.
Synergistic	Integration of objectives from diverse critical transitions and ambitions.	Biodiversity Program, Resilience Rotterdam, Healthy 010 Program, Rotterdam Go Green, Educational Program
Scale of Intervention	Scale level (small-win approach or area approach).	local

4.4.3. Sewer System Renewal and Energy Transition

Due to the energy transition and the sewer system renewal, Rotterdam Municipality found an opportunity to execute both projects together. To achieve this, the municipality used technology tools to visualise the conflict areas and negotiate with private companies to distribute the financial costs. Figure 21 shows how the municipality uses an approach delimited in phases. Table 10 indicates which IIDA implementation lenses were used. However, from the practical side, a new lens is perceived to be used: the time lens. This will be mentioned again in the next chapter.

From a technical perspective, enhancing urban resilience involves incorporating more greenery to increase shadow areas, which can reduce the urban heat island effect. Additionally, renewing sewer systems, explicitly separating dirty and rainwater, is critical to improve water management and reduce the risk of flooding during heavy rainfall events. On the other hand, on the environmental front, efforts are focused on minimising CO2 emissions. This is achieved through initiatives like the gas-free transition, which aims to reduce reliance on fossil fuels. Furthermore, efficiency is enhanced by opening streets for necessary infrastructure work once instead of multiple times. This reduces emissions, minimises community and environmental disruption, and shares excavation costs with the private company. Therefore, following the characteristics of climate-resilient infrastructure, both infrastructures have been designed, considering each interdependency through 3D visualisation. Furthermore, how they were executed aligns with the characteristics of minimising CO2 emissions.

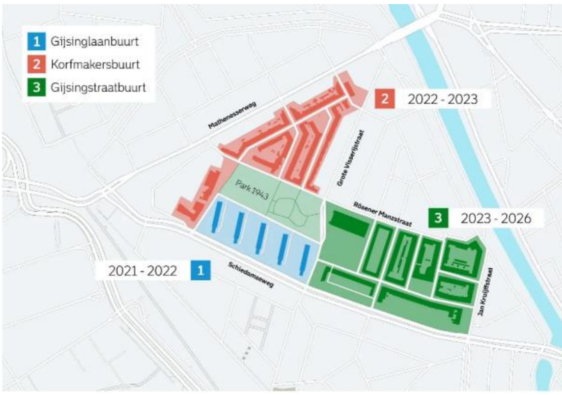

Figure 21: Energy Transition Project Plans in Bospolder-Tussendijken Area from Duurzaam010. (n.d).

Table 10 describes the implementation of IIDA in this project.

Table 10: Implementation Lenses Sewer System Renewal in Bospolder-Tussendijken Area from (Rotterdam Municipality, 2019b) and Ministerie van Algemene Zaken. (2020).

Lens	Description	Explanation
Transdisciplinary	Integration of skills and experience from different stakeholders and disciplines throughout collaboration.	Water Management Disciplines, Underground Designers, Landscape Designers, Residents, ENECO (heating company)
Synergistic	Integration of objectives from diverse critical transitions and ambitions.	Climate Adaptation, Maintenance, Energy Transition
Scale of Intervention	Scale level (small-win approach or area approach).	Area-approach
Technological	Integration of digital technologies and data.	GIS, 3D visualisation software

4.5. Conclusions

This chapter answered the following sub-question: “SQ3: How are municipalities implementing an integrated infrastructure design approach to enhance climate-resilient infrastructure? Through a document review, Rotterdam Municipality was used as a case study to find the answer to this question, where several documents were reviewed to understand how RM has been implementing this approach to enhance climate resilience. The municipality has been implementing IIDA through a holistic integration across various levels of project management—strategic, program, and project.

At the strategic level, RM facilitates the integration of departmental and organizational programs into cohesive strategic frameworks, which sets out long-term infrastructure objectives for the city. This level emphasises the importance of synergistic and transdisciplinary collaboration, aligning various stakeholders towards common goals and enabling the integration of diverse expertise and perspectives. At the program level, RM focuses on aligning policies, financial frameworks, and data related to infrastructure projects. At this level, the technology lens plays a critical role by standardizing the integration of digital data and technologies across different stakeholders, facilitating informed and coordinated decision-making. Lastly, at the project level, the formulation of project plans and the establishment of requirements through participation rounds illustrate the application of the functionality and transdisciplinary lenses.

The practical implementation of IIDA in projects like Water Plazas, Green-Blue Schoolyard and highlights its effectiveness. These projects integrate technical solutions with social considerations, enhancing community engagement and environmental sustainability while addressing specific climate impacts like flooding and heating. The combined approach not only meets immediate functional needs but also fosters a supportive social environment and enhances overall community resilience. On the other hand, the Bospolder-Tussendijken project enhance CRI by focusing on both the technical and environmental aspects, while also considering community impact and economic efficiency.

In conclusion, by implementing IIDA, municipalities are effectively enhancing CRI, since this approach allows for a nuanced integration of technical, social, and economic factor. Thus, through strategic planning, stakeholder integration, and innovative project execution, municipalities are setting a robust foundation for climate-resilient urban development.

Chapter 5: Thematic Analysis - Interviews

The chapter addresses the research sub-question “SQ4: What factors influence municipalities’ effectiveness in using an integrated design approach to enhance climate-resilient infrastructures?” This chapter structure is organised into five sub-sections for a detailed description of this phase. Section 5.1 details the data collection method selected for the mentioned subquestions. In section 5.2, the procedure for the selection of the interviewees is described. Section 5.3 explains the interview protocol used, while section 5.4 describes the data analysis procedure. Section 5.5 describes the factors from the interviews that influence the municipality’s effectiveness in using IIDA. Section 5.6 describes the new IIDA lenses founded in practice. Lastly, Section 5.7 concludes the chapter by answering the sub-question.

5.1. Data Collection through Interviews

The data was collected through two types of interviews: unstructured and semi-structured, since each type offers different advantages to the research. The first type is suitable for acquiring knowledge and customising questions to the interviewer's experience (Chauhan, 2022). Thus, unstructured interviews were used to interview a role for the first time. For example, the first interview with an energy advisor was unstructured to explore the role’s function within the municipality and his influence on local infrastructure projects. Seven unstructured interviews were done, and all data were obtained through meeting notes and transcripts.

On the other hand, in semi-structured interviews, the interviewer can steer the interview flow without discouraging detailed responses (Thumburmung et al., 2016). This type of interview helped guide the interview in collecting the data necessary to answer the sub-questions. Therefore, a protocol guide was created with open questions to avoid yes-no answers. Fifteen semi-structured interviews were conducted, and all data were collected through meeting notes and transcripts.

5.2. Selection of Interviewees

The interviewees selected for the data collection are characterised into two groups: management roles and disciplinary roles. Even though the first group are not involved directly in the design process, from the document review, it was noticed that the implementation of IIDA needs to be aligned with the work procedure at different project management levels (strategic, programme and project). Therefore, these roles were invited to participate in the interviews since their responsibilities and tasks can influence the outcome of the design process. These participants fulfilled the following criteria:

A. Roles: Participants with a management role whose responsibilities directly or indirectly influence the conception of urban infrastructure projects and the design process. Some examples are project managers, process managers, and program managers.

B. Urban Infrastructure: Participants' responsibilities and tasks can influence the design outcome of the open space, sewerage system, or heating network.

C. Experience: Participants must have at least half a year in their role to ensure they understand and are familiar with the municipality's work procedure. Project and program managers should have experience in projects where IIDA has been implemented.

The second group, disciplinary roles, participated in the design phase. They fulfil the following criteria:

A. Roles: Participants with disciplinary roles and knowledge needed in the design phase. They could have technical expertise in urban infrastructures (open space, sewerage, or heating networks) or in the design process.

B. Urban Infrastructure: Participants' responsibilities and tasks can influence the design outcome of the open space, sewerage system, or heating network.

C. Experience: Participants have experience working in integrated design projects or pilots.

Considering the limitations of the interviews, such as the lack of transparency or the difficulty of maintaining the anonymity of the participants (Knott et al., 2022), the data will be anonymised in codes. Table 11 presents the list of roles that participated in the interviews. Each participant was assigned a code to prevent the reader from identifying them, giving the interviewees more freedom and trust to express themselves openly (Knott et al., 2022).

Table 11: List of selected participants for interviews

Category	Code	Role	Interview Type	Interview Duration (min)
Management Roles	MR1	Process Manager	Unstructured	47
	MR2	Strategic Advisor	Semi-Structured	43
	MR3	Project Manager	Semi-Structured	54
	MR4	Integral Manager	Semi-Structured	53
	MR5	Programma Manager	Semi-Structured	59
	MR6	Project Manager	Semi-Structured	55
	MR7	Programma Manager	Semi-Structured	54
	MR8	Project Manager	Unstructured	45
Disciplinary Roles	DR1	Urban Water Advisor	Unstructured/ Semi-Structured	40/47
	DR2	Infrastructure Design Advisor	Unstructured/ Semi-Structured	40/80
	DR3	Urban Water Advisor	Semi-Structured	45
	DR4	Urban Design Advisor	Semi-Structured	54
	DR5	Underground Design Advisor	Unstructured	45
	DR6	Circular Advisor	Unstructured	53
	DR7	Urban Design Advisor	Semi-Structured	40
	DR8	Energy Advisor	Unstructured	40
	DR9	Energy Advisor	Semi-Structured	49
	DR10	Landscape Designer	Semi-Structured	57
	DR11	Landscape Designer	Semi-Structured	57

The selected participants were found and contacted in different ways. For example, through the municipality's supervisor network, contacts related to a specific project or pilot related to the integrated design approach, suggestions from potential participants who could not participate due to their schedules and suggestions of the interviewees. Selecting participants from different project teams or different personal networking ensures that the collected data represents better the actual situation of the municipality.

5.3. Semi-Structured Interview Protocol

The municipality's email invited all participants to participate in the interview. Participants who voice-recorded interviews received a confidential agreement form in the email. The agreement form describes the study's objective and explains how the data will be stored and managed. The first emails and the agreement form were prepared in Dutch and English so that participants could understand all the instructions and reduce misunderstandings. Another email describing the themes was sent to participants who required more information about the interview.

On the interview day, interviewees were reminded that the interview would be recorded, and the structure was explained. The interview was structured in three stages. The first stage started with introduction questions, during which the interviewees introduced their roles, responsibilities, and years of experience. The second stage began with introducing the themes and the predetermined questions, see Appendix B. The four themes included awareness of climate-resilient infrastructure, influence factors in the design phase for climate resilience, challenges and enablers in using an integrated infrastructure design approach and recommendations to extend this approach to other urban infrastructure projects. Lastly, in the last stage, interviewees were asked for additional comments and suggestions for potential participants.

5.4. Thematic Analysis Procedure

All data from interviews were subjected to a thematic analysis. This technique is precious for offering a detailed and flexible understanding of the topic while being less time-consuming than other analytical methods (Humble & Mozelius, 2022). Moreover, thematic analysis facilitates identifying and articulating key themes emerging from the data, providing a comprehensive view of fundamental concepts and issues (Lochmiller, 2021). These characteristics make this analysis suitable for the collected data since this research topic demands a holistic approach. Lastly, this analysis allowed the discernment of challenges, barriers, and enablers to determine the municipality's influential factors of effectiveness.

The thematic analysis procedure was done by adapting the following step-by-step systematic process developed by Naeem et al. (2023), see Figure 22, and using the software Atlas ti. This process starts with selecting the quotations, which was done two times: at the end of each interview from the meeting notes and once the transcripts were ready. Moreover, after each interview, registration of the ongoing reflections was done through memos. These memos helped select quotations since some characteristics, like the interviewee's tone, were registered. Some keywords were selected from these quotations to be used later to code them. The coding process has to be done through a blended approach: first, through inductive coding, followed by deductive coding. Linneberg and Korsgaard (2019) explain that starting the coding process with inductive coding ensures that the analysis will be loyal to the collected data and still allow the possibility to elaborate further on the theory in the second coding cycle. Therefore, the first-cycle coding was created directly from the interviewees' quotations, ensuring that the codes do not involve the external thoughts of the researcher (Linneberg & Korsgaard, 2019).

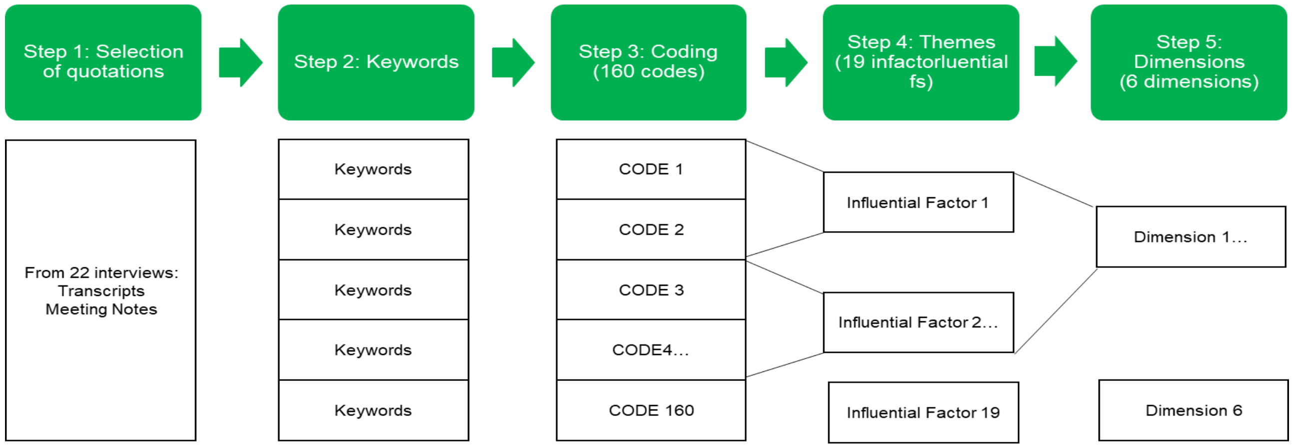

Figure 22: A systematic thematic analysis process adapted from Naeem et al. (2023)

The second cycle started once all the transcripts and meeting notes were coded. For the deductive coding, pre-defined codes from the literature review were created, which later were used as guidance to make the themes. At the end of this process, 160 codes were formulated. During the formulation of codes, some patterns were distinguished, which helped to group the codes into themes. For example, codes such as "positive - creativity, drive new solutions", "negative - lack adaptability, reluctance to take risks", "positive - collaborative, drive shared objectives", and other similar codes were grouped under the theme "Internal Actor Soft's Skills". Each theme represents an influential factor that impacts the municipal's effectiveness in enhancing climate resilience through an integrated infrastructure design approach. The data collected found 19 influential factors described in the next section.

5.5. Influential Factors in Integrated Infrastructure Design Approach's Implementation in Rotterdam Municipality

The thematic analysis identified nineteen factors, which were subsequently categorized into six dimensions: Human Capacity, Organizational Culture, Governance, Information and Knowledge, Project Development Process, and Finance, as detailed in Table 12. This diverse range of dimensions highlights the importance of adopting a comprehensive perspective that is crucial for municipalities to effectively implement an integrated design approach. Moreover, organizing these factors into distinct dimensions helps municipalities to recognize and prioritize critical elements such as human capacity, organizational culture, information, and knowledge. In this subsection, each dimension and its associated influential factors are thoroughly discussed. Additionally, a detailed examination of each factor provides insight into the context of their identification and the rationale behind their associated codes.

Table 12: List of Influential Factors per Dimension

Dimension	Influential Factors
Human Capacity	Internal Actor's Soft Skills
	Internal Actors' Awareness to Enhance Climate-Resilient Infrastructure
	Internal Actors' Awareness and Willingness to Change
Organisational Culture	Internal Actors' Engagement
	Internal Actors' Awareness of Roles and Capacities of Other Actors
	Cross-Disciplinary Collaboration
Governance	Policies and Regulations at the Municipal Level
	Higher Level Support in Climate Resilience
Information & Knowledge	Utilising Pilot Project for Knowledge Transfer and Innovation
	Cross-Departmental Information Sharing and Alignment
	Knowledge Sharing and Retention
	Technology Tools
Project Development Process	Alignment of Integrated Design Approach in Project Management Levels
	Criteria for Climate-Resilient Infrastructure
	External Actors' Engagement
	Integration Intervention Scale
	Timing for Decision-Making in Design Integration
	Technical Design
Finance	Budget Allocation

5.5.1. Human Capacity Dimension

This dimension groups the influential factors related to internal actors' competencies and knowledge. This dimension aims to highlight the foundation's organisation for enhancing climate-resilient infrastructure with the awareness and the right skills from the internal actors. Three influential factors related to this dimension were found: internal actors' soft skills, internal actors' awareness to enhance climate-resilient infrastructure and internal actors' awareness and willingness to change

Internal Actors' Soft Skills

This influential factor was created from 21 codes coming from management and discipline roles, see Table 13. It was emphasized as the most critical by all interviewees, highlighting essential skills such as collaboration, a holistic view, proactivity, and open-mindedness. For instance, MR5 noted, "The process is important, but it will not succeed if the individual professional is not willing to understand", underscoring the detrimental effects of lacking open-mindedness in project development. Additionally, MR4 highlighted the necessity of this soft skill, stating, "one needs to be open-minded also to know about other aspects", which is crucial for developing appropriate strategies. Similarly, DR10 emphasized the collective attitude required: "I think it is everyone's attitude to be open. We have to value everyone's few points and then to come to a good strategy for the area".

On the other hand, as noted in sub-section 2.2.4, during the Adaptation Phase of the Climate Resilience Cycle, there is an emphasis on the need for organisational innovation in processes. The interviews revealed that for such innovations to be effective, it is imperative for internal actors to possess the soft skills listed in Table 13. For example, collaboration is crucial for enhancing synergy, while proactivity drives adaptability and encourages a shift in the organization's mentality.

Table 13: Influential Factor: Internal Actor's Soft Skill - Codes

Influential Factor: Internal Actor's Soft Skills			
Codes	Number of Interviewees		
	MR	DR	Total
Negative - lack of adaptability, reluctance to take risks	-	1	1
Negative - lack of holistic view, barrier to integrated projects	-	1	1
Negative - lack of holistic view, impact on the success of projects	1	-	1
Negative - lack of open-mindedness	1	-	1
Negative - lack of proactivity	-	1	1
Positive - collaborative, drive shared objectives	3	5	8
Positive - collaborative, enhance synergy	-	1	1
Positive - communication, informed actors.	-	1	1
Positive - creativity, drive new solutions	1	2	3
Positive - cross-functional skills, drive holistic view	4	3	7
Positive - curiosity, drive teamwork	-	1	1
Positive - holistic view, enhances resilience	3	2	5
Positive - negotiation, drive solutions	1	1	2
Positive - open-mindedness, drive new solutions	1	4	5
Positive - persistence, successful results	2	1	3
Positive - persuasive, drive budget allocation	1	-	1
Positive - persuasive, steer mentality change	2	1	3
Positive - proactive, enhanced adaptability	-	1	1
Positive - proactive, enhance innovation	1	2	3
Positive - proactive, lead by example.	-	2	2
Positive - strategic, resourcefulness	2	1	3

Internal Actors' Awareness to Enhance Climate-Resilient Infrastructure

This influential factor was created from seven codes coming mostly from discipline roles, see Table 14. This factor was formulated from the answers obtained in theme 1 of the interviews, see Appendix B. Some discipline actors highlighted awareness of local environmental conditions; for example, DR5 mentioned, “We live in a Delta that has many geological problems because there is subsidence when the water levels go down.”. Others emphasised the existence and urgency of adapting: “It is a matter of time because everybody needs to realise that what used to be the standard solution is not a standard solution in the future” by DR1 and “We have a problem, and we have to change ourself.” by DR2. Furthermore, some management roles noticed a need for change in finding solutions and adapting municipal project development processes; as MR7 mentioned, “You also need to redesign, and that is also a whole different process.”.

Table 14: Internal Actors' Awareness to Enhance Climate-Resilient Infrastructure - Codes

Influential Factor: Internal Actors' Awareness to Enhance Climate-Resilient Infrastructure			
Codes	Number of Interviewees		
	MR	DR	Total
Awareness of the city's environmental conditions	1	1	2
Awareness of climate impacts	1	1	2
Change of mentality for climate-resilient infrastructure	2	3	5
Climate-resilient infrastructure is not a choice.	-	1	1
Every role needs to acknowledge climate variations.	-	1	1
Positive - persuasive, steer mentality change	2	1	3
Time urgency for climate-resilient infrastructure	-	2	2

Internal Actors' Awareness and Willingness to Change

This influential factor was created from eight more codes from both roles; see Table 15. This factor was formulated from the answers obtained in theme 2 of the interviews, see Appendix B. Disciplines and management roles are aware of the benefits of this approach, as DR1 pointed out how through IIDA, new ideas are possible to be thought of, “they have got creative ideas that I would not have thought about, […] And that is the interesting part of the integrated design.” Furthermore, DR2 emphasised that solutions from a siloed approach will not be feasible for the city since “if you did it only sectoral, you would make a bigger sewage pipe and nobody likes to walk through a sewer. I mean, it is nothing for it. There is no value besides getting the water out”. On the other hand, some management roles are becoming more aware of losing opportunities if projects are not developed with an IIDA; like MR7 said, “I think if we just look at it from a maintenance side, sometimes we miss those opportunities”.

Table 15: Influential Factor: Internal Actors' Awareness and Willingness to Change - Codes

Influential Factor: Internal Actors' Awareness and Willingness to Change			
Codes	Number of Interviewees		
	MR	DR	Total
Awareness of the Integrated Design Approach positive outcome	-	1	1
Awareness of the limitations of the siloed approach	2	3	5
Integrated design necessary for climate resilience	2	2	4
Negative - lack of adaptability, reluctance to take risks	-	1	1
Positive - persuasive, steer mentality change	2	1	3
Time urgency for climate-resilient infrastructure	-	2	2
Unique opportunity to use the Integrated Design Approach	-	4	4
Ways to spread Integrated Design Approach: Open discussions	2	1	3

5.5.2. Organisational Culture Dimension

This dimension groups the influential factors related to the behaviour and interactions of the internal actors within the municipality. These interactions can be promoted or discouraged by the organisational culture of the municipality. Three influential factors related to this dimension were found: internal actor’s engagement, internal actors' awareness of roles and capacities of other actors and cross-disciplinary collaboration.

Internal Actors' Engagement

This influential factor was created from eleven codes from management and discipline roles, see Table 16. This factor was formulated from the answers obtained in themes 3 and 4 of the interviews, see Appendix B. Different actors from both types commented on management roles being critical to enhancing climate-resilient infrastructure since "The project manager's job is to see and think of which specialists are needed in the project team." (MR3). Moreover, DR4 explains that "people in positions like project managers or people in charge of a design process can help to have a broad view and include more topics in the individual process." Therefore, MR5 considers awareness necessary to achieve IIDA projects successfully and the need for people to be committed ("awareness and willingness are not embedded in your organisation's DNA, then you will not succeed").

Table 16: Influential Factor: Internal Actors' Engagement - Codes

Influential Factor: Internal Actors' Engagement			
Codes	Number of Interviewees		
	MR	DR	Total
Frustration feeling	1	3	4
Importance of awareness and willingness in the organisation	1	-	1
Importance of seeking to do something different	-	1	1
Management role influence in engaging internal actors	2	2	4
Motivation coming from personal decisions	3	1	4
Positive - committed	1	5	6
Positive - empathetic, drive change for climate-resilient infrastructure	3	3	6
Need of many drivers to change	-	1	1
Rigid mindset from some roles	1	3	4
The initiator is responsible for involving inner departments	2	-	2
The initiator responsible for enhancing climate-resilient infrastructure	-	2	2

Internal Actors' Awareness of Roles and Capacities of Other Actors

This influential factor was created from six codes, mainly from discipline roles, see Table 17. This factor was formulated from the answers obtained in theme 3 of the interviews, see Appendix B. Interviewees highlighted the importance of all actors being important to enhance climate-resilient infrastructure DR3 said: “Almost everyone. We can start bottom up, start from top to bottom, and we are all departments”.

Table 17: Influential Factor: Internal Actors' Awareness of Roles and Capacities of Other Actors- Codes

Influential Factor: Internal Actors' Awareness of Roles and Capacities of Other Actors			
Codes	Number of Interviewees		
	MR	DR	Total
Ambiguous recognition of management's role in climate resilience	2	4	6
Every role is essential for climate resilience	1	5	6
Physical representation of "invisible" stakeholders as environment	-	1	1
Recognition of other's capacities	3	2	5
Recognition of one's capacity	1	2	3
Unvalued feeling	-	1	1

However, this perception that all roles are important is crucial in management roles since they involve the necessary disciplines in the project team and what things will be included at the program level. For that reason, MR5 emphasised “take the other's field of expertise seriously and value it as much as your own”.

Cross-disciplinary Collaboration

This influential factor was created from nine codes, mainly from disciplines and management roles, see Table 18. This factor was formulated from the answers obtained in theme 3 of the interviews, see Appendix B. Both types of roles emphasised personal network as necessary; as MR4 mentioned, “Sometimes it is more about the network you have with people, and you can find all your colleagues who work on different aspects and put it all together”. However, DR11 perceives this as a problem, too, “the weak point in that process is that I need a personal network” since people can leave or be moved to another position, starting to create their own personal network again, slowing collaboration. On the other hand, there is a strong division between the maintenance department and development department, as MR7 expressed, “We have Stadsontwikkeling, the design colleagues of Rotterdam, who are the people who want those changes.” This highlights the importance for both departments to cooperate and collaborate since redesigning is part of the maintenance phase when talking about climate-resilient infrastructure lifecycle, see Figure 9 in section 2.3.

Table 18: Influential Factor: Cross-Disciplinary Collaboration - Codes

Influential Factor: Cross-Disciplinary Collaboration			
Codes	Number of Interviewees		
	MR	DR	Total
Importance of having a common goal within departments	1	1	2
Importance of supportive departments	-	1	1
Need for cooperation within departments.	-	1	1
Need for more internal coordination within departments.	-	1	2
Need for personal networking	2	3	5
Negative - separation of (re)design and maintenance	2	-	2
Positive - empathetic, improve collaboration	1	2	3
Not good communication from a specific department	1	-	1

5.5.3. Governance Dimension

This dimension groups the influential factors related to the role of policies and regulations regarding climate resilience. Two influential factors associated with this dimension were found: policies and regulations at the municipal level and higher-level support in climate resilience.

Policies and Regulations at the Municipal Level

This influential factor was created from thirteen codes, mainly from disciplines and management roles, see Table 19. This factor was formulated from the answers obtained in theme 3 of the interviews, see Appendix B. Many actors mentioned collaboration agreements as an enabler to work with external stakeholders, like “the electricity company has to add more cables, they inform the municipality, and then all the utilities are informed that there will be a project on this date on that street. Each utility has the chance to have greater utilities. So, the water, the sewage, and data, of course, telecom” (DR9). These agreements have reinforcement characteristics since “they have work they do together. Otherwise, they wait five years" (MR8). Furthermore, DR11 emphasises that these policies should be "specifically measurable".

Table 19: Influential Factor: Policies and Regulations at the municipal level - Codes

Influential Factor: Policies and Regulations at the municipal level			
Codes	Number of Interviewees		
	MR	DR	Total
Collaboration agreements enhance innovation with parties.	-	3	3
Collaboration agreements, enhance planning with parties	2	3	5
Collaborative policy to enhance climate-resilient infrastructure	1	-	1
Establish rules within departments.	-	2	2
Internal sectorial rules/standards	-	2	2
Need of updating of regulations	-	1	1
Need for uniform city-level policy for climate actions	3	1	4
Pilots can lead to change in legislation.	-	1	1
Policies should be measurable and concrete	1	1	2
Policy to evaluate pilots	1	2	3
Policy to incentivise the use of an integrated design approach	1	-	1
Regulations profit to enhance climate-resilient infrastructure	1	-	1
Storage of agreement	-	1	1

Higher Level Support in Climate Resilience

This influential factor was created from five codes, mainly from discipline roles, see Table 20. This factor was formulated from the answers obtained in theme 3 of the interviews, see Appendix B. Many actors considered it beneficial to receive national support through EU regulations, as DR6 mentioned, "At least it will take longer. Now, the EU. Regulations. Moreover, that is the same. It also takes longer if we do not make the bridge." Moreover, MR2 supported that opinion, "when we started in 2008, it was not very much discussed nationally. There were no regulations, no programme. So it was sometimes difficult for us in the city to have this discussion."

Table 20: Influential Factor: Higher Level Support in Climate Resilience - Codes

Influential Factor: Higher Level Support in Climate Resilience			
Codes	Number of Interviewees		
	MR	DR	Total
EU rules	1	2	3
Importance of each infrastructure depends on the country's culture.	-	1	1
Lack of national interest makes it difficult to discuss climate resilience at the municipal level	1		1
National support	1	6	7
Politics influence to enhance climate-resilient infrastructure	4	-	4

5.5.4. Information & Knowledge Dimension

This dimension groups the influential factors in generating and managing knowledge and information and the technology needed to transform information into data. Four influential factors related to this dimension were found: utilising pilot project for knowledge transfer and innovation, cross-departmental data sharing and alignment, knowledge sharing and retention and technology tools.

Utilising Pilot Project for Knowledge Transfer and Innovation

This influential factor was created from fourteen codes, mainly from discipline roles, see Table 21. Interviewees mentioned pilot projects on learning new ways of working, as MR2 commented: “We want to do a pilot for that just to learn how this works. And now we are using it as a common measure”. Another benefit is replicating these pilot projects once citizens look for positive results. MR6 experiences that change the reaction of citizens in his quotation, “Maybe a seed was planted in the previous period, but schools came out of their own to us, “Is there still a subsidy?” Because we want it too. However, DR2 considers that people should be more involved in participating in pilot-projects, since “if you do not know it yourself, you do not learn it from books. You will only learn it by doing it, and then you can also play a better role.” In this aspect, DR6 supports it as “if you do not get the experience, you do not get the trust in the new systems.”

Table 21: Influential Factor: Utilising Pilot Project for Knowledge Transfer and Innovation - Codes

Influential Factor: Utilising Pilot Project for Knowledge Transfer and Innovation			
Codes	Number of Interviewees		
	MR	DR	Total
Create conditions for a period where people can follow those changes.	-	1	1
Evolution from pilot to typical project	1	-	1
Gathering knowledge from pilots	2	3	5
Good results have a good influence on citizens' future projects	1	1	2
Importance of municipality to have a good image	1	1	2
Importance of learning the process of pilots	-	2	2
Learning by doing	1	1	2
One learns more by being involved than as an observer.	-	1	1
Pilots allow risks	-	1	1
Steer others by being an example	2	2	4
Support base as selection criteria for pilots	2	-	2
Uncertainties from the process of new transitions	-	2	2
Use pilots to increase actors' confidence.	-	2	2
Use pilots to try innovative solutions	1	1	2

Cross-Departmental Information Sharing and Alignment

This influential factor was created from ten codes, mainly from discipline roles, see Table 22. This aims to highlight the importance of sharing information. Like DR5 comments, using technology tools such as “graphic information systems, it is the vehicle that allows you to do those spatial analyses.” Furthermore, DR3 expressed the consequences of not having easily accessible information: “Because when you are too late to go to the other parts to know their wishes, you are busy with the design. It makes it difficult to adjust your design.” Furthermore, it slows down the design process since discipline actors have to “come from the department that designs the system. So before we design our system, we go to the other department and say this is what I am going to do. How about your assets? How about your trees? How about the greenery? Moreover, this is the interaction between all the departments during the planning and the design” (DR3).

Table 22: Influential Factor: Cross-Departmental Information Sharing and Alignment - Codes

Influential Factor: Cross-Departmental Information Sharing and Alignment			
Codes	Number of Interviewees		
	MR	DR	Total
Difficulty in matching planning	2	1	3
Importance of technology to manage data	-	2	2
Knowing late departments' wishes	-	2	2
Lack of accessibility of project plan schedule	2	-	2
Mapping climate impacts	1	-	1
Mapping current conditions of urban infrastructures	-	4	4
Need to transform data.	-	1	1
No information about other department plans	-	2	2
Project registration of ideas	-	1	1
Share information about how the organisation works.	-	2	2
Go from department to department to verify an idea.	-	2	2

Knowledge Sharing and Retention

This influential factor was created from eight codes, mainly from discipline roles; see Table 23. This factor highlights the importance of retaining information and knowledge from actors and pilot projects. On the one hand, DR11 is concerned when someone new enters the job at the municipality. This person will have to "discover how the municipality works, and the problem was […]nobody really had this position before me for at least half a year, […] so I had to discover myself, how does it work? What is the process to follow? However, also, how do you do this successfully?". This causes a slowdown until the new person learns how to fulfil their role. On the other hand, despite Rotterdam Municipality having multiple pilot projects, MR3 indicated that "although they made learning questions before they started the process. Nevertheless, yeah, there are just no standards".

Table 23: Influential Factor: Knowledge Sharing and Retention - Codes

Influential Factor: Knowledge Sharing and Retention			
Codes	Number of Interviewees		
	MR	DR	Total
Collect knowledge to teach others	3	2	5
Importance of climate adaptation knowledge	1	-	1
Knowledge needed as selection criteria for pilots	-	1	1
Loss of knowledge when a colleague leaves the organisation	-	1	1
No standards for retrieving knowledge	1	-	1
One learns more by being involved than as an observer.	-	1	1
Open Knowledge	1	1	2
Ways to spread Integrated Design Approach: Workshop	-	1	1

Technology Tools

This influential factor was created from four codes, mainly from discipline roles, see Table 24 This influential factor is related to the use and accessibility of technology tools such as 3D visualisation, like DR5, which highlights "3D, that is, in the development of 3D for the subsurface. As a unique vehicle that allows you to see what is happening concerning the soil, the depth, and how you can build on the surface." This is supported by management role MR5, who find this a solid tool to reserve space for specific infrastructures "we have visualised. Indeed if in the future we want to have this and that and that there, space must be reserved now". Lastly, interviewees emphasise the use of GIS too".

Table 24: Influential Factor: Technology Tools - Codes

Influential Factor: Technology Tools			
Codes	Number of Interviewees		
	MR	DR	Total
Importance of communication technology	-	1	1
Importance of technology to manage data	-	1	1
Importance to use 3D visualisation	2	4	6
Positive - proactive, enhanced innovation	1	2	3

5.5.5. Project Development Process Dimension

This dimension groups the influential factors related to the development of local infrastructure projects through the three project management levels (strategic, program, and project). Six influential factors were associated with this dimension: alignment of integrated design approach in project management levels, external actors' engagement, criteria for climate-resilient infrastructure integration intervention scale, timing for decision-making in design integration, and technical design.

Alignment of Integrated Design Approach in Project Management Levels

This influential factor was created from ten codes, mainly from discipline roles, see Table 25. This influential factor is related to aligning integration at the three management levels (strategic, programme, and project). Many actors, such as DR6, consider integration should start at a higher level than a project, "the best way to implement it to standardise it. Is basically at the level of definition of the assignment but not on project level even higher.". This idea is also supported by management roles such as MR6 ("a new programme") and MR5 ("at every scale level, you need to want to adopt this way of working").

Table 25: Influential Factor: Influential Factor: Alignment of Integrated Design Approach in Project Management Levels- Codes

Influential Factor: Alignment of Integrated Design Approach in Project Management Levels			
Codes	Number of Interviewees		
	MR	DR	Total
Assess requirements before the scoping phase	1	1	2
Need of flexible scope project	-	1	1
Need of integration at programma level	3	2	5
Need to adapt the process.	-	1	1
Planning ahead	1	1	2
Positive - finding synergies increases the chance of success.	-	1	1
Rigid process, loss of opportunities to enhance climate-resilient infrastructure	1	1	2
Rigid process, regular outcomes	1	1	2
The importance of aligning every management level	1	3	4
The importance of a team project having common goals	2	-	2

External Actors' Engagement

This influential factor was created from ten codes, mainly from discipline roles, see Table 26. This influential factor is related to the engagement of external actors such as citizens. For example, DR10 noted, "What is being done now is to go as early as possible to the residents, even if you do not have anything.". This highlights the importance of building trust with the citizens. However, MR8 addresses a specific challenge related to community needs and expectations, "The greenery of the neighbours is very strict. Nevertheless, those are not matched with the needs of the neighbours." This highlights the necessity of aligning project goals with the actual desires and requirements of the community, but also to keep informing citizens the reasoning behind municipality's decision to enhance climate-resilient infrastructure.

Table 26: Influential Factor: External Actors' Engagement - Codes

Influential Factor: External Actors' Engagement			
Codes	Number of Interviewees		
	MR	DR	Total
Awareness of involving stakeholders beforehand	1	4	5
Awareness of the role of external parties	1	-	1
External parties involved in the design	2	-	2
Good results have a good influence on citizens' future projects	1	1	2
Importance for municipalities to have/keep steering power	1	1	2
Importance of building a network with citizens	1	3	4
Importance of municipality to have a good image	1	1	2
Influence of citizens to enhance climate-resilient infrastructure	4	2	6
Private companies see climate adaptation as an investment	1	-	1
Share information about how the organisation works.	-	2	2

Criteria for Climate-Resilient Infrastructure

This influential factor was created from ten codes, mainly from discipline roles, see Table 27. This influential factor relates to the design criteria that designers use. For example, DR3 emphasises the importance of the maintenance phase: "It is good to consider maintenance because when you make something, you have to think that what you decide must be maintained."

Table 27: Influential Factor: Designer Criteria for Climate-Resilient Infrastructure - Codes

Influential Factors: Designer Criteria for Climate-Resilient Infrastructure			
Codes	Number of Interviewees		
	MR	DR	Total
Awareness of municipalities' ambitions	3	2	5
Brainstorming diverse design solutions	-	1	1
Consider life cycle infrastructure during the design	1	6	7
Consider mitigation	1	-	1
Importance of thinking about the materials' characteristics for climate-resilient infrastructure		1	1
Important to focus on the user's perspective	1	4	5
Including environmental considerations in the design	1	4	5
Lack of climate-adaptive assessment from departments		1	1
Need for flexible design.	-	2	2
Need to consider time in the design of climate-resilient infrastructure	2	4	6

While MR5 highlights thinking about the execution phase during the designing, "I did not want to have to argue about this during implementation, so from the start, all those profiles are part of the area agreement established with Havensteder and Eneco.". These highlight the importance of considering the future infrastructure phase in the design process. Additionally, DR2 mentioned, "You have to design an infrastructure with the fact of time, the changing time in perspective", bringing another type of IIDA lens: time.

Integration Intervention Scale

This influential factor was created from seven codes, mainly from discipline roles, see Table 28. This factor is related to the intervention scale the municipality uses to integrate. MR5 connects this intervention scale les with a time lens since “To me, the integral design also means anticipating future developments, but not everything needs to be immediate. […]. It is thoroughly integrated. I am already considering where future trees might be placed within those designs. […] So, the integral design concept can also involve anticipation. Moreover, using this time lens, “You can better make the reservation tomorrow and then look up later to see whether I need this reservation, but at least you have a reservation” (DR9). Furthermore, the combination of the intervention scale lens and time lens allows us to anticipate conflict zones due to lack of space; as DR5 commented, “I made the first conflict maps, and we made the first maps to see how we could solve that with the process of changing the sewers.”

Table 28: Influential Factor: Integration Intervention Scale - Codes

Influential Factor: Integration Intervention Scale			
Codes	Number of Interviewees		
	MR	DR	Total
Assessment of current conditions to find opportunities for the future	2	2	4
Combination of different scale	2	2	4
Consideration of the future regarding the area	1	2	3
Human resource limitation	2	-	2
Mapping current conditions of urban infrastructures	-	4	4
Taking interdependencies into consideration	-	6	6
Use of area approach	2	5	8

Timing for Decision-Making in Design Integration

This influential factor was created from five codes, mainly from discipline roles, see Table 29. The significance of this factor comes from considering adjustments within the design process. For instance, DR4 emphasises the importance of early consideration, "If in the process, we need to, I do not know, include more trees or do these types of things, then you are stretching the quality. So it would be to take these considerations beforehand before they are already limiting or scoping the project.". Furthermore, the concept of value extends beyond financial metrics, encompassing broader societal benefits. MR4 introduces the value wheel, illustrating that "money is not the only thing you look at. However, it is also about human capital, the capital of society, like how healthy the city is, how safe the city is or not.".

The necessity for strategic decision-making and prioritisation is further supported by DR11's insight, "You really have to choose between this task or that task. You cannot do them both, but at least ensure you have made it." This reflects the inevitable trade-offs and choices that must be made throughout the process, highlighting the critical nature of prioritisation as described by MR5.

Lastly, DR1 commented, “Stadsbeheer still has to accept the result, so that is not really important with the initiator, but in the end, the way we make our design is, of course, depends on what Stadsbeheer wants." Acknowledging a risk that projects will be accepted from an asset mindset.

Table 29: Influential Factor: Timing for Decision-Making in Design Integration - Codes

Influential Factor: Timing for Decision-Making in Design Integration			
Codes	Number of Interviewees		
	MR	DR	Total
Assess requirements before the scoping phase	1	1	2
Holistic evaluation tool for decision-making	1	-	1
Importance of making decisions, preventing losing opportunities	4	3	7
Maintenance department approving, risk of asset mindset	1	2	3
Positive - finding synergies, increasing chance of success	-	1	1

Technical Design

This influential factor was created from six codes, mainly from discipline roles, see Table 30. This factor is related to the technical design that internal actors consider due to climate resilience. For example, DR1 says, “Every 5-10 years, new calculations of the sewer system, so new data on rains is updated., while MR5 emphasises that it “was climate resilient in the sense that we went from a single sewer system to two separate systems.” And using “natural elements and maybe reduce the amount of hardware needed” (DR4). However, there are some discussions about the differences between engineers and architecture capacities, so DR2 suggests starting with the design concept and later focusing on the technical part. “As soon as you have a concept like the water square that engineers do not design. Architects conceptualise it, and then you need the engineers to make it happen to how do you get get the rainwater out afterwards”.

Table 30: Influential Factor: Technical Design - Codes

Influential Factor: Technical Design			
Codes	Number of Interviewees		
	MR	DR	Total
Natural elements as infrastructure	-	1	1
Technical aspect to enhance climate-resilient infrastructure	3	3	6
Technical aspects after	-	2	2
Unblended rules due to environmental conditions	-	1	1
Update code buildings have a different pace with new transitions.	-	1	1
Update data and calculations for technical codes.	-	2	2

5.5.6. Finance Dimension

This dimension group is conformed to one influential factor: budget allocation. This influential factor was created from six codes between management and discipline roles, see Table 31. From quotations as “ There are many agendas with different budgets” from MR1 and “It is asset-based, […] we have a different system for the sewer. All the assets have multi-year planning with budgets” from MR7, it reflects that the current budget allocation and the projects developed with an integrated design approach are not aligned. This has a negative impact when projects are postponed due to the dependency of diverse departments. MR7 gives an example: “City Development starts struggling with their money and starts delaying, then City Management are also too.”

Table 31: Influential Factor: Budget Allocation - Codes

Influential Factor: Budget Allocation			
Codes	Number of Interviewees		
	MR	DR	Total
Diverse budget allocation	3	1	4
Flexible use of budget	-	1	1
An integrated design approach requires initial cost investment	3	-	3
Labeled money makes it harder to take risks.	-	2	2
Struggle to extend the budget	3	1	4
The financial struggle of one department affects the other	2	1	3

5.6. Implementation Lenses from Practice: Time and Finance

During the thematic analysis, two implementation lenses were identified: time and finance. The former was discovered within the dimension of the project development process as part of the influential factor of design criteria for climate-resilient infrastructure. The time lens pertains to the consideration of the future in design. This can involve planning for future projects within the area. A practical example is the Bospolder-Tussendijken project. For instance, MR5 reported the need to project the alignments of secondary heating pipelines that were not yet scheduled for installation. Consequently, the profiles of the heating pipelines were designed concurrently with the sewerage and green areas, ensuring that these infrastructures maintain the minimum required distance to avoid heat impact. Furthermore, another example of the time lens is the consideration of the lifecycle of infrastructure, such as Water Plazas, which are considered for their filling and draining phases throughout their lifespan. Ultimately, this time lens is used alongside the scale interval lens, merging space and time to identify conflict zones between the interdependencies of local infrastructures, as DR5 expressed.

Lastly, the financial lens was identified within the financial dimension as part of the influential factor of budget allocation. This arises from the synergy lens, as the municipality allocates budgets based on its strategic ambitions. For instance, the greenery programme has a dedicated budget, the energy transition programme has another, and the sewerage renewal programme has yet another. Consequently, when integrated projects are undertaken, the final budget for such a project is composed by consolidating the budgets from these individual programmes. This approach ensures that resources are allocated effectively, supporting the integrated development of various infrastructure initiatives in alignment with broader municipal objectives.

5.7. Conclusions

This chapter answers "SQ4: What factors influence municipalities' effectiveness in using an integrated design approach to enhance climate-resilient infrastructures?" through a thematic analysis from 22 interviews done in Rotterdam Municipality, the case study. In total, 160 codes were formulated from the transcripts and meeting notes of the interviews. From these codes, nineteen themes were created, and these themes were labelled as influential factors. These factors influence Rotterdam Municipality's effectiveness in using an integrated design approach to enhance climate-resilient infrastructure. These factors were grouped into six dimensions to visualise the diverse aspects municipalities must pay attention to in order to implement this approach across their organisations.

Human Capacity: Internal Actors' soft Skills, Internal Actors' Awareness to Enhance Climate-Resilient Infrastructure and Internal Actors' Awareness and Willingness to Change.

Organisational Culture: Internal Actors' Engagement, Awareness of Roles and Capacities of Other Actors and Cross-Disciplinary Collaboration.

Governance: Policies and Regulations at Municipal Level and Higher Level Support in Climate Resilience.

Information & Knowledge: Utilizing Pilot Project for Knowledge Transfer and Innovation, Cross-Departmental Information Sharing and Alignment, Knowledge Sharing and Retention and Technology Tools.

Project Development Process: Alignment of Integrated Design Approach in Project Management Levels, Criteria for Climate-Resilient Infrastructure, External Actors' Engagement, Integration Intervention Scale, Timing for Decision-Making in Design Integration and Technical Design.

Finance: Budget Allocation.

On the other hand, municipalities should additional consider Time and Financial lenses when implementing an integrated design approach to enhance climate-resilient infrastructures. Thus, this study focuses on seven implementation lenses: Functional, Transdisciplinary, Synergistic, Intervention Scale and Technological identified in the literature, and Time and Financial identified in practice.

PART III
Roadmap Development

This last part combines Parts I and II's theoretical and practical findings into a strategic roadmap for municipalities to implement an integrated design approach effectively. This part is divided into Chapter 6, which explains the development of the roadmap and its validation through experts; Chapter 7, which discusses the final results and limitations; and Chapter 8, which concludes and recommends implementing an integrated design approach effectively.

Chapter 6: Roadmap Development and Expert Validation

This chapter describes the strategic roadmap's development and validation through an expert evaluation procedure and presents the final roadmap. Moreover, this chapter aims to answer the RQ: "*How can municipalities enhance climate-resilient infrastructure through an effective implementation of an integrated design approach?"*. To answer the research question, this chapter is divided into three sections: Section 6.1 explains the development of the preliminary roadmap based on the literature and case study findings (document review and thematic analysis from interviews). Section 6.2 describes the expert validation procedure, and section 6.3 presents the final roadmap.

6.1. Preliminary Roadmap Development

The preliminary roadmap was developed based on the findings from the literature review (Part I) and case study (Part II). Figure 23 shows how the previous chapters were used.

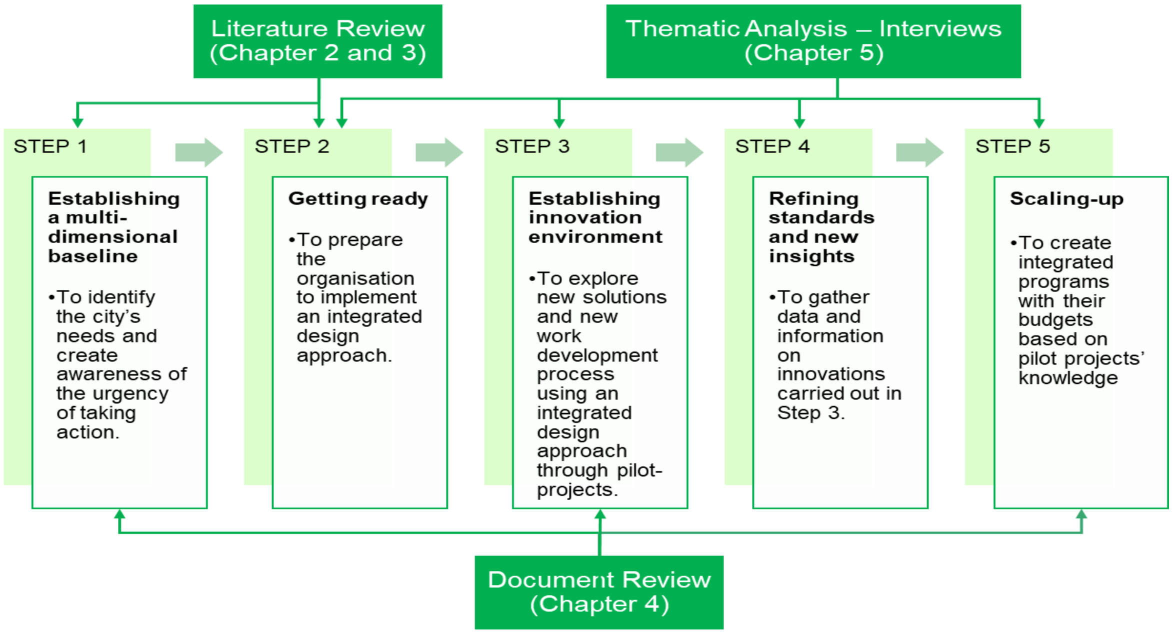

Figure 23: Preliminary Roadmap Development Process

The roadmap suggests long-term actions for municipalities to effectively implement an integrated design approach. Foreseen an overview of the long-term actions can allow municipalities to plan and highlight the awareness of the time urgency that some actions will require.

6.1.1. Preliminary Roadmap: Steps Description

The preliminary roadmap consists of five steps, as Figure 24 illustrates.

Step 1: Establishing a multi-dimensional baseline

The creation of this step starts from the document reviewed. It is recognised that Rotterdam Municipality plans to undertake maintenance projects for the next four years. Therefore, the maintenance department already has enough information on its current assets. However, this does not apply to every municipality. Thus, to develop a roadmap for municipalities in general, establishing a multi-dimensional baseline will allow them to identify the city’s needs and create awareness of the urgency of taking action. The assessment actions were created from the dimensions found and verified with a climate resilience literature review to confirm that it also considers climate resilience aspects. In that way, the external actor's assessment focuses on citizens (user mindset) and other local infrastructure authorities (infrastructure’s interdependencies).

Step 2: Getting ready

Once the municipality knows the baseline of each aspect, this step aims to prepare the organisation to implement the approach. In this step, the actions focused mainly on the supportive departments such as information and technology management. Furthermore, consolidating the strategic maintenance plans with other local infrastructure authorities created a supportive context for the internal actors to innovate in the next step. For example, consolidating strategic plans with external actors means close collaboration, steering their involvement to the program and project level.

Step 3: Establishing an innovation environment

This step was formed based on the literature review on how municipalities can implement integrated design approaches. Furthermore, the practical findings from the interviews aligned with the theory. Analysing the influential factor “designer criteria for climate-resilient infrastructure”, discipline roles value seeking new solutions. Some benefits of creating successful pilot projects are a good image for the municipality, steering through an example, and the possibility of allowing risks, especially since one challenge of climate-resilient infrastructures is the uncertainties of the effects of climate variations. Lastly, this step explores a new developing process of working with an integrated design approach.

Step 4: Refining standards and new insights

This step was designed to gather data and information on innovations in Step 3. It aims to standardise the knowledge generated about the integrated approach in project development. Moreover, during the interviews, participants highlighted the importance of sharing knowledge across the organisation and with external actors.

Step 5: Scaling-up

This step aimed to scale up this approach by creating integrated programs based on the budget estimation of pilot projects. In this step, internal actors, especially discipline roles, emphasised the importance of continuing training and doing research sessions.

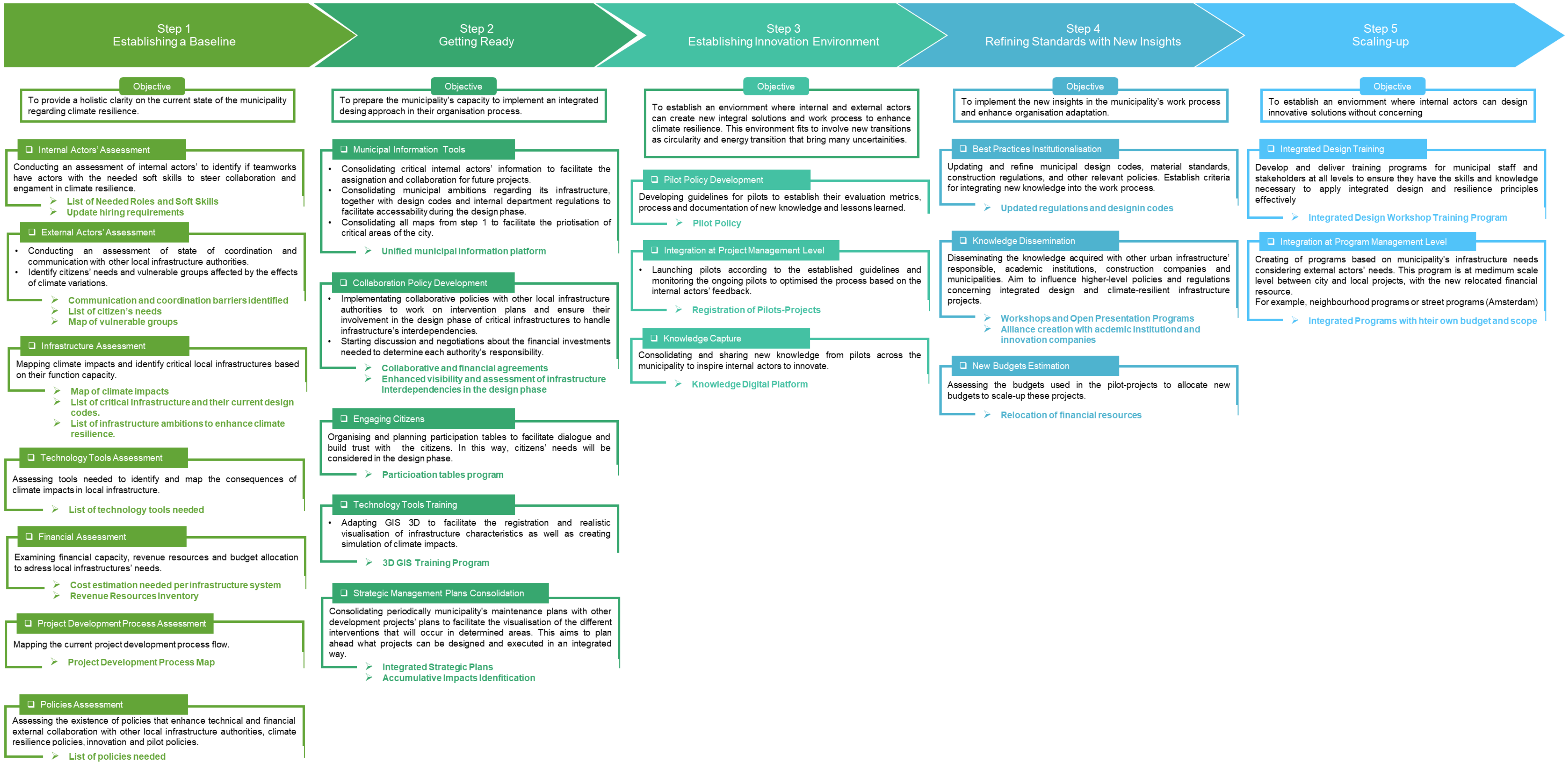

Figure 24: Preliminary Strategic Roadmap to implement integrated design approach at the municipal level

6.1.2. Selecting actions

The influential factors and dimensions were used as a guideline to brainstorm and collect all the actions of the roadmap. For example, the influential factor "Utilising Pilot Project for Knowledge Transfer and Innovation" guides the recommended actions that enhance pilot-project implementation and the importance of gathering lessons learned from them. The last one created the action of developing a pilot projects policy. Appendix C shows the table that was used to visualise what actions tackle each dimension, which later was used to find the pattern of the action flows for the final roadmap. Moreover, this visualisation tool allowed us to analyse if another action could tackle more factors. This aimed to offer actions to help municipalities focus on actions that could bring more value.

6.2. Expert Validation

The preliminary roadmap has been tested through expert validation meetings within Rotterdam Municipality, Dordrecht Municipality and Utrecht Municipality. These validation meetings aimed to test if the steps and actions tackle the influential factors in Chapter 5 and the practicality for municipalities to use this roadmap. The procedure for the validation meetings and the results are explained in the following subsections.

6.2.1. Expert Validation Phase

The first step of this phase was the selection of the experts. Since the preliminary roadmap focuses on a strategic level to enhance climate-resilient infrastructure, some experts should be climate resilience advisors responsible for anchoring climate resilience in infrastructure projects. Moreover, the holistic results of the influential factors required a strategic organisational expert in charge of the long-term plans of the municipality. Lastly, due to the integrated design approach being "relatively" new in practice, the perspective from an asset manager would be insightful on how the roadmap is presented. Therefore, three experts from Rotterdam Municipality were selected, and two participated in the interview phase. Additionally, two experts from outside were contacted to test if the roadmap fits other municipalities. Table 32 presents the expert's role and years of experience. Each expert name was anonymised, where RM= Rotterdam Municipality, DM =Dordrecht Municipality, UM=Utrecht Municipality, CR=Climate Resilience, S=Strategic, AM= Asset Management and ID = Infrastructure Design Advisor.

Table 32: List of Experts' Participants in the Validation Phase

Code	Expert' Role	Years of Experience
RM-CR	Climate Resilience Advisor	13
DM-CR	Climate Resilience Advisor	11
UM-AM	Head of Water Sewerage and Pumping Stations	0.5
RM-S	Strategic Advisor	5
RM-ID	Infrastructure Design Advisor	19.5

All validation meetings besides UM-AM and RM-ID were in person. For each meeting, the validation procedure was divided into three sections: an explanation of the influential factors, an explanation of the roadmap actions and how these actions tackle those factors, and a discussion about the roadmap's practicality. Since the research time was limited and the roadmap had a holistic character, it was improved after each validation session to enhance its readability and practicality. Figure 24 shows the preliminary roadmap presented to the first expert (RM-CR), while Figure 30 in Appendix D shows the final draft presented to the last expert (RM-ID).

6.2.2. Expert Validation Results

The general results from the expert session are presented in Table 33, where N/A means that their expertise is not applicable, and therefore, no comments were mentioned. Experts were asked to verify whether the actions tackled the influential factors. Experts from Rotterdam and Dordrecht Municipality agreed on the roadmap's content (actions and outcomes) and can potentially scale up the implementation of an integrated infrastructure design approach. However, some agree on some actions but hesitate since although the action tackles the factor, these actions could require long-term to achieve the expected outcomes. Lastly, RM-CR and RM-S agreed on the content of the roadmap and perceive its use as checklist for future references.

Table 33: Experts General Appreciation of Roadmap Actions' Validation

Dimension	Influential Factors	Expert Validation				
		RM-CR	DR-CR	UM-AM	RM-S	RM-ID
Human Capacity	Internal Actor's Soft Skills	N/A	Agree	Agree	Agree	Agree
	Internal Actors' Awareness to Enhance Climate-Resilient Infrastructure	N/A	N/A	N/A	Agree	Agree
	Internal Actors' Awareness and Willingness to Change	N/A	N/A	N/A	Agree	Agree
Organisational Culture	Internal Actors' Engagement	Agree	N/A	Agree	Agree	Agree
	Internal Actors' Awareness of Roles and Capacities of Other Actors	Agree	Agree	Agree	Agree	Agree
	Cross-Disciplinary Collaboration			Agree	Agree	Agree
Governance	Policies and Regulations at the municipal level	Agree	Agree	N/A	Agree	N/A
	Higher Level Support in Climate Resilience	Agree	N/A	N/A	N/A	N/A
Information & Knowledge Management	Utilising Pilot Project for Knowledge Transfer and Innovation	Agree	Agree	Agree	Agree	Agree
	Cross-Departmental Information Sharing and Alignment	Agree	Agree	Agree	Agree	Agree
	Knowledge Sharing and Retention	Agree	Agree	N/A	Agree	Agree
	Technology Tools	Agree	Agree	Agree*	Agree	N/A
Project Development Process	Alignment of Integrated Design Approach in Project Management Levels	Agree	Agree	N/A	Agree	N/A
	Designer Criteria for Climate-Resilient Infrastructure	N/A	N/A	Agree	N/A	Agree
	External Actors' Engagement	N/A	Agree*	Agree	Review	Agree
	Integration Intervention Scale	N/A	N/A	Agree	Review	N/A
	Timing for Decision-Making in Design Integration	N/A	N/A	Agree*	Agree	N/A
	Technical Design	N/A	N/A	Agree*	N/A	Agree
Finance	Budget Allocation	N/A	Agree	Agree	Agree	N/A

Agree*: the experts agree with the objective of the action, however, these actions could require long period of time to achieve the expected outcome.

Visual Presentation Format

Due to the extensive range of actions outlined in Steps 1 and 2 of the preliminary roadmap draft (Figure 24), DM-CR noted that not all municipalities can assess everything simultaneously, constrained by financial and human resources. Additionally, since this strategic roadmap encompasses long-term actions, DM-CR suggested that the figure should reflect the time these actions require. Consequently, using the dimensions as guidance, action flows were developed. Meanwhile, RM-ID proposed that the content of the final draft roadmap (Figure 30, Appendix D) could be presented in alternative format such a booklet to enhance its usability among senior municipal officials that look to gain more knowledge about IIDA implementation.

Roadmap User

The preliminary roadmap draft's holistic nature made identifying “a” responsible user challenging. Through discussions with UM-AM and RM-S, responsible roles were identified. However, it requires self-organisation from the main managers to demand the availability of roles to form a multidisciplinary strategic team.

Action Flows

Some experts criticized the terminology used in the action flows, noting discrepancies between the language and the author's intended message. For instance, the term “participatory tables” suggests active citizen involvement in decision-making, which is not typically the case for strategic decisions. A more accurate description would be “planning informative sessions,” which municipalities use to inform citizens about future actions and maintain their engagement. On the other hand, RM-ID viewed the use of diverse dimensions as a positive framework for guiding the action flows. However, he recommended incorporating these dimensions explicitly into the roadmap to emphasize the importance of a broad perspective when implementing IIDA within an organization.

6.3. Final Roadmap Development

Based on the comments and feedback from the experts, some changes were made to the roadmap's visualisation. These changes aim to enhance the roadmap's practicality for municipalities. Figure 25 shows how the steps were developed based on the previous chapters (literature review, document review and interviews) and from comments and feedback from expert validation. .

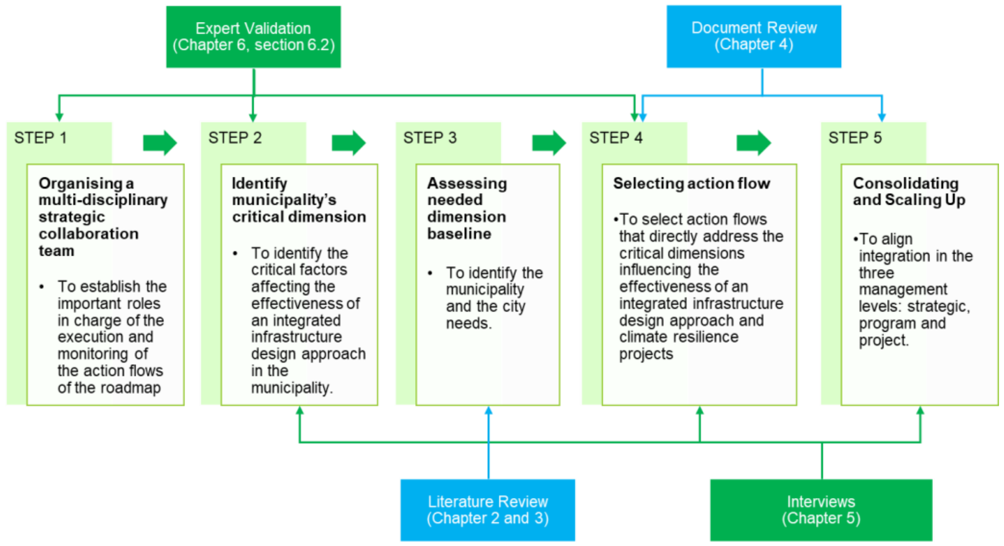

Figure 25: Final Roadmap Development Process

6.3.1. Final Roadmap: Steps Description

Step 1: Organising a multi-disciplinary strategic collaboration team

Since the factors influencing the effectiveness of the municipality pertain to various dimensions (human capacity, organisational culture, governance, information and knowledge management, project development process, and finance), there is no singular responsible party within the municipality to ensure the effective implementation of the integrated approach. From these dimensions, six pivotal roles within the municipality have been identified that must collaborate: urban designers, head manager of local infrastructure, process manager, financial manager, human resource and climate resilience policy advisors, and information manager. Table 34 delineates the functions of each role in this roadmap.

Table 34: Final Roadmap Step 1 – Role Functions

Role	Function	Focus
Urban Designers Team	Internal Actors' Assessment. External Actors' Assessment. Project development process assessment.	Infrastructure needs.
Head Manager of Each Municipal Infrastructure		
Process Manager		Project development process.
Financial Manager	Financial assessment.	Budget allocation and restructuration.
Human Resource Policy Advisor Climate Resilience Policy Advisor	Existing policies assessment.	Climate resilience and collaboration policies.
Information Manager	Data and information management assessment.	Municipal data and information management.

Step 2: Identify and prioritise municipality's critical dimension

"In this step, the multidisciplinary team conducts surveys to identify the critical factors influencing the effectiveness of an integrated infrastructure design approach in the municipality. Once identified, they can prioritize these critical dimensions (human capacity, organisational culture, project development process, governance, information and knowledge and finance) and select the necessary assessments for the next step.

Step 3: Assessing the needed dimension baseline

This step has the same objective of step 1 of the preliminary roadmap, section 6.1.1, in which this step aims to establish a multi-dimensional baseline. Through these assessments, the team will identify the municipality and the city's needs.

Table 35: Final Roadmap Step 3 – Actions and Outcomes

Action	Description	Outcome
Internal Actors' Assessment	o Conducting an assessment of team projects to ensure that internal actors have the following soft skills: holistic view, open-mindedness, proactivity, collaboration, and empathy. o Conducting an assessment of needed management roles to steer integration, such as an integral manager. o Conducting an assessment of the disciplines needed to enhance climate resilience: water specialists, landscape and urban designers, ecologists, underground designers, and circular advisors.	o List of needed roles and soft-skills
External Actors' Assessment	o Conducting an assessment of the state of coordination and communication with other local infrastructure authorities. o Identify citizens' needs and vulnerable groups affected by the effects of climate variations.	o List of communication and coordination barriers identified o List of citizens' needs related to climate resilience o Map of vulnerable groups
Current Policies Assessment	o Conducting an assessment of existing policies related to technical and financial collaboration with other local infrastructure authorities, climate resilience policies, and pilot-project policies.	o List of policies needed
Infrastructure Assessment	o Mapping the effects of climate variations on local infrastructures, see Appendix A1 for an example. o Identify critical local infrastructure based on their function capacity.	o Map of climate impacts o List of critical infrastructure and their current design codes o List of infrastructure ambitions to enhance climate resilience
Financial Assessment	o Examining municipal financial capacity, revenue resources and budget allocation to address local infrastructures' needs.	o Cost estimation needed per infrastructure system o Revenue resources inventory
Project Development Process Assessment	o Mapping current project development process flow between municipal departments.	o Project development process map
Information Management Assessment	o Conduct an assessment of the municipality's existing data and information procedure guidelines.	o Diagnosis of the state of municipal data and information management

Step 4: Selecting Action Flows

This step aims to ensure that each selected action flow is aligned with the specific needs and priorities identified through earlier surveys and assessments, thereby optimizing the impact and effectiveness of municipal efforts in their critical dimensions.

Table 36: Final Roadmap Step 4 – Actions and Outcomes

N°	Action	Description	Outcome
1	External Work Agreements	o Contact other local infrastructure authorities, such as public and private utilities companies, to collaborate on intervention plans. This aims to ensure their involvement in the design of critical infrastructure projects to handle infrastructures' interdependencies.	o Collaborative agreements. o Enhanced visibility and assessment of infrastructure interdependencies during the design.
2	External Financial Agreements	o Starting discussions and negotiations about sharing needed financial investments and recovery responsibilities.	o Financial agreements with other local infrastructure authorities
3	Engaging Citizens	o Organising and planning information channels to keep citizens informed about the city's ambitions related to climate resilience and the importance of pilot projects. Prioritising citizens from vulnerable areas.	o Citizens develop trust in the municipality's commitment to climate resilience, particularly in vulnerable areas
4	Internal Collaboration Policy Development	o Implementing incentive policies to enhance collaboration o Update hiring requirements to include needed soft-skills.	o Collaborative organisational culture.
5	Pilot Project: Policy and Execution	o Developing guidelines for pilot projects to establish their evaluation metrics, process, and documentation of new information and lessons learned.	o Pilot-project guidelines and success evaluation criteria.
6	Best Practices Institutionalisation	o Establishing evaluation criteria for integrating pilot-projects knowledge to update municipal design codes, material standards, departmental regulations and other relevant policies.	o Evaluation Criteria. o Updated regulations, design codes and relevant policies.
7	Information and Knowledge Dissemination	o Consolidating critical internal actors' information to facilitate the assignment and collaboration for future projects. o Consolidating municipal ambitions regarding its infrastructure, design codes and departmental regulations. o Consolidating all maps from step 2 to facilitate the prioritisation of critical areas of the city.	o Unified municipal information platform.
		o Establish data and information gathering, storage and accessibility guidelines. o Creating training programs for internal actors to follow the guidelines. o Monitoring compliance with guidelines.	o (Update) data and information guidelines. Data and information gathering training program
		o Consolidating and sharing new information from pilot projects across the municipality. o Disseminating the knowledge acquired with other local infrastructure authorities and municipalities. Aim to influence higher-level policies and regulations concerning integrated design and climate-resilient infrastructure. o Develop and offer training programs for internal actors to ensure they have up-to-date knowledge from integrated projects.	o Integrated design workshops. o Open presentation programs. o Alliance with academic institutions and research companies

Step 5: Consolidating and Scaling-Up

Before following step 5, actions from step 4 must be completed. For instance, before moving forward with Action 8 (Strategic Plans Consolidation), the outcomes of Actions 1 and 2 (Collaborative and financial agreements with other local infrastructure authorities), as well as Action 3 (gaining citizens' trust), need to be achieved.

Table 37: Final Roadmap Step 5 – Actions and Outcomes

N	Action	Description	Outcome
8	Strategic Plans Consolidation	o Consolidating periodically the municipality's maintenance plans with other development projects' plans to facilitate the visualisation of conflict areas due to projects' interventions. This aims to plan for projects that can be designed and executed in an integrated way.	o Integrated strategic plans. o Accumulative impact identification.
9	Integrated Pilot-Projects Development and Execution	o Launch integrated pilot projects according to the established guidelines and monitor the ongoing pilots to optimise the process based on participants' feedback.	o Integrated design project knowledge. o Integrated work procedure knowledge. o Integrated budget and planning knowledge.
10	Integrated Programs Development	o Creating programs based on the municipality's infrastructure needs considering external actors' needs.	o Integrated Programs with their own budget and scope.

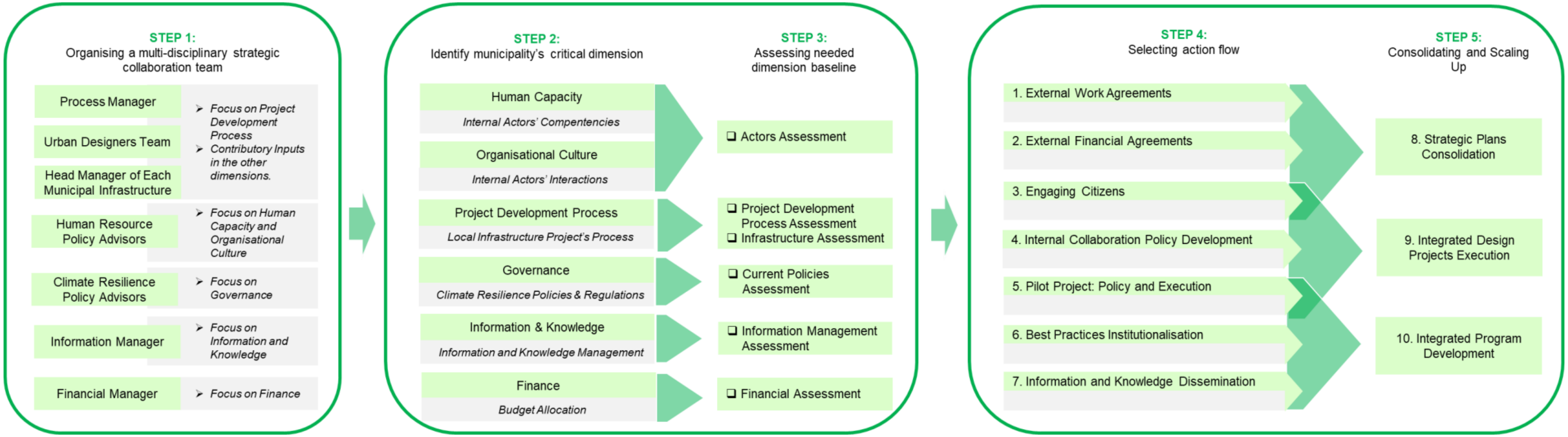

Figure 26: Final Strategic Roadmap for Municipalities to Effective Implement an Integrated Infrastructure Design Approach to Enhance Climate-Resilient Infrastructures

Conclusions and Future Directions

Chapter 7: Discussions and Limitations

This chapter is divided into two sections: Section 7.1 discusses the findings of the research with the current literature, and Section 7.2 explains the limitations of the research and its results.

7.1. Discussions of the Research Findings

Climate-resilient infrastructure is an urgent topic worldwide due to the uncertainties of the effects of climate variations. IPPC (2022) forecasts a temperature increase of 1.5°C in the following decades. However, many countries have already been suffering economic losses. For example, the EU estimated 111.7 billion in economic losses in assets only in 2021 and 2022 (European Environment Agency, 2023). In this urgency, municipalities' role has gained significant recognition to enhance climate resilience since they have tools to implement mitigation and adaptation strategies (Eidelman et al., 2022). However, implementing both strategies increases intervention projects, making the siloed approach less effective for municipalities in managing their infrastructure (French, 2014). Municipalities can implement an integrated design approach to achieve climate-resilient infrastructure. From an academic point of view, this research added theoretical knowledge in the following way:

Climate-Resilient Infrastructures

The research starts by delving into the main characteristics of climate-resilient infrastructures. Miller et al. (2018) noted a shift from a focus on designing solely to prevent failure towards a more proactive approach to designing to be prepared to manage those consequences, Hallegatte et al. (2019) emphasized the importance of adopting a user mindset over an asset mindset, advocating for a user-centered approach to infrastructure design. Additionally, the OECD (2018) underscored the significance of comprehensive planning, design, and maintenance strategies for resilient infrastructure development. Consequently, through the literature review, climate-resilient infrastructure is defined as any infrastructure planned, designed, and constructed with the dual goals of minimizing CO2 emissions and ensuring adaptability to climate variations throughout their lifecycle.

On the one hand, the literature review reveals the necessity of considering the climate resilience cycle in the infrastructure lifecycle. This integration aims to heighten awareness among infrastructure managers regarding the expanded responsibilities of the operational phase, which now encompass activities beyond routine maintenance. Such activities include assessment, redesign, and even reconstruction in response to the effects of climate adaptation. However, incorporating redesign tasks into the operational phase poses new challenges for local infrastructure authorities, as it requires a shift from traditional project development processes that compartmentalize redesigning and maintenance tasks. Thus, adapting these processes becomes mandatory to mitigate fragmentation.

Moreover, the operational phase assumes the responsibility not only for adaptation but also for prevention. Infrastructure must be robust enough to withstand the impacts of climate variations, as highlighted by Snelde et al. (2012) and Nagumey & Qiang (2007), cited in Twumasi-Boayke & Sobanjo (2018) and Shakou et al. (2019). Additionally, the adaptability phase underscores the importance of organizational adaptability and an understanding of infrastructure interdependencies in enhancing climate resilience, echoing the insights of Carhart and Rosenberg (2017).

On the other hand, it is essential to note that although the Adaptability Phase typically occurs after the impact of climate variations (Absorption Phase) in the reviewed literature, this sequence is not necessarily reflected in practice. A specific example of this can be observed in the analysed case study, where the municipality takes a more proactive stance by initiating the adaptation of its local infrastructures, such as roads and open space. This initiative takes advantage of the need to intervene in some regions of the city of Rotterdam for different reasons, such as the renewal of infrastructures whose technical lifespan is functional ending (Hertogh et al., 2018). Therefore, this case exemplifies that local authorities should not wait for infrastructures to be directly impacted by climatic events to begin adapting their designs and enhancing their climate resilience. Experience demonstrates the importance of adopting a preventive and proactive approach, seizing intervention opportunities that arise for various reasons to incorporate climate resilience considerations into the planning and design of local infrastructures. This proactive attitude can significantly contribute to reducing the vulnerability of communities to extreme climatic events like flooding due to heavy precipitation. This discussion highlights the intricate relationship between climate resilience and infrastructure management, underscoring the need for approaches that address both present challenges and future uncertainties.

Connecting Climate-Resilient Infrastructure and Integrated Infrastructure Design Approach

In light of the complexities surrounding climate resilience and infrastructure management discussed earlier, municipalities are increasingly turning to the use of an integrated infrastructure design approach as a means to effectively address both present challenges and future uncertainties. From the literature review, this approach offers significant advantages for municipalities by collaborating across different sectors and disciplines, encouraging a holistic view, fostering innovative solutions, and adding co-benefits. Thus, this approach ensures that stakeholders from various fields participate in the planning and design process (Shoulund et al., 2021), reducing intervention conflicts and analyzing interdependencies. For example, in the Bospolder-Tussendijken project, considerations of intervention scale and time allowed for the integration of additional infrastructure. This included the planning for primary heating pipelines and future secondary pipelines, ensuring adequate space for installations and preventing heat from these pipelines from affecting the sewer system and green areas.

Additionally, adopting a holistic perspective enables municipalities to identify opportunities for integrating functions and aligning infrastructure projects with broader city ambitions, promoting more sustainable development (Warbroek et al., 2023). Moreover, integrated design fosters innovation, resulting in solutions that leverage the collective knowledge of technical disciplines and designers. This was the case with the Water Plazas projects, where internal actors who participated in the initial projects recognised that one from the same discipline would probably not think about that solution; thus, thanks to that integrated design approach involving the interaction of a variety of specialities, it was possible to obtain that innovative solution. Furthermore, this approach emphasizes understanding the environmental context of infrastructure locations (Keuters et al., 2021), allowing for the incorporation of environmental elements and stakeholder interests into functional specifications. An example of these characteristics is found in the Green-Blue Schoolyards projects. These initiatives were crafted with the user mindset, with the students at the forefront of the design process. By prioritizing the needs and experiences of the students, the specifications were tailored to create an environment not only for recreational activities but also to serve as an educational space. This approach fosters new opportunities for students to engage in classes outdoors, facilitating the development of social skills and environmental awareness.

Implementation of an integrated Infrastructure Design Approach at the Municipal Level

To date, the research's focus has primarily centred on integration related to the design process itself (Vooredent, 2017; Zeiler, 2019; Keusters et al., 2021) and the differing perceptions of integration from the perspectives of stakeholders engaged in the process. For instance, Visser (2020) identifies seventeen interpretations of integration within design contexts. However, the organisational implications of adopting an integrated design approach have yet to be examined thoroughly. Through the practice component of this study, seven lenses were founded: five emerging from a literature review—functionality, synergy, transdisciplinary, intervention scale, and technological—and two from the case study, time and financial lenses. The initial five lenses, derived from the literature, were structured based on insights gained from document reviews. This structuring facilitated an analysis of the potential implications for local infrastructure authorities when implementing this approach.

An insightful observation is that certain types of interdependencies can unveil additional implementation lenses crucial for enhancing climate-resilient infrastructure. For instance, Carhart & Rosenberg (2017) highlight the interdependencies between the lifecycle impact stages (planning, construction, operation), which later was encountered during the interview phase as a Time lens. This lens focuses on anticipating how the design phase might influence the construction, operation, and maintenance phases, as well as future projects in the vicinity of the infrastructure, as happened in the Bospolder-Tussendijken project. In the project, the program manager had to address the execution phase of the heating network, facilitating the development of new design regulations for future projects.

Lastly, although most examples of integrated design projects are multifunctionality infrastructures, not all projects designed in an integrated manner are multifunctional. Visser (2020) concluded that integration in design is related to different interaction lenses; hence, from a municipal perspective, integration can occur in various forms, and not all lenses need to be implemented. The importance of understanding the various implementation lenses for municipalities lies in recognising how their standard infrastructure management needs to adapt to incorporate this approach in their regular process. Thus, a comprehensive awareness and understanding of these lenses enable municipalities to take proactive steps to modify their project development processes, ensuring the effective utilisation of this approach.

Factors that influence the implementation of the Integrated Infrastructure Design Approach

This research included a case study involving a document review and thematic analysis from twenty-two interviews. This analysis identified nineteen influential factors impacting the effectiveness of municipalities in adopting this approach. These insights complement the findings of Warbroek et al. (2022), who identified institutional barriers such as sectoral budgeting and sector-specific objectives. By focusing on identifying the factors that influence the implementation of this approach, it was possible to not only identify the challenges faced by the case study municipality but also collect the drivers that led the internal actors of the municipality to adopt this approach before it was standardized and incorporated into their process. Consequently, the most prominent influential factors are related to the dimension of human capacity. Furthermore, from these insights, a strategic roadmap was developed, delineating actionable steps for the effective implementation of this approach within municipal organisations. As a result, this study furnishes a practical, strategic framework for municipalities aspiring to enhance climate-resilient infrastructure through the implementation of an integrated infrastructure design approach.

7.2. Research Limitation

The limitations inherent in the research are the following:

- Given the diversity of climate impacts and urban infrastructure priorities that vary by geographic context, findings from a study focused on a single city may not be generalisable to other urban contexts. However, this concentration on a specific case allows for a detailed and holistic exploration, contributing significantly to a deeper and more informed understanding of implementing an integrated infrastructure design approach at the municipal level.

- The experts who validated the roadmap come from Dutch municipalities facing similar challenges; therefore, other influential factors may appear in non-Dutch municipalities, requiring additional action flows.

- The roadmap was developed under Rotterdam Municipality's organisational culture. The municipality has a horizontal hierarchy, which motivates bottom-up initiatives seeking to adapt and change. Therefore, given that the roadmap was created to offer a strategic path for municipalities, the use of the roadmap for some municipalities will highly depend on municipal head managers or city council, especially if they have a vertical hierarchy.

Chapter 8: Conclusions and Recommendations

The research aimed to provide a roadmap to effectively implement an integrated design approach at the municipal level within climate-resilient infrastructure. This chapter presents the conclusions in section 8.1 and recommendations in section 8.2.

8.1. Answer to Research Question

The study was conducted in three parts to address the research question:

RQ: "How can municipalities enhance climate-resilient infrastructures by effectively implementing an integrated design approach?"

To address the research question, a detailed strategic roadmap was developed, defining the necessary steps and actions that enable municipalities to implement the integrated design approach within their organisation effectively. Additionally, the roadmap aims to enhance climate resilience in local infrastructures.

First, a literature review was conducted to identify the characteristics of climate-resilient infrastructure (CRI). The review revealed that CRI features an adaptable and integrated design, which allows for continuous usage despite climate variations while minimising uncertainties from interdependencies with other local infrastructures. An example of this is the Water Plazas, designed to temporarily store rainwater and subsequently serve as public spaces for social interaction and recreation. Additionally, CRI construction is both sustainable and robust, aimed at reducing CO2 emissions and enhancing resilience to climate impacts. For instance, in the Bospolder-Tussendijken area, a heating network project was integrated into the sewer system renewal plan. This integration reduced the need for extensive excavation, thereby lowering energy consumption.

Moreover, maintenance responsibilities for CRI require adaptability for tasks such as redesign and rebuilding to enhance climate resilience. The findings from the case study highlight the need for municipalities to adapt their project development process, requiring that City Management include redesigning actions in their department. Furthermore, those responsible for CRI must recognise the negative impacts of interdependencies between local infrastructures on climate resilience and consider these in the design phase. In this case, Rotterdam Municipality acquired new insights for developing regulations by considering the placement of the new heating network in the renewal project. This initiative highlighted the need for specific insulation levels for the pipes and established the minimum distance required to prevent any impact on the surroundings, such as local greenery.

Subsequently, through thematic analysis, nineteen factors affecting the municipality's effectiveness in implementing this integrated infrastructure design approach (IIDA) to enhance CRI were extracted. These factors were grouped into six dimensions to which municipalities should pay attention: human capacity, organisational culture, governance, information and knowledge, project development process and finance. From these dimensions, the following are related to enhance CRI:

- The Human Capacity Dimension emphasises the competencies and knowledge of internal actors in CRI and IIDA. This dimension encompasses two key aspects: Firstly, it addresses the awareness of internal actors regarding climate resilience, a pivotal component in the Prevention Phase of the Climate Resilience Cycle. Secondly, awareness and willingness to change are considered, which play a crucial role in the adaptation phase. This dimension is reflected in action flows 4 and 7.

- The Organisational Culture Dimension emphasises cross-disciplinary collaboration, which enhances that not only technical aspects are considered in the project, but also environmental and social aspects. This dimenion is reflected in action flow 4.

- The Governance Dimension emphasises internal policies and regulations regarding climate resilience to ensure that actors' decisions are aligned with municipal standards. This dimenion is reflected in action flows 6.

- The Project Development Process Dimension emphasises the alignment of integration in all project management levels to increase the chance of finding synergy in projects, reflected in action flows 8, 9 and 10. Furthermore, it considers the engagement of external actors as other local infrastructure authorities, reflected in action flow 1, and citizens (users), reflected in action flow 3. The first enhances taking interdependencies within local infrastructures into consideration, and the second enhances user mindset. Moreover, design criteria for CRI and technical design are considered in action flows 5, 6 and 7. With these results, the strategic roadmap was developed to answer the research question, see Figure 25.

Lastly, collaborative governance is paramount, involving cross-government collaboration at various levels to anchor climate resilience from the national to the municipal level. This collaborative approach fosters information sharing and ensures that all stakeholders are informed of new policies related to climate resilience. Therefore, for municipalities to effectively implement integrated design in order to enhance climate resilience, they must:

- Foster Soft Skills: Municipalities need actors with soft skills such as a holistic view, proactivity, collaboration, and empathy to appreciate the contributions of each role. For that, municipalities can organise workshops and revise their recruitment process to promote and steer a collaborative and innovative culture. Furthermore, actors need the support to experiment with new solutions through pilot projects where they can learn without the risks associated with a standard project.

- Support Departments' Role: Support departments like information and technology are crucial for more effective implementation, as managing data and information gathered from pilot projects is essential. This information dissemination across the municipality and to other public entities is vital for steering adaptations of national regulations.

- Information Accessibility: Easy access to internal information will enable municipalities to update their internal regulations as new information transforms into knowledge. Updating the regulations ensures that policies remain relevant based on the latest insights and data.

- Project Integration and Scaling: With the points above in place, project integration can be consolidated, facilitating the scaling up of integrated projects. This approach makes carrying out larger-scale and more extensive integrated projects easier, significantly enhancing the capacity to build climate-resilient infrastructure.

In summary, by investing in a culture that values soft skills, encourages innovation, and emphasises the importance of information and technology support, municipalities can significantly improve their ability to design and implement climate-resilient infrastructure.

8.2. Recommendations for Practice and Future Research

To scale up the use of an integrated infrastructure design approach in the municipal organisation, the following recommendations were formulated for Rotterdam Municipality, other municipalities, colleagues and future research recommendations.

8.2.1. Recommendations for Rotterdam Municipality

Rotterdam Municipality exhibits a robust culture of innovation and collaboration; however, based on the interview results and following the strategic roadmap, the municipality needs to address some dimensions to scale up the implementation of IIDA.

Human Capacity

Workshops for Awareness and Skill Development: Conduct workshops aimed at enriching managerial knowledge on the broader impacts of their role in climate resilience. These sessions can include case studies that highlight successful engagement strategies and discussions on the latest research in climate-resilient infrastructure. Workshops should also focus on developing soft skills that are crucial for internal and external actors' engagement, such as holistic view, negotiation and proactivity.

Information and Knowledge Dimension

- The development of a pilot project policy: Establish a policy that provides a standard template for pilot project participants. This template should facilitate the documentation of essential aspects of projects in line with IIDA's implementation principles, such as functionality, transdisciplinary approaches, synergy, technology, scale of intervention, timing, and financial considerations.

- A digital bibliothek: Although Rotterdam Municipality possesses a digital platform for internal actors to share experiences and insights, its current design lacks user-friendliness, particularly when accessing information about pilot projects. Introducing a 'Digital Bibliothek' section would enhance the accessibility of this information. This improvement is crucial to ensure that valuable knowledge from these pilot projects does not remain confined to personal networks or specific departments.

- Digital internal regulations register: Interviews revealed that internal actors frequently need to consult various departments to obtain information on the latest internal regulations, policies, and design codes. By updating and centralizing this information on the existing digital platform, the municipality can reduce time expenditures and enhance communication across departments. Getting a regulation register is particularly important given the uncertainties associated with energy transition projects and would contribute significantly to informed decision-making.

Finance Dimension

Collection and Utilization of Financial Data from Pilot Projects: To effectively forecast and allocate budgets for future integrated projects and programs, it is crucial to gather detailed financial data from existing pilot projects. As illustrated in Figure 26, the recollection of this financial data should include specific circumstances of each pilot project's integrated design. For instance, Pilot Projects A and B incorporated different types of ambitions, which likely influenced their budgetary needs and outcomes. By leveraging statistical methods, Rotterdam Municipality can use these detailed financial analyses to estimate budgets for developing new, integrated programs. This strategic approach ensures that funds are more precisely allocated, enhancing the efficiency and scope of future project implementations.

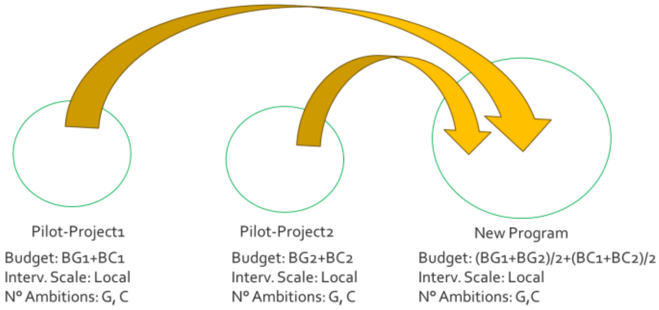

Figure 27: New budget estimation from pilot projects

8.2.2. Recommendations for Other Municipalities

It is recommended that leading authorities adopt the roadmap as a framework to increase awareness about the necessary actions and actors involved in enhancing climate-resilient infrastructure. Additionally, this roadmap provides holistic strategic actions, accounting for future challenges. Thus, it serves as an effective tool for planning and initiating these actions at the most opportune times within their specific contexts. Additionally, fostering a collaborative and innovative culture within the organization and among other local authorities, private companies, and academic institutions is crucial. The importance of academia should not be overlooked, as the complexity of climate resilience solutions and integrated approaches demands robust research and innovation capabilities.

For municipalities facing significant financial and technical challenges, there are additional recommendations:

- Engaging other local infrastructures: it is important for these municipalities to collaborate with other local infrastructure entities to distribute financial responsibilities, enhancing the overall efficacy of the initiative.

- Engaging research institutions: It is crucial to record meteorological data to identify vulnerability zones and critical local infrastructures. For this reason, it is highly recommended to communicate and collaborate with research entities to facilitate data acquisition and continuous training for managers and disciplinary actors in climate resilience.

- Start with small intervention scale: implementing IIDA could start with charrettes in pilot projects.

8.2.3. Recommendations for Future Researches

Upon concluding the research, several areas have been identified for future investigation:

- The research establishes that the three levels of management, strategic, program, and project, should incorporate integration with a particular emphasis on the program level. From the findings, decision-making concerning the scope and budget of projects with an integrated design approach must happen at the program level. Thus, there is a need for additional study on integration within program management.

- Considering municipalities' diverse budgetary priorities, which extend beyond local infrastructure to encompass a wide range of public services, future research is urgently needed to explore strategies for aligning municipal budget allocations with integrated design approaches. Future studies should investigate how municipalities can effectively restructure their budgeting processes to support climate-resilient infrastructure development while still meeting other critical service demands.

- This research explores the influential factors from a municipal perspective; however, further study is necessary to understand external actors, such as other local infrastructure authorities and private companies, in the integration process.

- The research scope involves enhancing climate-resilient infrastructure during project development before it goes to tender. Thus, further research will be needed to see how this influential factor affects the success of integrated design projects.

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Appendixes

Appendix A: Climate Variation Effects Maps of Rotterdam

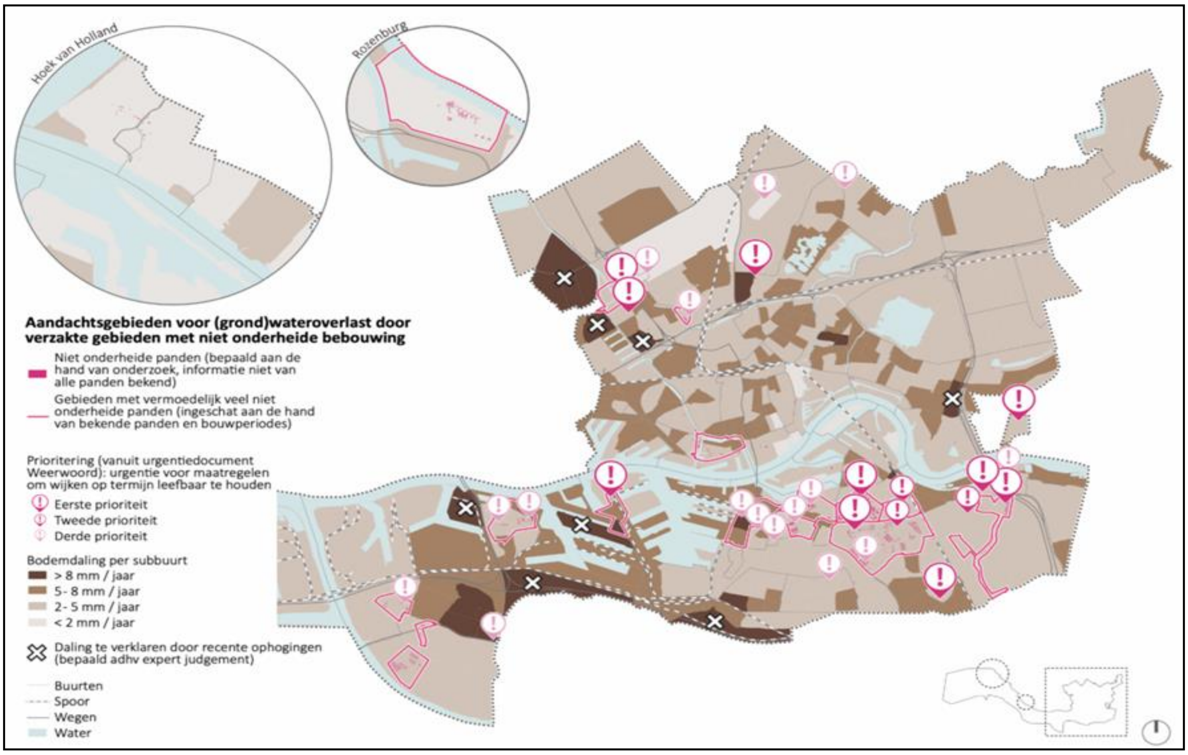

Figure 28: Map of Rotterdam: Land-subsidence priority areas

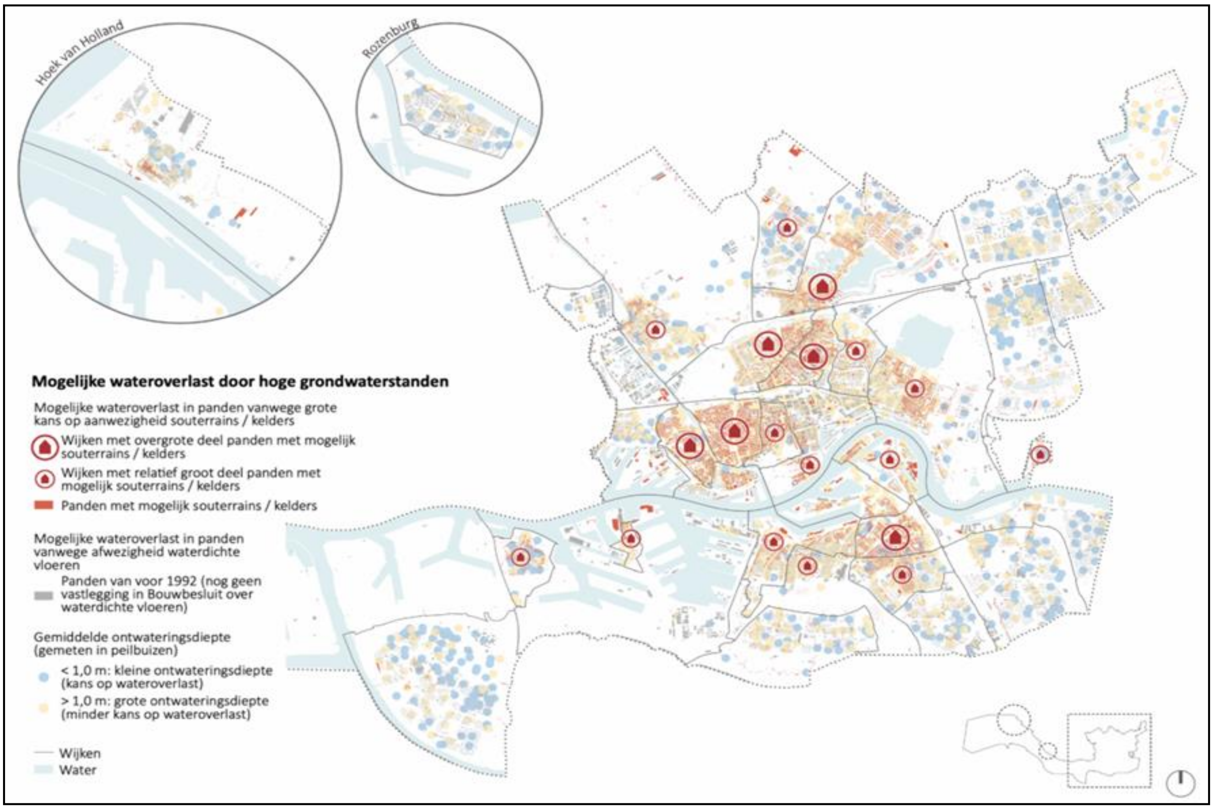

Figure 29: Map of Rotterdam: Onderground flooding areas

Appendix B: Interview Structure

All Interviews started with the introduction general questions:

- Could you please describe your specific role and responsibilities within the municipality?
- How many years of experience do you have in this role?
- How long have you been emplyed with the municipality?
- What type of infrastructure projects have you been involved? (If aplicable)
- Which assets were considered in the project? (If aplicable)

The interview's structure follows four themes formulated from the literature review of the case study. The structure was used as a guide and depending on the interviewees' answers some questions omitted as they have already answered.

➢ Theme 1: Awareness of climate-resilient infrastructure

This theme aims to gather information about the actors' perspectives inside the organisation regarding their and others' influence to achieve climate-resilient infrastructure. The outcomes seek to understand the point of view of different actors related to climate resilience in urban infrastructures.

- From your perspective, what factors make an urban infrastructure climate-resilient?
- How does your role consider climate resilience in urban infrastructure projects?
- What motiveates you to take those considerations?
- From your perspective, what roles within the organisation or team project are crucial to enhace climate resilience in urban infrastructures?
- How has been your experience working with them?
- Has there been any discussions between their role perspective and yours regaring climate resilience? Can you elaborate it?
- What other actors do you consider important to enhance climate resilience? How do you involve them in the project?

➢ Theme 2: Influence factors in design for climate-resilient infrastructures

It aims to gather information about the influence of the (re)design phase to enhance climate reslience in urban ifnrastructure and to explore the opportunities and the importance of using IIDA.

- From your perspective, how does the design phase influence climate resilience in urban infrastructure?
- During the design phase, do you consider the interdependencies of other infrastructures? Why yes, or why not?
- What factors do you consider in the design due to climate change?
- What factors could influence that the outcome of the project regarding its climate resilience?
- Could you describe your experience of a project where it had a silo approach? and an integrated design approach?
- What opportunities do you find in an integrated design approach to enhance climate resilience in urban infrastructure?

➢ Theme 3: Challenges and enablers during IIDA implementation

It aims to gather information about the barriers actors encounter at the operational level when using an IIDA. Moreover, the enablers they perceive from the organisation to continue using IDA.

- Could you describe your overall experience with integrated design approach in your projects?

- What do you consider were the key factors that motivated you to adopt an integrated design approach?
- From your perspective, what factors helped you to implement an integrated design approach?
- Could you share some challenges you encounter? How were they adressed?

➢ Theme 4: Recommendations and suggestions to extend the use of IIDA to more projects.

It aims to gather information about possible improvements the organisation could improve to support actors in extending IIDA to more projects. Some questions were formulated with a focus on other collegues and municipalities to find recommendations that can be applicable not only for the case study.

- What type of resources do you think would be beneficial to extend the use of IIDA?
- What would you recommend/advice to collegues who have only participated in siloed projects and willing to use IIDA?
- What do you think are the key points that other municipalities should pay attention to implement IIDA in their organisation?

Appendix C: Actions Visualisation

Table 38: Actions from Initial Dimensions for the Preliminary Roadmap

<table>
<tr><th rowspan="2">Dimension</th><th rowspan="2">Influential Factors</th><th colspan="5">Actions to Adress Influential Factors</th></tr>
<tr><th>Step 1</th><th>Step 2</th><th>Step 3</th><th>Step 4</th><th>Step 5</th></tr>
<tr><td rowspan="6">People</td><td>Actor's Soft Skills</td><td rowspan="4">S1. Internal Actors' Assessment</td><td></td><td rowspan="6">S3. Integration at Project Management Level</td><td></td><td rowspan="4">S5. Integrated Design Training</td></tr>
<tr><td>Internal Actors' Engagement</td><td rowspan="3">S2. Municipal Information Consolidation</td><td rowspan="3">S4. Best Practices Institutionalisation</td></tr>
<tr><td>Cross-disciplinary Appreciation</td></tr>
<tr><td>Cross-disciplinary Collaboration</td></tr>
<tr><td rowspan="2">External Stakeholders' Engagement</td><td rowspan="2">S1. External Actors' Assessment</td><td>S2. Building Citizens' Trust</td><td rowspan="2">S4. Knowledge Dissemination</td><td></td></tr>
<tr><td rowspan="2">S2. Collaboration Policy Development:</td><td rowspan="3"></td></tr>
<tr><td rowspan="2">Institution</td><td>Policies and Regulations at municipal level</td><td rowspan="2"></td><td>S3. Pilot Policy Development</td><td>S4. Best Practices Institutionalisation</td></tr>
<tr><td>Higher Level Support in Climate Resilience</td><td></td><td></td><td rowspan="3">S4. Knowledge Dissemination</td></tr>
<tr><td rowspan="5">Design</td><td>Internal Actors' Awareness to Enhance Climate-Resilient Infrastructure</td><td rowspan="3">S1. Internal Actors' Assessment</td><td rowspan="3">S2. Municipal Information Consolidation</td><td rowspan="3">S3. Integration at Project Management Level</td><td rowspan="3">S5. Integrated Design Training</td></tr>
<tr><td>Internal Actors' Understanding of the Need for an Integrated Design Approach</td></tr>
<tr><td>Designer Criteria for Climate-Resilient Infrastructure</td><td rowspan="3">S4. Best Practices Institutionalisation</td></tr>
<tr><td>Pilot-Project Flexibility for Innovation</td><td></td><td></td><td rowspan="3">S3. Pilot Policy Development</td><td></td></tr>
<tr><td>Technical Design</td><td>S1. Infrastructure Assessment</td><td rowspan="2">S2. Municipal Information Consolidation</td><td>S5. Integrated Design Training</td></tr>
<tr><td rowspan="3">Information & Knowledge Management</td><td>Cross-Departmental Data Sharing and Alignment</td><td rowspan="2"></td><td rowspan="2">S4. Knowledge Dissemination</td><td rowspan="2"></td></tr>
<tr><td>Knowledge Sharing and Retention</td><td></td><td>S3. Knowledge Capture</td></tr>
<tr><td>Technology</td><td>S1. Available Technology Tools Assessment</td><td>S2. Technology Tools Training</td><td></td><td></td><td>S5. Integrated Design Training</td></tr>
<tr><td rowspan="4">Project Management</td><td>Alignment of Integrated Design Approach in Project Management Levels</td><td>S1. Project Development Process Assessment</td><td rowspan="2">S2. Strategic Management Plans Consolidation</td><td rowspan="2">S3. Integration at Project Management Level</td><td rowspan="3"></td><td rowspan="3">S5. Integration at the Programma Management Level</td></tr>
<tr><td>Integration Intervention Scale</td><td rowspan="2"></td></tr>
<tr><td>Timing for Decision-Making in Design Integration</td><td></td><td></td></tr>
<tr><td>Budget Allocation</td><td>S1. Financial Assessment</td><td></td><td></td><td>S4. New Budget Estimation</td><td></td></tr>
</table>

Appendix D: Roadmap Drafts

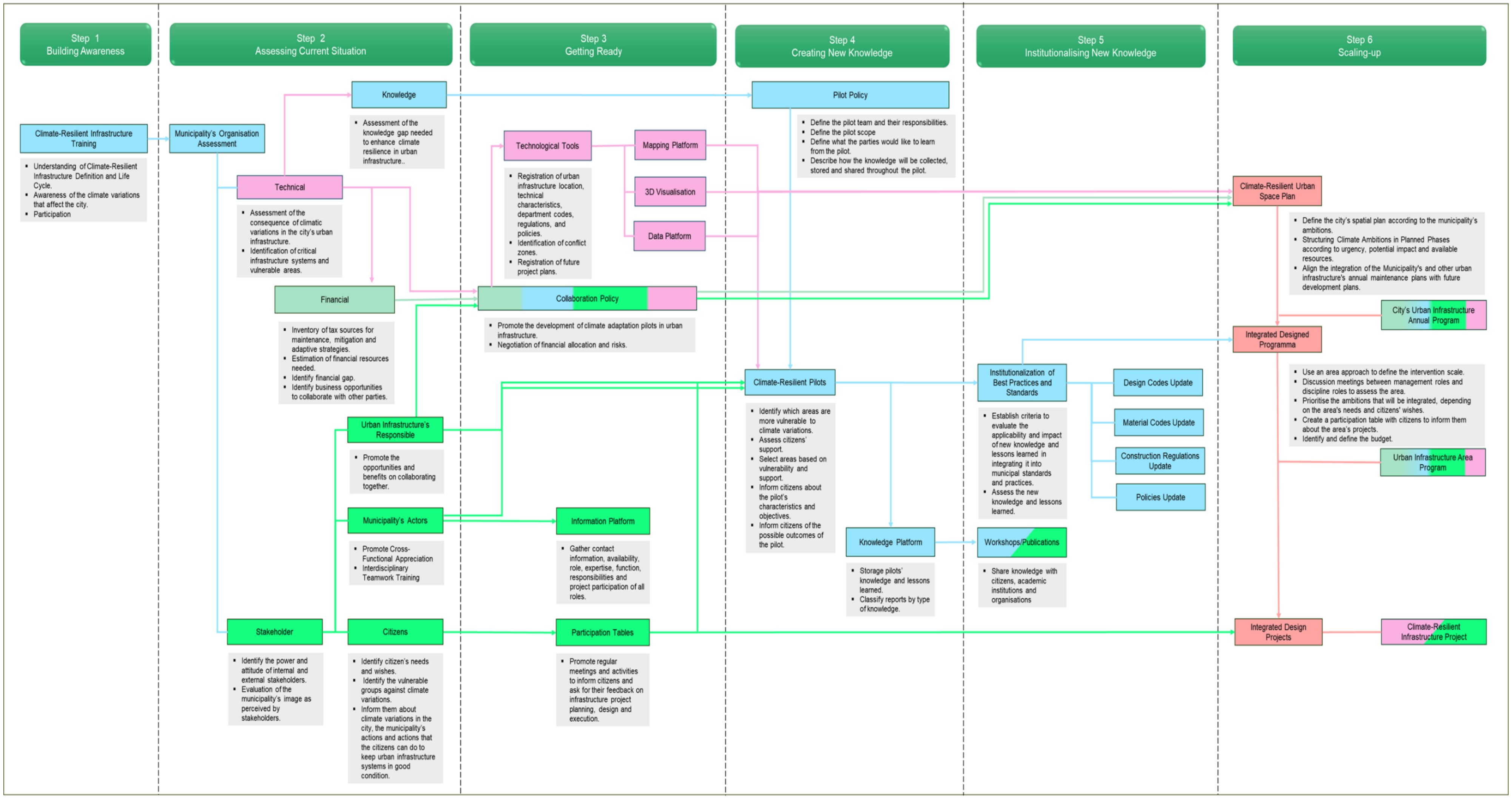

Figure 30: Preliminary Roadmap Draft from Progress Meeting II

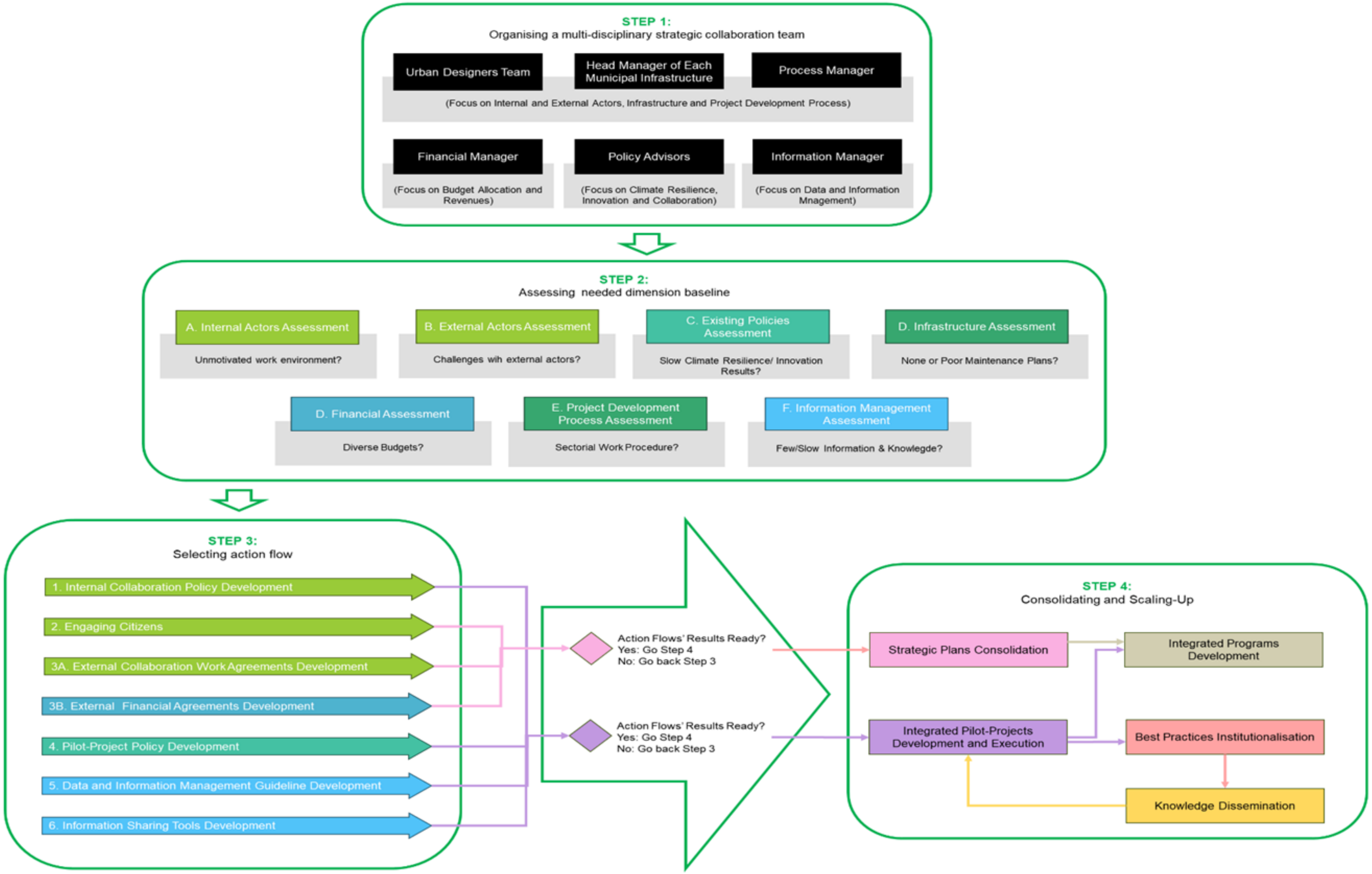

Figure 31: Final Roadmap Draft from Validation Phase