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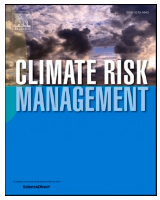

From Silos to Synergy: Conceptualizing an integrated infrastructure design for climate resilience in Rotterdam

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A B S T R A C T

In recent years, municipalities have been recognised for their crucial role in protecting cities from climate change impacts by adopting mitigative and adaptive strategies to enhance climate resilience. However, anchoring these strategies demands multiple interventions, which are often hindered by the current siloed organization of departments and disciplines. An integrated infrastructure design approach (IIDA) can co-create a process that converges sectors, disciplines, and actors' interests to tackle this challenge. To this end, this research explores how municipalities can effectively implement IIDA to enhance climate-resilient infrastructures. The city of Rotterdam served as a case study involving a thematic analysis of 21 interviews with internal actors of the municipality. This study identified 19 key factors influencing a municipality's effectiveness in using an integrated design approach to enhance climate resilience. These influential factors belong to six different dimensions: Human Capacity, Organisational Culture, Governance, Communication, Project Development Process and Finance. The findings suggest that it is essential that actors within municipalities have soft skills such as proactivity and open-mindedness for collaboration. Furthermore, it is necessary to foster an innovative and collaborative culture to enable the development of pilot projects. This, in turn, helps update standards and scale up implementation by aligning integration at the three management levels: strategic, program, and project. Based on the findings, we recommend establishing a multi-dimensional baseline, setting up a communication strategy and tools, build human and institutional capacity through pilots and living labs. This can help municipalities implement an integrated infrastructure design in their organisation, offering a promising future in designing climate-resilient infrastructures.

1. Introduction

Extreme weather events induced by climate change threaten human settlements, especially in urbanized areas with intensive land

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use and dense population. Urban infrastructure needs to be resilient, adapting to climate change while mitigating its impact (Shakou et al., 2019). Since urban infrastructures are physically clustered and functionally integrated, a siloed approach is becoming less effective in achieving climate-resilient infrastructure (Shen 2019). However, current urban infrastructures are still planned, designed and maintained separately by departments (French 2014). For example, road and sewer departments plan and design their infrastructure independently, increasing the number of interventions in the city.

To reduce the risk of unforeseen vulnerabilities, the interdependencies between infrastructures must be considered. An integrated infrastructure design approach (IIDA) can anticipate these interdependencies and turn them into an opportunity to improve the overall resilience of the system (Grafius et al. 2020). Especially, since urban infrastructure systems are increasingly decentralized (Derrible, 2017), IIDA offers opportunities to integrate various perspectives during the design process and provide holistic interventions (Verheijen, 2015). It requires transdisciplinary collaboration and co-creating a process that crosses the boundaries of each discipline (Fortuin, et al., 2024). By collaborating with stakeholders, IIDA can minimize service interruptions while reducing the cost and resources for renewal tasks (Jayasinghe et al. 2023).

Municipalities face various urban transitions (e.g., energy transition, climate adaptation, and mobility transition) while combating ordinary urban issues (e.g., solid waste collection, pollution, and high resource consumption) (Enshassi et al. 2014). They have a direct role in developing projects and enforcing policies related to public transit, urban design, and land-use planning (Eidelman et al. 2022), and they have a considerable influence in mitigating climate change impacts within urban settings. However, due to the complexity of climate adaptation, municipalities are challenged with a lack of resources and standardised processes. IIDA can help municipalities routinize climate adaptation projects with various stakeholders. The main research question is "How can municipalities enhance climate-resilient infrastructures by effectively implementing an integrated design approach?".

The Rotterdam municipality in the Netherlands is chosen for the case study. Dutch cities are experiencing extreme rainfall, droughts and heatwaves during summer while their urban infrastructures require maintenance and renewal (Climate Adaptation Services, 2023). At the same time, Dutch cities face urban challenges from the convergence of several system transitions such as circularity, energy transition, and sustainable transition (Lim et al., 2023). These trends directly influence primary urban infrastructures including sewage systems, open public spaces (green areas and street roads) and heating networks which are the main concerns for municipalities. Therefore, this research focuses on these urban infrastructures.

The rest of the paper is organized as follows. The literature review section provides a theoretical background of climate-resilient infrastructure and IIDA principles, as well as local government's characteristics for climate adaptation. The methodology section introduces how data is gathered, prepared and analysed. The findings section provides the result, especially focusing on the influential factors in implementing IIDA in municipalities. The discussion section reflects the findings with current literature and the conclusion

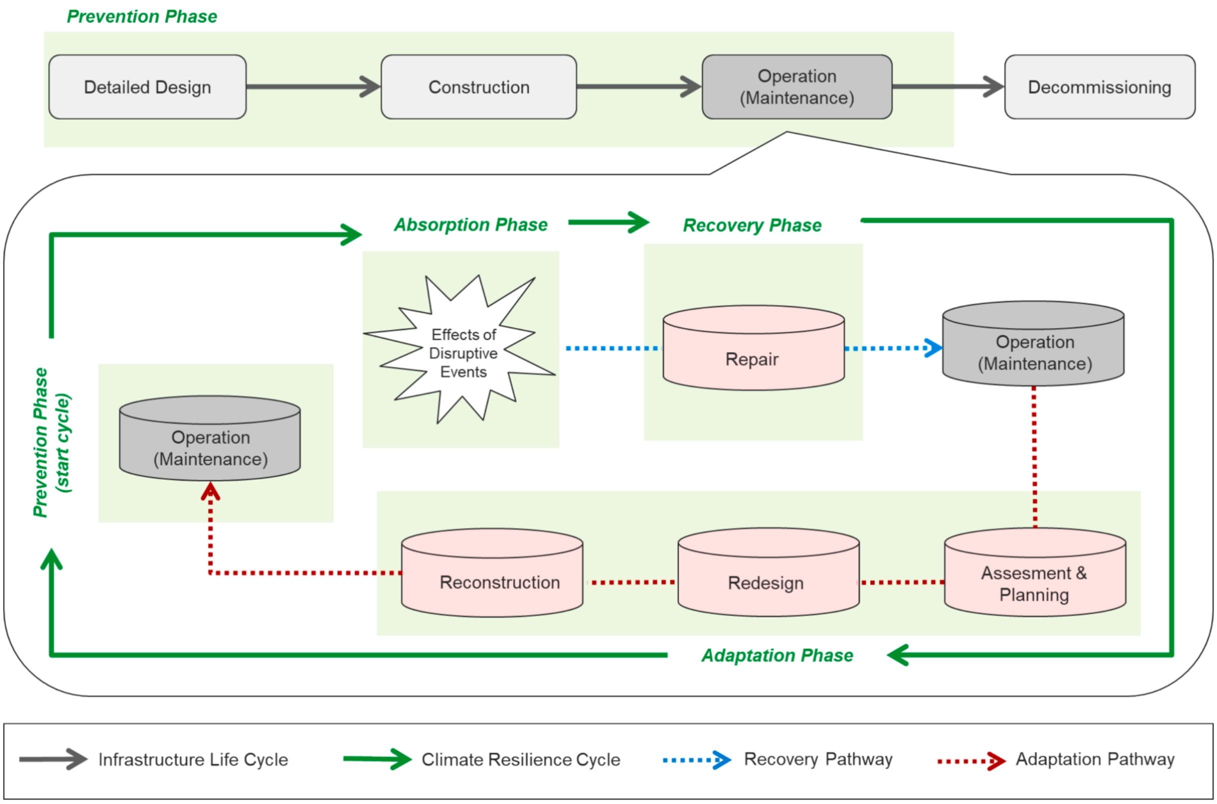

Fig. 1. Incorporating Climate Resilience Cycle in Infrastructure Life Cycle.

section points out the limitations, significance and future research directions.

2. Climate resilient infrastructure and local government's climate adaptation capacity

2.1. Climate resilient infrastructure

Historically, resilience in infrastructure was associated with specific vulnerabilities within established risk thresholds, adopting what could be described as a 'fail-safe approach' (Ahern, 2011). 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 no longer holds, revealing the need for infrastructures that are robust, adaptable, and flexible (Miller et al., 2018). Consequently, the concept of resilience has evolved towards a 'safe-to-fail' design wherein organisations need to be prepared to manage the consequences of infrastructure's failures.

Hallegatte et al. (2019) offer three levels of perspective to understand infrastructure resilience. The first level is the individual physical asset, where resilience translates into a reduction in the life cycle costs of the asset. The second level concerns the infrastructure network, examining the strength and the ability of infrastructure network to provide continuous and reliable services. This level encompasses other critical elements such as human capacity and operational facilities. The third level includes user perspective, where the resilience lies in the ability to mitigate the full impacts on communities and ensure their well-being during and after the disruptive events.

While Hallegatte et al. (2019) provide different levels of resilience in infrastructure, the OECD (2018) highlighted the process – planning, designing, and managing – of infrastructure projects. This means infrastructure projects should be climate-resilient, minimizing CO_2 emissions (Shakou et al., 2019). Considering the variations in climate conditions, resilience is no longer a static design but a process of continuous improvement through the life cycle of the infrastructure (OECD, 2018). In this sense, climate-resilient infrastructure is more than returning to the original state after the shock, rather it is an evolving process over time (Rehak et al., 2018). Therefore, climate-resilient infrastructure can be defined as any infrastructure planned, designed, and built to minimise CO_2 emission while continually adapting through its life cycle to ensure its services' continuity after climate variations.

Fig. 1 illustrates the infrastructure life cycle and climate resilience cycle. The lifecycle of infrastructure typically starts with detailed design and construction phases. These initial stages, along with the operational phase, form part of the **Prevention Phase**. Modifications to building codes and related standards are recommended to infuse climate resilience during the planning and design stages (Proag, 2021). The **Absorption Phase** is when the infrastructure is operating and exposed to the variable climate impact that may cause disruptions (Rehak et al., 2018). This phase is characterised by the robustness of the infrastructure to absorb disruptions without losing its function (Shakou et al., 2019). After the immediate disruptive effects have subsided, the **Recovery Phase** begins. It is a short-term phase aimed at restoring infrastructure functionality to a basic operational level (Mulowayi, 2017). The ability to recover depends mainly on the availability of institutional, material, and financial resources (Shakou et al., 2019) for the infrastructure to be repaired or replaced.

Once the infrastructure is repaired, it goes back to the operation. However, when the infrastructure system remains unchanged during the operation, it remains susceptible to future disruptive events. Therefore, the **adaptation phase** is initiated, and the organisation learns from the disruptive effects to enhance climate resilience (Rehak et al., 2018). The adaptation phase consists of assessment & planning, redesign, and reconstruction phases. Infrastructure can be reconstructed with a flexible design to accommodate future climate changes (Sánchez-Silva & Calderón-Guevara, 2022). Then the infrastructure re-enters the operational phase with improved resilience characteristics, starting a new resilience cycle.

2.2. Implementing integrated infrastructure design approach at the municipal level

Enhancing climate resilience in urban infrastructures requires a shift from a silo approach to a more integrated approach (Johnston, 2022). Breaking silo can be done in two ways: internal and external integration (Jagger, 2009). Internal integration is integration within a sector, for example, the combination of road and railway in the transportation sector. External integration means integration between sectors, for example, combining a geothermal network (energy) with the sewerage system (water). Visser (2020) extended the concept of 'integration' in the design field, concluding that integration refers to the interrelation of various components when addressing a problem.

The IIDA effectively integrates various disciplinary knowledge and practices from decentralised urban infrastructure systems to achieve resilience (Derrible, 2017). IIDA involves multiple angles and perspectives to co-create holistic solutions and enrich the project's sociological, cultural, ecological and economic value (Verheijen, 2015). There are various integrations in IIDA, including functional, stakeholder, goal, scale, and technological integrations.

Functional integration refers to integrating various urban infrastructures' functions by co-locating them within a single project (Voorendt, 2017). Multifunctional infrastructures can perform multiple purposes and provide various benefits (Ninan et al., 2024). For example, green–blue infrastructures serve as water storage, cooling urban heat, stress reduction, and space for social gatherings (Siehr et al., 2022). *Stakeholder integration* means integrating the interdisciplinary skills and experiences of stakeholders to develop innovative and holistic solutions (Keusters et al., 2024; Schoulund et al., 2021). *Goal integration* combines objectives of transitions like mobility, energy, circularity, and climate adaptation, recognizing the interconnectedness of spatial elements. Projects that integrate these transitions provide synergies and reduce adverse effects (Warbroek et al., 2023; Cucuzella & Goubran, 2018). For instance, combining heat grids with water retention areas can address both energy transition and climate adaptation needs.

Scale integration refers to combining different levels of urban infrastructure, ranging from small wins approach to an area-oriented approach. Small wins focus on achieving gradual changes at a local level (Termeer & Dewulf, 2019), while an area-oriented approach suits large, complex projects involving multiple parties and sectors (Heeres et al., 2012). *Technology integration* focuses on utilizing digital technologies and data to enhance infrastructure resilience. Technologies like the Internet of Things, Artificial Intelligence, Building Information Modelling, and Agent-based Modelling can improve climate resilience throughout the infrastructure lifecycle (Argyroudis et al., 2022). These integration lenses offer comprehensive perspectives for implementing IIDA in municipal contexts, addressing various aspects of infrastructure planning and design.

Like any other infrastructure project, the IIDA approach also starts with the design phase, defining the scope, costs, stakeholders and risks of the project (Keusters et al., 2021). It starts with exploring the problem, inventorying environmental elements, actors' interests, and the project's goal (Voorendt, 2017). Then, the primary function and specifications are defined along with criteria, boundary conditions and requirements. Life cycle thinking and system thinking are necessary to gather all the information from the integrated disciplines (Voorendt, 2017).

At the municipal level, IIDA can be implemented through various strategies that facilitate interaction and collaboration among stakeholders. For example, a series of workshops can be a low-huddle method to bring various stakeholders to the table (Kilbane & Roös, 2023). During the workshops, key stakeholders and citizens can actively participate in project design and planning by providing detailed analysis. Municipalities can also employ pilot projects to test the viability of innovative approaches and new ideas on a controllable scale (Hughes et al., 2020). Living labs can be another approach on a larger scale, discovering and combining innovative solutions at the local level (Schäfer & Scheele, 2017). Living labs facilitate both top-down initiatives focusing on vulnerabilities of infrastructure systems and bottom-up initiatives emphasizing social vulnerabilities (Schäfer & Scheele, 2017). Therefore, municipalities are at the core of implementing interventions for climate-resilient infrastructure.

2.3. Role of local government in climate adaptation

Local governments' climate adaptation plans should be tailored to municipalities' specific climate challenges and governance structures (Reckien et al., 2023). Effective climate adaptation requires a detailed understanding of local characteristics, which encompass the vulnerability and capacity of regions. These characteristics include factors such as a city's population, exposure to climate events, and adaptive capacities. The latter includes economic capacity (e.g., gross domestic product (GDP) per capita, unemployment rate) and institutional capacity (e.g., organizational structure, networks, leadership) (Reckien et al., 2015). Moreover, Rogers et al. (2024) distinguish two key local characteristics relevant to climate adaptation efforts: (1) the *authority to adapt*, which refers to the mandates and directives from higher levels of government that provide municipalities with a clear framework for adaptation actions, and (2) the *capacity to adapt*, encompassing the resources, networks, and governance structures enabling municipalities to implement these actions.

Collaboration is pivotal to addressing climate change, requiring coordination between various state and non-state actors (Head & Alford, 2013). However, siloed bureaucratic structures and limited capacities often hinder local governments from facilitating such partnerships (Leiren & Jacobsen, 2018). Difficulty in standardizing the adaptation process also hinders local government's climate adaptation efforts, and therefore, often results in ad hoc, reactive, and even maladaptation (Rogers et al., 2024). Eckersley and Olazabal (2024) emphasize the importance of understanding how governance structures and inter-institutional networks shape municipalities' resilience. There is a need for insights into how local governments can actively transcend siloed governance and foster collaboration for climate adaptation.

Table 1
List of Interviewees.

Category	Code	Role	Interview Type	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	Program Manager	Semi-Structured	59
	MR6	Project Manager	Semi-Structured	55
	MR7	Program 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	Circularity 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

3. Methodology

3.1. Data collection and analysis methodology

Following pragmatism, this research focuses on addressing practical challenges and generating actionable recommendations (Creswell, 2009). The pragmatic approach is particularly relevant for climate-resilient infrastructure design, especially for the municipalities that have a direct impact on the project outcomes. Pragmatism also encourages a reflective and iterative research process (Morgan, 2014), which is essential for this research given its exploratory approach and its aim to gain a deep understanding of the municipality's perspective on climate-resilient infrastructure and integrated design approach.

While mixed methods align well with pragmatism, this research relies exclusively on qualitative methods. This choice is driven by the specificity and limited scope of the participants, as the study focuses on a single case: the Rotterdam municipality. The specific nature of this target group makes it difficult to collect a large enough sample for meaningful quantitative analysis. However, this limitation can be an opportunity, as the qualitative approach allows for in-depth exploration of participants' experiences (Morgan, 2014). Additionally, qualitative methods support a holistic analysis, offering valuable insights into the design of climate-resilient urban infrastructures.

The main source of data is interviews with experts within a municipality. Twenty-one interviews were conducted with experts in multi-disciplinary (urban designers, climate resilience advisors, energy transition advisors, water specialists and circularity advisors) and various roles at different managerial levels (strategic managers, program managers and project managers), see Table 1. There were exploratory unstructured interviews (Alam, 2002) with several experts (MR1 & 8, DR1, 2, 5,6, and 8) to understand the overall context of the municipality's practice toward resilience and infrastructure renewal. Based on this information, a semi-structured interview protocol was developed, identifying key questions. The interviews were conducted in English with meeting notes and later transcribed word for word.

Both unstructured and semi-structured interviews offer different advantages. The unstructured interview is suitable for acquiring knowledge and customising questions into the interviewer's experience (Chauhan, 2022). Thus unstructured interviews were used when interviewing each role type for the first time. For example, the first interview with an energy advisor (DR8) was unstructured in order to explore the role's function and its influence on local infrastructure projects. The subsequent interview with a similar role was

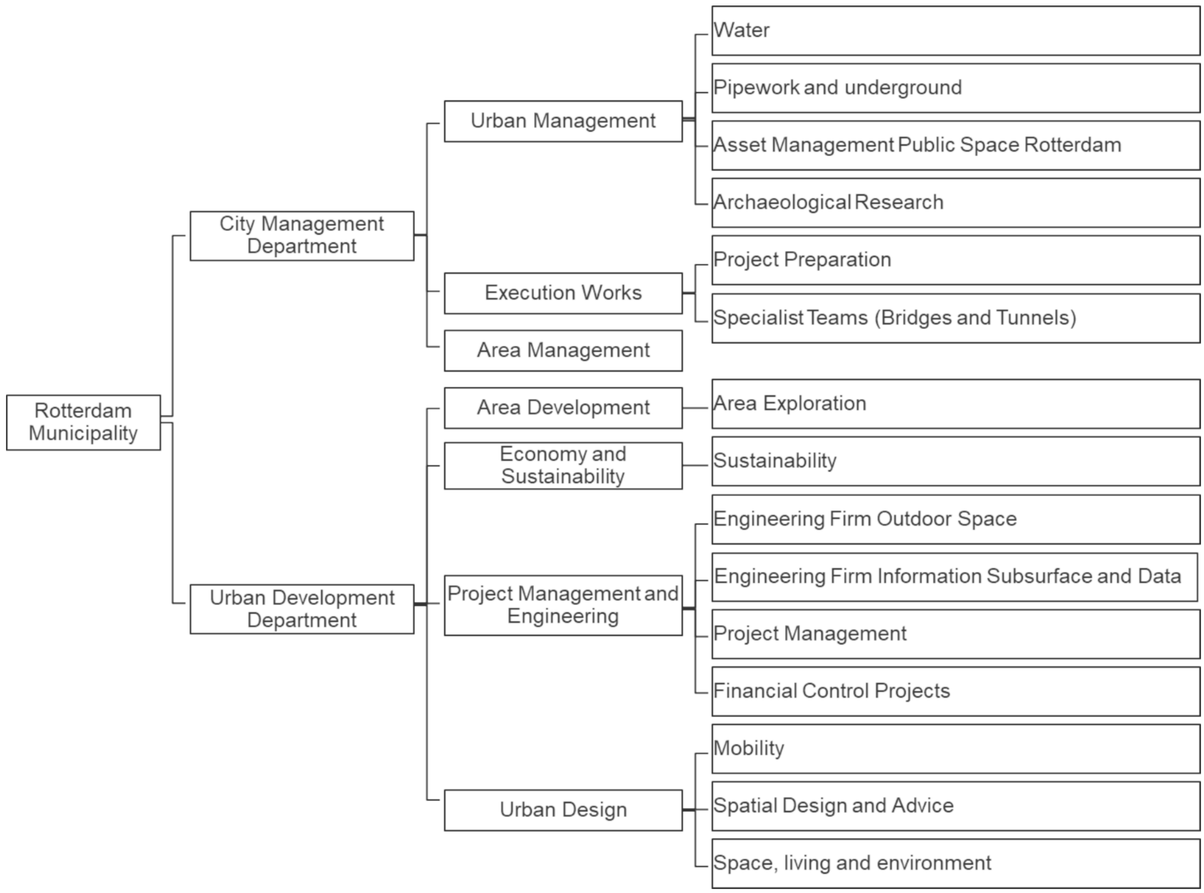

Fig. 2. Organizational Structure of Rotterdam Municipality, Highlighting Infrastructure-Related Departments and Sub-Departments.

semi-structured based on the insight from the unstructured interview. In total, seven unstructured interviews were done. All data were obtained through meeting notes and transcripts.

At the same time, semi-structured interviews allow the interviewer to steer the flow of the interview without discouraging detailed responses (Thumburmung et al., 2016). The interview started with introduction questions, asking the interviewee's role, responsibilities and years of experience. Then the questions from four topics were asked including 1) awareness of climate-resilient infrastructure, 2) influential factors in the design phase for climate resilience, 3) challenges and enablers in using integrated infrastructure design approach and 4) recommendations to extend this approach to other urban infrastructures projects. At the end of the interview, interviewees were asked for additional comments and suggestions for potential participants. In total, fourteen semi-structured interviews were conducted in this research.

A thematic analysis was chosen to analyse the data since it facilitates the identification of key themes, providing a comprehensive view of the issues (Lochmiller, 2021). The ATLAS.ti Scientific Software Development GmbH. (2024) was used for coding and analysis following Naeem et al. (2023)'s systematic process. The coding process employed a blended approach: inductive coding first, ensuring fidelity to the data, followed by deductive coding to develop the theory further (Linneberg & Korsgaard, 2019). This method ensured that the first-cycle codes were derived directly from the interviewees' quotations, maintaining the integrity of the data (Linneberg & Korsgaard, 2019). The second cycle of analysis commenced after coding all transcripts and meeting notes. Deductive coding involved using pre-defined codes derived from the literature review to guide the creation of themes. The whole process resulted in 160 codes. During code formulation, patterns emerged, allowing for the grouping of similar codes into themes.

3.2. *Context of Rotterdam municipality*

Among various Dutch cities, Rotterdam Municipality was chosen as the case study. Rotterdam is the second largest city in the Netherlands with a population of 671,319 people, as of October 2024 (Rotterdam Municipality, 2024). The most densely populated areas are mainly found in the city centre and near the port, reflecting the economic importance. Suburban areas are mostly residential areas with a lower population density. Rotterdam has a centralized decision-making structure, as the municipality is the sole governing body for urban development and infrastructure management. The municipality has two main divisions for the built environment: *Stadsbeheer* (city management) and *Stadsontwikkeling* (urban development). City Management oversees the operation and maintenance of all infrastructure assets within the city, while Urban Development provides the technical designs and solutions needed to execute these tasks. Fig. 2 highlights the sub-departments directly related to infrastructure projects.

Rotterdam is a significant area as Europe's largest port, however, its position in the Nile Delta makes it vulnerable to climate change impacts. This vulnerability has shaped the city's urban planning priorities over the past few decades. Since 2008, the city has undertaken climate change adaptation actions, guided by a strategic vision and water management plans (Rotterdam Municipality, 2019). Efforts began with the implementation of *'Water Plan 2'* and progressed with the launch of the *'Rotterdam Climate Proof Programme',* based on the *'Rotterdam Adaptation Strategy*' in 2013.

The municipality developed regional flood risk management in 2014, based on the '*National Delta Programme (2011–2024)'* by the central government (Delta Commissioner, 2011). Currently, the Rotterdam Municipality is focused on implementing the latest '*National Delta Programme 2024*' at the local level (Delta Commissioner, 2024). While the ultimate national goal is to be climate-resilient and water-robust by 2050, Rotterdam Municipality set out to achieve it by 2025 and developed '*Rotterdam Weerwoord*', a strategic response that analyses climate change impacts on the infrastructure. Fig. 3 shows climate resilience plans and strategies at the national, regional and municipal levels.

Rotterdam Municipality is also implementing IIDA in their infrastructure projects. Rotterdam's experience can provide insights into the influential factors for successfully implementing IIDA to enhance climate-resilient infrastructures. For instance, in the Bospolder-Tussendijken project, the scale and timing of interventions allowed for the integration of additional infrastructure, such as planning for primary and future secondary heating pipelines. This ensured adequate space for installations and prevented the heat from these pipelines from affecting the sewer system and green areas. Adopting a holistic perspective enables municipalities to identify

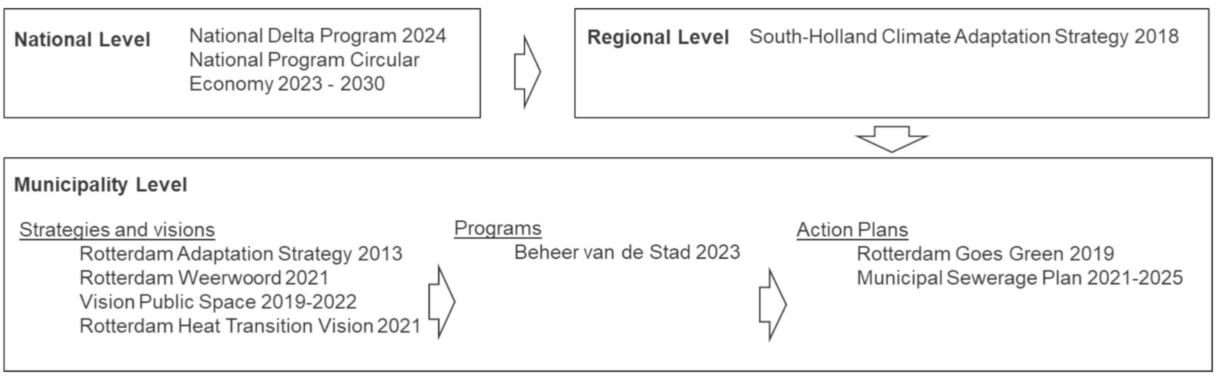

Fig. 3. Climate Adaptation Policies in Rotterdam.

opportunities for integrating functions and aligning infrastructure projects with broader city ambitions, promoting sustainable development (Warbroek et al. 2023).

4. Influential factors in implementing integrated infrastructure design approach at the municipal level

In terms of awareness of IIDA, most of the interviewees recognized its usefulness. DR1 pointed out new ideas are generated through IIDA, "*they have got creative ideas that I would not have thought about, […] And that is the interesting part of the integrated design.*" 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*". 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,

The factors that can facilitate implementing IIDA at the municipal level include 20 factors grouped into six dimensions: Human Capacity, Organisational Culture, Governance, Communication, Project Development Process and Finance (Table 2).

1) Human Capacity

Human capacity is related to internal actors' competencies and knowledge of climate resilience and IIDA. For organizational innovations to be effective, the internal actors need to possess soft skills for collaboration such as proactivity and open-mindedness. MR4 highlighted "*One needs to be open-minded also to know about other aspects*", which is crucial for developing appropriate strategies. In the same vein, MR5 noted, "*The process is important, but it will not succeed if the individual professional is not willing to understand*", underscoring the importance of proactiveness and open-mindedness. Similarly, DR10 emphasised open-mindedness should be embedded in the organizational culture: "*I think it is everyone's attitude to be open. We have to value everyone's few points and then come to a good strategy for the area*".

Some interviewees highlighted awareness of environmental vulnerabilities, 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. There was a strong willingness to change as DR2 notes: "*We have a problem, and we have to change oursel[ves].*" 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*.".

2) Organisational Culture

Organizational culture means internal actor's collective behaviour, value and interactions. The interviewees recognized that the leadership in management is critical to enhancing climate-resilient infrastructure. MR3 noted, "*The project manager's job is to see and think of which specialists are needed in the project team.*" 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.*" At the same time, all actors are

Table 2
Influential Factors that affect Integrated Infrastructure Design Approach Implementation at the Municipal Level

Dimension	Description	Influential Factors
Human Capacity	Related to internal actors' competencies and knowledge.	• Soft skills for collaboration • Awareness to climate-resilience • Willingness to change
Organisational Culture	Related to the behaviour and interactions of the municipality's internal actors.	• Leadership in managers • Awareness of roles and capacities of other actors • Network for cross-disciplinary collaboration
Governance	Related to the role of policies and regulations regarding climate resilience.	• Higher level support in climate resilience • Policies and regulations at the municipal level • Strategic decision-making
Communication	Related to the generation and management of knowledge and information.	• Cross-departmental information sharing and alignment • Knowledge sharing and retention • Technological tools for better communication • Utilising pilot project for knowledge transfer and innovation
Project Development Process	Related to the development of local infrastructure projects through the three project management levels (strategic, program, and project).	• Alignment of integrated design approach in project management levels • Overviewing project cycle • Integration intervention scale • Community engagement
Finance	Related to municipal's financial resources distribution.	• Budget allocation • Expanding project value

needed for climate-resilient infrastructure as DR3 said: "*Almost everyone. We can start bottom up, start from top to bottom, and we are all departments.*" This requires acknowledging other people's roles and capacities, as MR5 stated it is important to"*[take] the other's field of expertise seriously and value it as much as your own.*".

Another important aspect of the organization is the network. As shown in the previous section, the organizational structure in Rotterdam Municipality separates the maintenance and development departments. To find collaboration opportunities, a personal network becomes important 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.*".

3) Governance

Although a personal network can facilitate climate-resilient infrastructure projects, it can be dissolved since people can leave or be moved to another position, needing to build the network again. For stronger and lasting collaboration, higher level support is needed. The national support through EU regulations can set the project direction and facilitate collaboration. MR2 mentioned "*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.*".

Regulations such as collaboration agreements can be an enabler to work with external stakeholders. DR9 noted "*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)".

The experts also recognized the necessity for strategic decision-making and prioritisation as DR11 stated: "*You really have to choose between this task or that task. You cannot do them both.*" This reflects the inevitable trade-offs and choices that must be made throughout the process. There is a clear role in decision-making, highlighting the critical nature of prioritisation. DR1 also commented, "*But in the end, the way we make our design is, of course, depends on what Stadsbeheer [City Management] wants.*".

4) Communication

Another dimension to facilitate IIDA for climate-resilient infrastructure is communication by sharing information and knowledge. Lack of information slows down the design process. DR3 expressed the consequences of not having easily accessible information: "*When you are too late to go to the other parts to know their wishes, [...]it [is] difficult to adjust your design.*" The design phase needs all information from different actors, including assets, environments, requirements, etc., requiring active information and knowledge sharing. "*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? [...] This is the interaction between all the departments during the planning and the design*" (DR3).

Interviewees mentioned various ways to share information through technological tools. The use and accessibility of technology tools such as 3D visualisation and GIS can enhance communication. "*[They] allow you to see what is happening concerning the soil, the depth, and how you can build on the surface*. (DR5)" Pilot projects can be an opportunity to learn 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*".

5) Project Development Process

Interviewees acknowledge aligning IIDA in project management is important. The alignment can happen at the three management levels (strategic, programme, and project), but most importantly at a higher level. "*The best way to implement is to standardise it. [It] is basically at the level of definition of the assignment.* (DR6)" This idea is also supported by management roles MR5 also mentioned the importance of alignment at all levels: "*At every scale level, you need to want to adopt this way of working*".

Overviewing the project cycle is another important factor. DR4 emphasises the importance of early consideration, " *So it would be [better] to take these considerations [...] before they are already limiting or scoping the project*." 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*." 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 [other actors]*." These highlight the importance of considering the future infrastructure phase in the design process.

Municipality also needs to consider the intervention scale for integration. MR5 connects geographical scale and time scale: "*To me, the integral design also means anticipating future developments.. [...]I am already considering where future trees might be placed within those designs. [...] So, the integral design concept can also involve anticipation*." In the same vein, DR2 mentioned, "*You have to design an infrastructure with [...] the changing time in perspective.*".

Finally, how citizens are engaged during the design process can influence the result of project development. However, it is not easy to engage with the community due to different perspectives on local needs and expectations as MR8 addresses "*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 of the reasoning behind the municipality's decision to enhance climate-resilient infrastructure.

6) Finance

How a municipality allocates its budget to finance local infrastructure projects influences the project outcome. MR1 noted "*There are many agendas with different budgets*" while MR7 mentioned "*It is asset-based. [...] All the assets have multi-year planning with budgets.*" This reflects 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*.".

Furthermore, considering the broader value of the project, looking beyond the iron triangle (budget, scope and schedule) is important. For example, 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.*".

5. Discussion

Climate resilient infrastructure can be achieved with adaptable and integrated design, maintaining services despite climate variations and minimizing uncertainties arising from interdependencies with other infrastructures. Local governments play a critical role in developing climate-resilient infrastructure through awareness of climate impact and interdependency between infrastructure systems. This requires collaborative governance involving various stakeholders, co-creating a process to enhance climate resilience at a local level. Given the complexities surrounding climate resilience and infrastructure management, IIDA can be one of the innovative strategies to address current challenges and future uncertainties as it fosters collaboration across different sectors and disciplines, encouraging a holistic view and innovative solutions while providing co-benefits (Shoulund et al. 2021).

Yet, it is difficult for local governments to adopt IIDA due to limited institutional capacity such as siloed organizational structure, limited networks, and lack of leadership (Reckien et al., 2015; Leiren & Jacobsen, 2018). The case study of Rotterdam provides what needs to be addressed to effectively implement IIDA for climate-resilient infrastructure. The key influential factors are identified across six dimensions: human capacity, organizational culture, governance, communication, project development process, and finance. These dimensions are aligned well with both top-down (*authority to adapt*) and bottom-up (*capacity to adapt*) initiatives that are required for effective adaptation (Rogers et al., 2024).

Based on the identified influential factors, a roadmap was created. Since most of the current infrastructure is in the operation phase, the municipality should start with assessment and planning for adaptation. This requires **establishing a multi-dimensional baseline** to analyse the city's climate vulnerabilities and capacities. This involves checking internal and external actor's needs and skills, infrastructure assets' resilience, scanning available technological and financial tools, and understanding current project development processes and policies.

Once the municipality knows the baseline, **communication strategy and tools** should be set up. There should be an information platform where relevant information can be accessible to stakeholders. The municipality can draw out collaboration guidelines, including how to engage communities. This step can help share information and knowledge, align goals, strategies, and actions, and facilitate collaboration.

The municipalities further need to **build human capacity** such as leadership, soft skills, and networks as well as **institutional capacity** such as budgeting, policies and regulations. Initiating pilot projects and living labs can provide opportunities for cross-sectoral learning and knowledge transfer (Hughes et al., 2020; Schäfer & Scheele, 2017). Based on the knowledge and capacity built through pilot projects and living labs, the municipalities should then standardize and routinize them. The new insights can be incorporated into updated regulations, policies, and goals.

6. Conclusion

Integrated design fosters innovation, leveraging the collective knowledge of various disciplines and designers. Previous research has predominantly focused on integration within the design process itself (Vooredent, 2017; Keusters et al. 2024) and on differing stakeholder perceptions of integration. The organizational and practical implications for municipalities adopting an integrated design approach remain underexplored. This creates a gap between the theoretical understanding of integrated design and the practical, management-focused aspects required for its effective implementation.

This research explores the characteristics of climate-resilient infrastructure, IIDA, and the role of local governments. The research offers a visual representation of combining the infrastructure lifecycle with the climate resilience cycle. This integration aims to heighten infrastructure managers' awareness of their expanded responsibilities during the operational phase. Taking climate resilience into consideration, infrastructure managers now are responsible for activities such as assessment, redesign, and reconstruction in response to climate adaptation. Incorporating redesign tasks into the operational phase presents new challenges for local infrastructure authorities, requiring a departure from the traditional asset mindset to adapt their project development processes. The adaptation phase further highlights the importance of organisational capacity and understanding infrastructure interdependencies to enhance climate resilience (Carhart & Rosenberg, 2016).

Using Rotterdam as a case study, this research also reveals influential factors for effective IIDA implementation at the local level in terms of planning, resource allocation, and coordination across departments and stakeholders. Notably, human capacity emerged as a significant factor, following organisational culture, communication, governance, project development process and financial dimensions. The diversity of dimensions underscores the significance of adopting a holistic perspective, which is essential for municipalities to effectively address the implementation of an integrated design approach.

This study has several limitations. Given the diversity of climate impacts and urban infrastructure priorities that vary by geographic context, findings from this paper 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 the implementation of an integrated infrastructure design approach at the municipal level.

Despite this limitation, this research provides insights into the implementation of integration at the three levels of management (strategic, program and project), highlighting the importance of decision-making at the program level regarding the intervention scale for integration. Further research is needed about integration in program management. Implementing an integrated design approach will require adaptable organisations that are able to restructure their process and budgets. Thus, further research is needed on aligning municipal budget allocation with the integral work procedure. Finally, this research explores the influential factors from a municipal perspective. Further research is required to understand external actors such as other local infrastructure's responsible and private companies.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT in order to improve grammar and readability. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

CRediT authorship contribution statement

Angela Ordóñez Llancce: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Yirang Lim:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Theresa Audrey O. Esteban:** Writing – review & editing, Supervision, Methodology. **Joep van Leeuwen:** Validation, Supervision. **Johan Ninan:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Human participants

This research followed all necessary ethics approval, mainly by Human Research Ethics Committee (HREC) from the TU Delft including Data Management Plan. The Ethics coordinator for this matter is Thijs Slot. The HREC application was approved 22 September 2023.

Data availability

Data will be made available on request.

Data available on request due to privacy/ethical restrictions: The data that support the findings of this study are available on request from the corresponding author, Y. Lim. The data are not publicly available due to their containing information that could compromise the privacy of research participants.

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