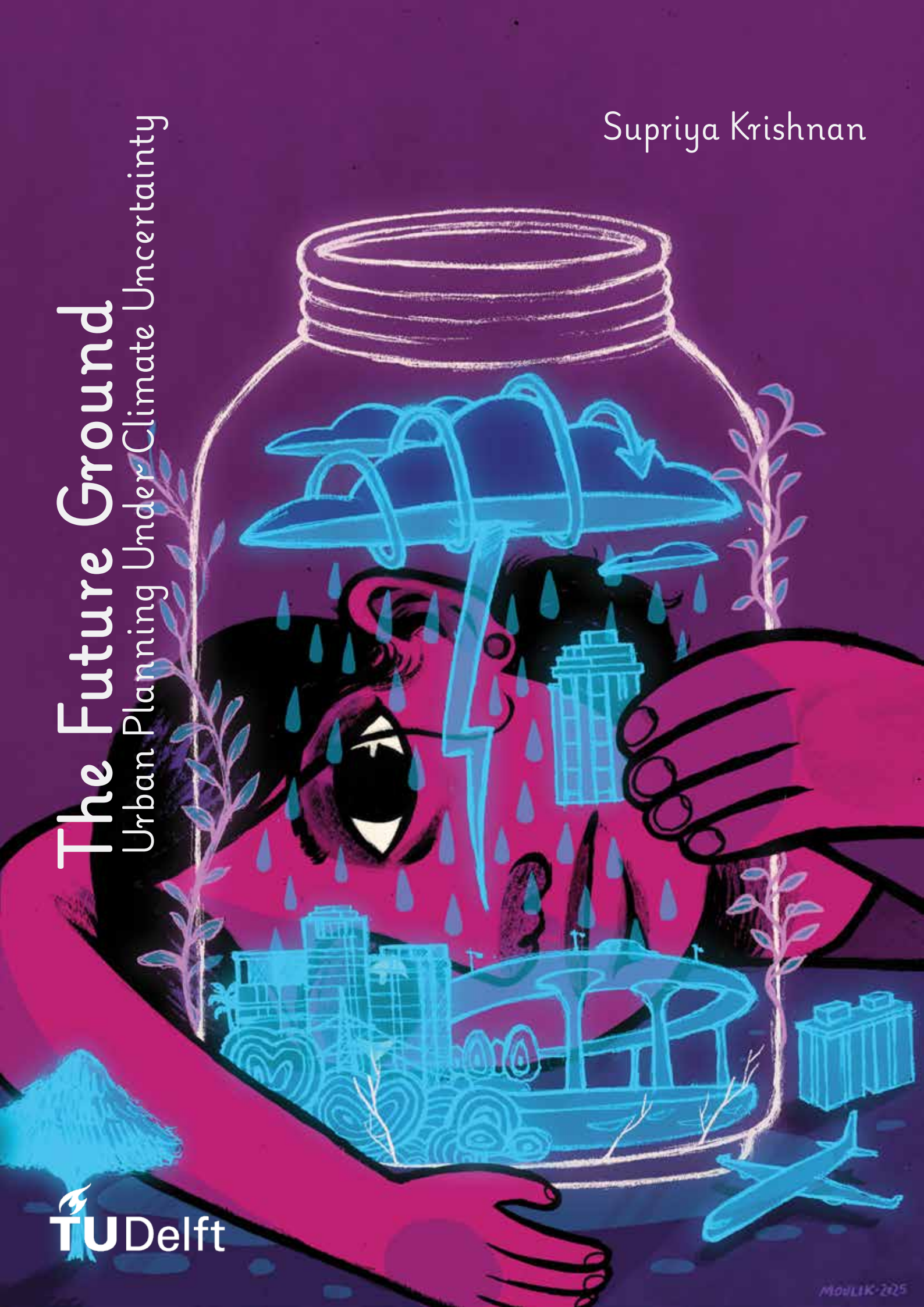
The Future Ground

Urban Planning Under Climate Uncertainty

Supriya Krishnan



TU Delft

THE FUTURE GROUND

Urban Planning Under Climate Uncertainty

Theoretical Contributions, Methodological Innovation, and Empirical Insights from Amsterdam and Mumbai

Dissertation

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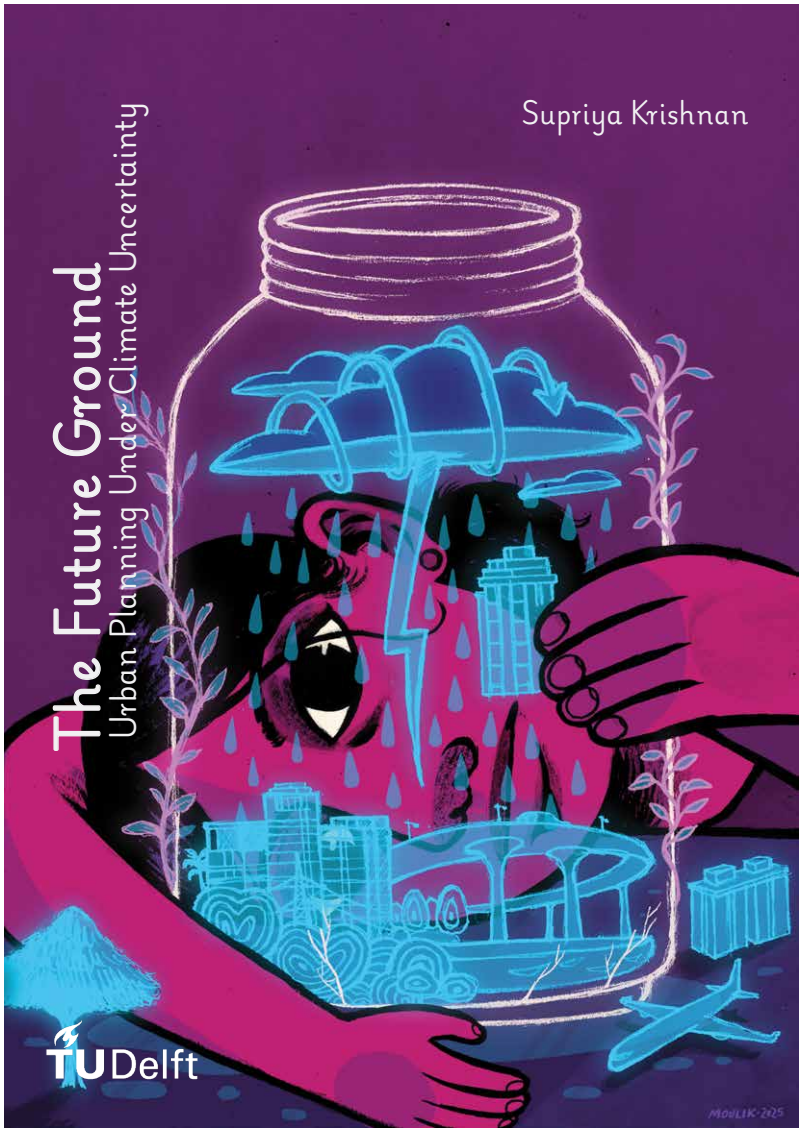
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The map used to be the stable ground beneath the planner's pen.
Today, the ground itself is negotiating its future.

To my parents, Indira and Krishnan

Preface

When I set out to begin this doctoral journey in urban planning, I was struck by a simple yet telling observation: very little of the foundational literature I was reading on resilience, adaptation, uncertainty, or future scenarios was authored by urban planners -despite them being central to how cities grow and adapt.

Engineers modelled infrastructure risk; economists projected urban futures; geographers mapped exposure; and environmental scientists quantified impacts. Each of these perspectives brought indispensable insights, but very few spoke to the actual practice of planning cities.

In most countries, urban planning is a formal, professional field. Urban planners - embedded in government agencies or consulting practices - are the ones who conceptualise urbanisation strategies, write the masterplans, draw zoning maps, envision infrastructure, and negotiate competing land-use futures that determine how cities grow, evolve, and respond to changes, disruptions and stress. Yet, the voice of planners was largely absent from the scientific debates shaping urban climate responses.

That absence became the starting point for this dissertation. As climate change is now shaping the future of cities, what role does urban planning play in mediating the future? How do planners make sense of uncertainty? How can long-term spatial strategies be reimagined to account for disruptions and changing lifecycles?

This research, situated within the emerging paradigm of climate urbanism, grew out of a need to bridge spatial reasoning with systemic thinking. The dissertation is as much about future cities as it is about how planners come to know and shape them. It reflects the belief that planners, when equipped with the right frameworks and methods, can play a central role in navigating the uncertainties of climate change and guiding transformative urban futures.

Contents

Summary

Context and Motivation

Cities are where the climate crisis is most acutely felt due to the convergence of people, economy, and infrastructure in increasingly dense and interdependent spatial systems. When urban systems intersect with hazard-prone geographies, the consequences of exposure are significantly amplified.

At the same time, cities are emerging as key arenas of innovation and experimentation. They offer opportunities to test new ideas, scale strategies, and deliver co-benefits - if supported by appropriate tools, governance mechanisms, and resources, making them central actors in achieving global climate goals [1]. The need for better mechanisms also underpins the IPCC's upcoming *Special Report on Climate Change and Cities*, which highlights the need for empirically grounded insights into how climate-related planning responses are developed and implemented.

While urban planning under climate change has been on the global development agenda for decades, progress remains uneven and does not reflect the urgency or systemic complexity of the climate threat. Many planning approaches continue to operate within institutional and temporal constraints that inhibit long-term thinking.

The way cities conceptualise and respond to climate risks has evolved markedly: from early emphases on mitigation and physical protection, to adaptation focused on adjusting urban systems, to resilience approaches oriented toward continuity and recovery. More recently, a shift toward transformative resilience recognises the need for deeper structural, institutional, and cultural change. Together, these trajectories converge under the paradigm of **climate urbanism** - an emerging field that places climate uncertainty, spatial interdependencies, and long-range transformation at the heart of urban development.

Despite advances in **urban resilience and climate adaptation frameworks**, most urban planning systems remain constrained along two key dimensions. First, they operate within short-term five to twenty years planning cycles - which limit foresight and prevents alignment with urban system lifecycles that extend 50-100 years. Second, they continue to follow a sectoral logic of *"one risk, one sector, one climate projection"*, where responses to floods, heat, and other risks are developed in isolation within specific silos. The dual constraint of temporal myopia and sectoral fragmentation hampers coordination across systems and timescales, creating path dependencies that lock cities into vulnerable development trajectories.

This research is positioned at the conceptual core of **climate urbanism** by examining how urban planning systems can embed **resilience thinking**, harmonise short- and long-term planning horizons, manage disruptions, and apply design thinking to steer urban transformation under conditions of climate uncertainty.

The research is **not** motivated by a lack of data-climate projections, resilience frameworks, or adaptation models which are increasingly available - but by the absence of mechanisms and methods to systematically

embed this knowledge into long-term urban, specifically spatial planning in the form of masterplans and urbanisation strategies. To address this, the dissertation adopts a **mixed-methods design** grounded in **Multi-Case Theory (MCT) building** and guided by a **Design Thinking** framework. This integration enables iterative movement between theory and practice: conceptual frameworks are developed, empirically refined through two contrasting metropolitan case studies, and translated into a new methodology for designing urban futures. The approach recognises that cities under climate disruption are complex, fragmented, and uncertain-requiring planning methods that can learn, iterate, and adapt over time.

Objective and Approach

The overarching aim of this dissertation is to strengthen urban planning trajectories under conditions of climate uncertainty. It does so by providing a rigorous **theoretical foundation**, **empirically grounded conceptual insights**, and a **computationally robust methodological framework**, which together enable planners to design and evaluate urban futures.

The research pursues four interrelated objectives:

1. **Theoretical Synthesis:** Advance and connect theories of urban resilience and planning under uncertainty by developing a unified framework that examines how resilience principles translate into planning responses across urban systems.
2. **Temporal Foundations:** Centralise the role of time in planning by conceptualising the temporal dynamics of urban transformation and harmonising infrastructure lifecycles with planning timeframes, thereby embedding temporality within resilience theory.
3. **Empirical Refinement:** Apply and iteratively refine the emerging conceptual framework in two contrasting metropolitan case studies-the Metropolitan Region of Amsterdam (MRA) and the Mumbai Metropolitan Region (MMR)-to examine how resilience and uncertainty are interpreted and operationalised in different planning contexts.
4. **Methodological Innovation:** Develop a blended scenario development approach, grounded in Design Thinking, that integrates qualitative narratives with computational land-use models, explicitly incorporating planners' tacit knowledge and spatial reasoning.

The metropolitan scale serves as the empirical and analytical focus of this research, as it enables coordination across sectors and jurisdictions. In this context, resilience is operationalised not through isolated projects but through spatial strategies and decision-support tools that link theory, data, and practice across systems.

Chapter Overview

Chapter 2 presents a large-scale systematic review of academic literature (1990-2021; 37,000 papers) and grey literature at the intersection of urban planning, resilience, and **Planning Support Systems (PSS)**. It identifies three core limitations in existing PSS: sectoral reductionism, weak treatment of uncertainty, and neglect of temporal dynamics. The

chapter concludes with a research agenda for reconceptualising PSS, setting priorities for advancing these tools to support long-term climate resilience.

Chapter 3 develops a unified conceptual framework linking resilience principles with planning under uncertainty. A comparative analysis of the Metropolitan Region of Amsterdam (MRA) and the Mumbai Metropolitan Region (MMR) illustrates how institutional capacities and planning cultures shape adaptive responses - with rigidity in Amsterdam's planning contrasting with fragmentated planning in Mumbai. The framework yields four propositions on flexibility, trade-offs, renewal as an entry point, and plural urbanisation strategies, thereby advancing theory on **planning under climate uncertainty**.

Chapter 4 deepens the theoretical contribution by introducing the concept of **arrhythmias** - misalignments between infrastructure lifecycles and planning horizons. This is critical for understanding how cities must account for disturbances and disasters that further disrupt temporal rhythms. It conceptualises cities as assemblages of overlapping temporal rhythms and demonstrates how neglecting these dynamics reinforces maladaptive path dependencies. Building on findings from MRA and MMR, the chapter shows how integrating temporality into resilience theory provides planners with a framework to harmonise short- and long-term strategies, moving from reactive adaptation to strategic transformation.

Chapter 5 presents **FutureScapes**, a methodology that blends narratives with stochastic land-use models to explore urban scenarios. Guided by Design Thinking, it embeds planners' tacit knowledge and spatial reasoning into computational workflows, generating spatially explicit, decision-relevant futures. Applied in Amsterdam, FutureScapes reveals trade-offs among densification, accessibility, biodiversity, and institutional inertia-illustrating how iterative methods can contextualise computational model outputs to support the development of long-term urban growth policies that account for multiple scenarips.

The PhD trajectory actively contributed to policy and professional arenas. I co-organised urban resilience training events with *UN-Habitat*, and earned fellowships and mentorships from programmes such as *C40 Cities Women4Climate*, the *Coalition for Disaster Resilient Infrastructure*, and *Allianz Re Climate Risk*. These engagements have expanded the societal reach and practical application of the research.

Samenvatting

Context en motivatie

Steden zijn de plek waar de klimaatcrisis het meest acuut wordt gevoeld, vanwege de samenkomst van mensen, economie en infrastructuur in steeds dichtere en onderling afhankelijke ruimtelijke systemen. Wanneer stedelijke systemen samenkomen in gebieden die gevoelig zijn voor gevaren, worden de gevolgen aanzienlijk versterkt. Tegelijkertijd zijn steden belangrijke arena's voor innovatie en experimenteren. Ze bieden mogelijkheden om nieuwe ideeën te testen, strategieën op te schalen en co-voordelen te leveren - mits ondersteund door passende instrumenten, governance-mechanismen en middelen, waardoor ze een centrale rol krijgen bij het bereiken van mondiale klimaatdoelen [1]. De behoefte aan betere mechanismen ligt ook ten grondslag aan het aanstaande *Speciale Rapport over Klimaatverandering en Steden* van het IPCC, dat de noodzaak benadrukt van empirisch onderbouwde inzichten in hoe klimaatgerelateerde planningsreacties worden ontwikkeld en geïmplementeerd.

Hoewel stadsplanning onder klimaatverandering al tientallen jaren op de mondiale ontwikkelingsagenda staat, blijft de vooruitgang ongelijkmatig en weerspiegelt deze niet de urgentie of systemische complexiteit van de klimaatdreiging.

Veel planningsbenaderingen blijven opereren binnen institutionele en temporele beperkingen die langetermijndenken belemmeren. De manier waarop steden klimaatrisico's conceptualiseren en erop reageren, is aanzienlijk geëvolueerd: van vroege nadruk op mitigatie en fysieke bescherming, naar adaptatie gericht op het aanpassen van stedelijke systemen, naar veerkrachtbenaderingen die gericht zijn op continuïteit en herstel. Meer recent erkent een verschuiving naar transformatieve veerkracht de noodzaak van diepere structurele, institutionele en culturele verandering. Samen convergeren deze trajecten onder het paradigma van klimaaturbanisme, een opkomend vakgebied dat klimaatonzekerheid, ruimtelijke onderlinge afhankelijkheden en transformatie op lange termijn centraal stelt in stedelijke ontwikkeling.

Ondanks de vooruitgang in veerkrachtige steden en klimaatadaptatie kaders, blijven de meeste stedelijke planningssystemen beperkt langs twee belangrijke dimensies. Ten eerste opereren ze binnen korte planningscycli van vijf tot twintig jaar - wat vooruitziendheid beperkt en afstemming met de levenscycli van stedelijke systemen, die 50 tot 100 jaar duren, verhindert. Ten tweede blijven ze een sectorale logica volgen van *één risico, één sector, één klimaatprojectie*, waarbij reacties op overstromingen, hitte en andere risico's geïsoleerd worden ontwikkeld binnen specifieke silo's. De dubbele beperking van temporele myopie en sectorale fragmentatie belemmert de coördinatie tussen systemen en tijdschalen, waardoor pad-afhankelijkheden ontstaan die steden vastzetten in kwetsbare ontwikkelingspaden.

Dit proefschrift positioneert zich in de conceptuele kern van klimaaturbanisme door te onderzoeken hoe stedenbouwkundige systemen veerkrachtdenken kunnen inbedden, planning op korte en lange termijn kunnen harmoniseren, verstoringen kunnen beheren en design thinking kunnen

toepassen om stedelijke transformatie te sturen onder omstandigheden van klimaatonzekerheid.

Dit onderzoek wordt niet gemotiveerd door een gebrek aan data klimaatprojecties, veerkrachtkaders en aanpassingsmodellen die steeds meer beschikbaar komen, maar door de afwezigheid van mechanismen en methoden om deze kennis systematisch in te bedden in langetermijnstedelijke, specifiek ruimtelijke planning in de vorm van masterplannen en verstedelijkingsstrategieën. Om dit aan te pakken, maakt het proefschrift gebruik van een mixed-methods design gebaseerd op Multi-Case Theory (MCT) en geleid door een Design Thinking-kader. Deze integratie maakt iteratieve beweging tussen theorie en praktijk mogelijk: conceptuele kaders worden ontwikkeld, empirisch verfijnd door middel van twee contrasterende grootstedelijke casestudies, en vertaald in een nieuwe methodologie voor het ontwerpen van stedelijke toekomstbeelden. De aanpak erkent dat steden onder klimaatverstoring complex, gefragmenteerd en onzeker zijn, en dat er planningsmethoden nodig zijn die in de loop van de tijd kunnen leren, herhalen en zich aanpassen.

Doelstelling en aanpak

Het overkoepelende doel van dit proefschrift is om trajecten van stedelijke planning te versterken onder omstandigheden van klimaatonzekerheid. Dit doet het door een rigoureuze theoretische basis te bieden, empirisch onderbouwde conceptuele inzichten, en een computationeel robuust methodologisch kader, die samen planners in staat stellen stedelijke toekomstscenario's te ontwerpen en te evalueren. Het onderzoek heeft vier onderling samenhangende doelstellingen:

1. **Theoretische synthese**: De theorieën over stedelijke veerkracht en planning onder onzekerheid verder ontwikkelen en met elkaar verbinden door een geïntegreerd kader te ontwikkelen dat onderzoekt hoe veerkrachtprincipes zich vertalen in planningsreacties in verschillende stedelijke systemen.
2. **Tijdelijke grondslagen**: De rol van tijd in planning centraliseren door de tijdelijke dynamiek van stedelijke transformatie te conceptualiseren en de levenscycli van infrastructuur af te stemmen op planningskaders, waardoor tijdelijkheid wordt ingebed in de veerkrachttheorie.
3. **Empirische verfijning**: Het opkomende conceptuele kader toe passen en iteratief verfijnen in twee contrasterende grootstedelijke case studies. de Metropoolregio Amsterdam (MRA) en de Mumbai Metropolitan Region (MMR) om te onderzoeken hoe veerkracht en onzekerheid worden geïnterpreteerd en geoperationaliseerd in verschillende planningscontexten.
4. **Methodologische innovatie**: Een blended scenario ontwikkelingsaanpak ontwikkelen, gebaseerd op Design Thinking, die kwalitatieve verhalen integreert met computationele landgebruiksmodellen, waarbij de impliciete kennis en ruimtelijke redenering van planners expliciet worden meegenomen.

De metropolitane schaal dient als de empirische en analytische focus van dit onderzoek, aangezien deze coördinatie over sectoren en rechtsgebieden mogelijk maakt. In deze context wordt veerkracht niet geoperationaliseerd via geïsoleerde projecten, maar via ruimtelijke strategieën en beslissingsondersteunende tools die theorie, data en praktijk over systemen heen met elkaar verbinden.

Hoofdstukoverzicht

Hoofdstuk 2 presenteert een grootschalige systematische review van academische literatuur (1990-2021; 37.000 artikelen) en grijze literatuur op het snijvlak van stedenbouw, veerkracht en Planning Support Systems (PSS). Het identificeert drie kernbeperkingen in bestaande PSS: sectorale reductionisme, zwakke behandeling van onzekerheid en verwaarlozing van temporele dynamiek. Het hoofdstuk sluit af met een onderzoeksagenda voor het herconceptualiseren van PSS, waarbij prioriteiten worden gesteld voor het verder ontwikkelen van deze instrumenten ter ondersteuning van langetermijnklimaatbestendigheid.

Hoofdstuk 3 ontwikkelt een geïntegreerd conceptueel kader dat veerkrachtprincipes verbindt met planning onder onzekerheid. Een vergelijkende analyse van de Metropoolregio Amsterdam (MRA) en de Mumbai Metropolitan Region (MMR) laat zien hoe institutionele capaciteiten en planningsculturen adaptieve reacties vormgeven. rigiditeit in Amsterdam contrasteert met fragmentatie in Mumbai. Het raamwerk levert vier proposities op over flexibiliteit, afwegingen, vernieuwing als uitgangspunt en pluralistische verstedelijkingsstrategieën, waarmee de theorie over planning onder klimaatonzekerheid wordt bevorderd.

Hoofdstuk 4 verdiept de theoretische bijdrage door het concept van aritmische misafstemmingen tussen de levenscycli van de infrastructuur en de planningshorizonten te introduceren. Dit is cruciaal voor het begrijpen hoe steden rekening moeten houden met verstoringen en rampen die de temporele ritmes verder verstoren. Het conceptualiseert steden als assemblages van overlappende temporele ritmes en toont aan hoe het negeren van deze dynamiek maladaptieve pad-afhankelijkheden versterkt. Voortbouwend op bevindingen uit MRA en MMR, laat het hoofdstuk zien hoe het integreren van temporaliteit in de veerkrachttheorie planners een kader biedt om kortetermijn- en langetermijnstrategieën op elkaar af te stemmen, waarbij ze overstappen van reactieve aanpassing naar strategische transformatie.

Hoofdstuk 5 presenteert FutureScapes, een methodologie die verhalen combineert met stochastische landgebruiksmodellen om stedelijke scenario's te verkennen. Geleid door Design Thinking, integreert het de impliciete kennis en ruimtelijke redenering van planners in computationele workflows, waardoor ruimtelijk expliciete, beslissingsrelevante toekomstscenario's worden gegenereerd. Toegepast in Amsterdam onthult FutureScapes afwegingen tussen verdichting, bereikbaarheid, biodiversiteit en institutionele inertie, wat illustreert hoe iteratieve methoden de resultaten van computationele modellen kunnen contextualiseren om de ontwikkeling van langetermijnbeleid voor stedelijke groei te ondersteunen dat rekening houdt met meerdere scenario's.

Het PhD-traject heeft actief bijgedragen aan beleids- en professionele domeinen. Ik mede-organiseerde trainingsevenementen over stedelijke veerkracht met UN-Habitat, en ontving beurzen en mentorschappen van programma's zoals C40 Cities Women4Climate, de Coalition for Disaster Resilient Infrastructure en Allianz Re Climate Risk. Deze samenwerkingen hebben de maatschappelijke reikwijdte en praktische toepassing van het onderzoek vergroot.

Introduction 1

1.1 Research Motivation

Urban planning under climate change has been on the global development agenda for decades, yet action on the ground continues to lag behind the **urgency** of adapting to climate impacts, compounded by the pressures of rapid urbanisation [1, 2]. The IPCC's forthcoming **Special Report on Climate Change and Cities** (expected in 2027) underscores this urgency by emphasizing that cities sit at the frontline of climate change, making forward-looking urban planning indispensable to safeguarding livelihoods, infrastructure, and economies. Yet translating climate adaptation, specifically urban resilience policies, into urbanisation strategies over the long-term remains challenging due to the complexity of urban environments [3–6]*.

Addressing climate change through urban planning requires a perspective that moves beyond the conventional five- to twenty-year linear timeframes of developing masterplans and urbanisation strategies. Such long-term planning processes must offer flexibility to adapt and transform under stresses and shocks, by being grounded in a deeper understanding of the temporal dynamics of urban systems, such as harmonizing the different lifecycles of urban systems and their differentiated responses for climate adaptation ensuring short-term gains do not compromise long-term goals.

Current urban planning approaches, however, remain unable to account for or adjust to climate disruptions within conventional planning, nor do they adequately support long-term transformation. The prevailing five- to twenty-year planning timeframes compel planners to follow a siloed *"one risk, one sector, one climate projection"* logic, producing fragmented responses in cities [3, 6, 7]. This is particularly problematic for hard urban infrastructures such as transport networks, water systems, and energy grids whose lifespans extend well beyond 50-100 years [8]. Planning responses for such systems must therefore be carefully aligned with specific institutional planning timeframes of urban regions, since decisions taken (or deferred) today will shape options and lock-ins for several planning cycles to come. The rigidity of urban systems underscores the importance of developing urban planning methodologies that enable coordination across interconnected systems and timescapes.

Urban resilience frameworks, rooted in socio-ecological systems theory, have gained prominence over the past decade, offering urban planners and policymakers principles to respond and adapt flexibly to climate-related shocks and stresses [9–12].

Over recent decades, the concept of resilience has evolved from an engineering notion of stability toward a dynamic and systemic understanding centred on adaptation and transformation within complex socio-ecological technological systems [3, 6, 13–15]. Based on the widely ac-

* Urban resilience policies refer to coordinated strategies and instruments that enhance a city's capacity to anticipate, absorb, recover, and adapt to climate-related shocks and stresses while maintaining essential functions and enabling transformative change in urban systems [3–6]

cepted definition by *Meerow, Newell, and Stults (2016)*, in this dissertation, urban resilience is understood as the capacity of urban SET (socio-ecological-technological) systems, operating across multiple spatial and temporal scales, to maintain or rapidly return to desired functions in the face of disturbance, to adapt to change, and to transform when existing structures constrain future adaptive capacity [6, 14, 16, 17]. *Chelleri (2012)* distinguished between engineering resilience (rapid recovery or "bouncing back") and ecological resilience (capacity to transform or "bouncing forward") further articulated through his "3-R" framework of *robustness, redundancy, and resourcefulness* [18]. *Chelleri et al. (2021)* further expanded the framework to conceptualize cities as SET systems in which resilience depends on the interplay among human, ecological, and infrastructural processes. The same study notes that although the more engineering-oriented, robustness- and safety-driven understanding of resilience appears to have been left behind in theory, inconsistencies remain in practice: interviews revealed that implementation continues to rely heavily on robustness and safety-driven measures [19].

Thus, we observe two mainstream approaches to urban resilience in the literature, typically reflecting resilience of infrastructure systems and socio-environmental systems respectively:

- **Bouncing back:** enabling rapid recovery from disruptions and restoring the status quo ante, often by strengthening individual urban systems such as buildings, transport corridors, or utilities to withstand disturbances [20–22].
- **Bouncing forward:** fostering adaptation and long-term transformation through significant changes in socio-environmental systems, infrastructure design, and service provision [14, 23, 24].

Cities embody both infrastructural and socio-environmental dimensions, requiring resilience strategies that combine robustness (to withstand disturbance) with adaptability (to adjust and evolve).

Existing approaches often operationalise resilience as incremental adjustment rather than strategic transformation, overlooking the structural and institutional shifts required to align planning systems with long-term climate realities. Most frameworks emphasise short-term "bounce-back" recovery, reflecting the pursuit of quick wins in post-disaster contexts [4, 20, 22, 25]. Although models for adaptive decision-making-such as dynamic adaptation pathways-offer ways to navigate climate uncertainty [26], urban planning remains largely reactive, privileging immediate risk responses over strategies that build systemic resilience [14, 23, 27]. The central challenge is thus to ensure that resilience-building efforts enable urban systems to "bounce forward", providing planners with pathways for long-term, transformative climate action.

Accordingly, this dissertation is driven not by a lack of evidence for planning under climate change - since climate projections, resilience frameworks, and adaptation models are increasingly available - but by the absence of mechanisms to systematically embed this knowledge into long-term urban planning responses.

The long-term planning perspective is particularly difficult to operationalize given extended timescales, the need to harmonize overlapping infrastructure lifecycles with planning timeframes, and general uncertainties in implementation [28]. Conventional planning limits strategic foresight [29], gives insufficient attention to temporal dynamics and flexibility [28], and remains burdened by institutional risk aversion and rigidity that significantly constrains the capacity of urban planners to respond

to complexity, and uncertainty [3, 30–32]. As a consequence, cities risk locking themselves into vulnerable development trajectories, reinforcing maladaptive path dependencies that constrain future adaptation options [33–35].

However, vulnerability is not simply the outcome of poor urban planning choices; it also reflects structural pressures on developable land, spatial concentration of economic prosperity, infrastructure connectivity, and a booming urban economy which intensify competition for space. For example, between 1985 and 2015, urban growth in high-risk flood zones outpaced growth in low-risk areas, particularly in upper- and middle-income countries, a trend documented by **Seto et al. (2012)** among others [36, 37]. The trend cannot be explained by maladaptive planning alone - it also reflects the spatial concentration of economic prosperity, infrastructure connectivity, and limited developable land, which intensify competition for space.

In contexts such as the low-lying areas of the Netherlands, for instance, high-value urban and industrial development persists in flood-prone regions not because of planning neglect, but because of the protective capacity of resilient water and energy infrastructures that make continued occupation possible - albeit at rising maintenance and risk costs. Such infrastructural resilience can delay necessary spatial transformation, inadvertently reinforcing path dependencies that are difficult to reverse. This empirical reality illustrates that vulnerability is co-produced by economic geography, planning and governance capacity and how urbanization strategies guide growth, beyond mere by exposure to hazard.

As cities prepare for unprecedented investments amid escalating risks, planners play a pivotal role in laying the groundwork for resilient urban futures. Achieving urban transformation requires reconceptualising planning as an adaptive process-one that balances the immediate pressures of growth and housing demand with the long-term need to steer urban systems toward safer, more sustainable configurations. Crucially, this must be underpinned by a deep understanding of the spatio-temporal consequences of urban development trajectories and their interaction with infrastructural and environmental thresholds [38, 39].

Despite growing awareness of these needs, the methodological instruments and planning cultures needed to operationalise such long-term planning approaches that allow evaluating options, design-led iterations and experimental approaches still struggle to penetrate formal planning [40]. Previous scholarship shows that planning approaches that embrace iterative learning - essential to work with uncertainty - such as *Design Thinking* are fragmented and underdeveloped for mainstream strategic planning, particularly in large scale metropolitan contexts demanding long-term foresight [41–44].

Climate urbanism has emerged as a critical framework for understanding how cities are reconfigured as central arenas of climate action [45, 46]. It denotes an evolving mode of urbanism in which infrastructures, governance practices, and social relations are reshaped in response to the imperatives of climate change, encompassing both mitigation and adaptation. Climate urbanism highlights how urban actors engage in climate action and how these interventions transform not only the material fabric of cities but also the organisation of urban life. Beyond sectoral initiatives, it interrogates how climate imperatives reconfigure the spatial, institutional, and socio-political logics of urban planning. Within this discourse, the present dissertation contributes to debates on climate

urbanism by examining how planning approaches can evolve to embed climate resilience within long-term urban transformation.

Conceptually, the dissertation is grounded in **urban resilience theory** as its primary theoretical lens, while it generates applied insights for the domain of **urban climate adaptation** [†] and **urban planning** as the arena where theory is applied and tested.

Specifically, this thesis makes two interrelated contributions:

- **Conceptual Contributions**
  - Takes Planning Support Systems (PSS) as the analytical entry point for examining how urban planning approaches can evolve to embed climate resilience over long timescales.
  - Advances theory on urban resilience and urban planning under climate uncertainty by connecting the two domains through a unified analytical framework and by unpacking their implications into planning responses across diverse urban systems.
  - Advances the conceptual understanding of temporal dynamics of urban systems under climate-related disruptions. It conceptualises the **temporal dimensions of urban transformation** and harmonising overlapping infrastructure lifecycles with formal planning timeframes. This focus on temporality responds to recent calls for phase-based and long-term planning approaches, aligning with frameworks such as adaptation pathways [26]. This thesis aims to foreground time or temporality not only as a contextual parameter but as an organising principle for resilience - arguing that accounting for temporal dynamics is essential to planning under climate disruptions.
  - Above theories are applied to two contrasting metropolitan case studies.
- **Methodological contribution**
  - By developing a blended approach to design long-term urban land use scenarios grounded in design thinking and design science. It extends design-led, user-centric modelling traditions by actively embedding practitioner knowledge in model formulation and interpretation - capturing the preferences and spatial reasoning processes of urban planners within simulation-based decision-support. By integrating qualitative insights and quantitative rigour, the framework enhances policy-relevance of scenario-based modelling to shape urbanisation patterns and guide long-term development trajectories.

The investigation is underpinned by spatial planning, encompassing both physical master plans and urbanisation strategies that integrate decisions across multiple urban systems and spatial scales to prepare for, absorb, recover from, and adapt to climate-related disruptions [48–50]. The focus on spatial planning was purposefully chosen by the PhD candidate, given her academic training and professional expertise in urbanism, urban planning, and policymaking.

The next sections review how current urban planning addresses climate resilience, highlighting gaps this research will address.

[†] Urban climate adaptation refers to the process by which cities adjust their physical, social, and institutional systems to actual or expected climate impacts. It encompasses targeted interventions such as flood protection, heat mitigation, or infrastructure retrofitting aimed at reducing vulnerability and safeguarding urban functions [47].

1.2 Background: An Overview of Urban Planning Approaches for Climate Resilience

Urban planning theory is characterised by a central tension between fixed, structured approaches and the flexibility needed to adapt to evolving climate conditions [3]. Conventional "structured" approaches, derived theoretically from the Rational Planning Model, have guided master plans and zoning regulations on the basis of fixed horizons and single-growth projections [51–53]. Once established, such plans often remain rigid reference points until the next planning cycle (ranging from five to twenty years).

Although long-term plans (20+ years) exist, they rarely provide the fine-grained resolution required to guide district or neighbourhood-level decision-making. Regional or metropolitan urbanisation strategies may outline climate adaptation or resilience goals, but these only translate into isolated projects or pilot cases rather than scaling up across the region. This challenge is compounded by the **decentralised nature of urban master planning**, in which authority is distributed across levels of government and sectoral agencies - transport, housing, water, energy - each with distinct priorities. From a climate perspective, this fragmentation prevents coherent strategies.

Institutional fragmentation becomes particularly problematic under conditions of **climate uncertainty**, where complex trade-offs must be negotiated between short-term gains and long-term risks across sectors and jurisdictions. Addressing these trade-offs requires decision-making frameworks that are both **robust** - i.e. able to deliver acceptable outcomes across a wide range of futures - and **flexible** - i.e. able to adjust course as new information emerges or priorities shift. Approaches such as adaptive pathways and robust decision-making exemplify this dual orientation, providing structured ways to keep options open, sequence interventions over time, and revisit choices as uncertainties unfold [54–56]. Without a long-term view and cross-scalar coordination, fragmentation risks reinforcing negative path dependencies and constraining opportunities for building sustained urban climate resilience.

In practice, however, climate risks are often addressed incrementally, a common expression of which is *tactical urbanism* - such as temporary parks or shelters to alleviate waterlogging and heat stress - which provides short-term relief where resources or institutional capacity for long-term strategies are lacking [57]. Not embedding tactical actions within a coherent strategic vision, is particularly concerning given that climate impacts unfold over decadal to centennial timescales, often involving irreversible thresholds and cascading risks [58, 59].

While such interventions can build awareness and deliver quick wins, they risk reinforcing a culture of short-termism and diverting attention from the structural, long-term changes required for urban resilience.

A critical theoretical perspective that engages with such interconnectedness of urban systems is Systems Thinking (ST), which provides a broad lens to understand how changes in one system-such as transportation-trigger cascading effects across others, such as housing and land use [60–62]. ST frames cities as complex adaptive systems, enabling planners to recognize interdependencies, feedback loops, and unintended consequences across urban sectors.

While ST has advanced theoretical understanding of urban complexity, it remains largely descriptive, offering limited operational guidance [63]. It translates systems concepts into practice through structured tools such as Planning Support Systems (PSS), adaptive pathways, and scenario frameworks that translate complexity into decision-support processes. PSSs, for instance in the form of interactive GIS-based tools (computational models and visualisations) can help planners explore spatial scenarios and decisions [64]. Tools like INDEX and UrbanSim [65] integrate spatial analysis with participatory mechanisms-through interactive "smart boards" for community input-to balance infrastructure requirements, and values. Yet even these approaches often underrepresent the spatiotemporal dynamics of urban systems (e.g., the overlapping lifecycles of construction, maintenance, renewal, and replacement) and the disruptions from climate change.

While transition theory has been effective in steering socio-technical systems toward sustainability through phased experimentation and innovation [66, 67], its integration into urban planning and land-use frameworks-where spatial and temporal interdependencies are central to resilience-remains limited [68, 69]. As Frantzeskaki et al. (2017) emphasise [70], urban transitions require embedding experimental practices and learning processes within formal planning systems, yet this connection remains underdeveloped in practice.

This reflects a broader disconnect: although individual sectors are now articulating long-term climate goals, the mechanisms for translating and spatializing these ambitions within formal urban planning processes are underdeveloped [71]. In particular, the absence of a systems-approach limits the ability of planning institutions to capture interdependencies and cascading effects across urban systems. This points to an equally underdeveloped temporal dimension: current planning paradigms insufficiently account for the lifecycles of urban systems and the disruptive rhythms of climate impacts, from acute shocks to slow-onset stresses.

This lack of alignment between planning timeframes and the temporal dynamics of climate, risks reinforcing negative feedback loops between sectoral planning strategies, overlooking critical intervention windows and the spatial organisation of the built environment, that ultimately poses challenges for integrated, place-based approaches to climate resilience [28, 72].

Finally, while climate action plans in the real world often prioritize mitigation targets, the academic literature on urban planning disproportionately emphasizes adaptation, particularly in relation to resilience and uncertainty. Hence, there remains a gap in theoretical frameworks that can guide cities in translating resilience thinking into actionable adaptation strategies.

In summary, planning approaches remain constrained by rigidity, institutional fragmentation, and incrementalism, and lack mechanisms for translating resilience thinking into actionable adaptation strategies.

1.3 Research Gaps

The intersection of urban planning and climate change presents critical, unresolved challenges across the domains of resilience, adaptation, and planning approaches. This section identifies four distinct but interconnected scientific gaps that this thesis addresses.

GAP 1: There is a lack of Planning Support Systems (PSS) that support long-term, integrated planning for climate resilience.

Planning Support Systems (PSS) are widely acknowledged as promising tools for long-term urban planning. They have supported implementation of diverse planning concepts such as smart cities [73], participatory planning [74], land-use management, and emergency management [75, 76]. Yet their potential to address the inherently "wicked" nature of urban problems under climate change remains theoretically underspecified [64, 77–80], due to the following reasons identified from literature.

First, most PSS remain sectoral and reductionist, addressing discrete issues rather than capturing interdependencies across urban systems and urbanisation strategies-an essential dimension of resilience [81, 82]. While sectoral applications (e.g., road adaptation costs [83], blue-green infrastructure design [77], low-carbon energy siting [84]) show value, PSS fall short in enabling integrated approaches. Scaling up resilience requires tools that help planners select and sequence responses across multiple sectors, for which no systematic PSS currently exist.

Second, PSS are typically built around a small number of model-driven fixed scenarios, limiting their capacity to engage with uncertainty or incorporate adaptive pathways [26, 54]. Integrating the 'black box' of PSS models with the on-ground preferences of planners, especially for metropolitan planning and policymaking has well known limitations such as the over-emphasis on communication and consensus-building, while offering little guidance for managing contested priorities or trade-offs for the long-term [85–91]. Addressing these shortcomings requires embedding flexibility into PSS design, particularly by integrating temporal aspects such as intervention windows, system lifecycles, and planning timeframes [92]. Yet, as Geertman (2017) notes, many PSS remain prototypes or academic exercises, rarely embedded in masterplanning processes [64, 79]. Misalignment with infrastructure lifecycles and institutional rigidity further constrains their relevance. Consequently, the uptake of PSS in addressing unstructured "wicked" problems of climate change at the level of masterplans or urbanisation strategies remains limited [82]. Further, as noted by Pettit et al. (2018) [73], challenges in PSS implementation often arise from the gap between technical model outputs and the decision contexts of planners, while Goodspeed (2016) [93] similarly highlights how conventional scenario planning approaches struggle to accommodate uncertainty and evolving stakeholder values.

GAP 2: Urban Resilience principles are conceptually well-developed but lack systematic theoretical frameworks that connect them for urban planning under climate uncertainty.

The limitations of PSS are closely tied to a broader scientific gap in urban planning: the absence of systematic frameworks that translate resilience principles into concrete planning responses under climate uncertainty. Despite extensive theoretical work on resilience, planning still relies heavily on traditional "one risk, one sector" approaches, where isolated scenarios are produced to address specific risks within narrowly defined urban systems. Such methods insufficiently capture interdependencies among urban systems and their interactions with surrounding land-use functions [20–22].

Over the past two decades, resilience scholarship has articulated principles such as flexibility, redundancy, multifunctionality, and multiscalarity

[9–12]. Yet in practice, these often translate into incremental, short-term strategies focused on "bouncing back" from disruptions [14, 24]. As a result, resilience frameworks remain under-operationalised, offering limited guidance for designing long-term, transformative strategies [94]. This constrains the ability of planning institutions to incorporate long-term goals or scale responses beyond sectoral fixes [95], and risks reinforcing maladaptive lock-ins.

A further limitation lies in the treatment of uncertainty. Conventional planning continues to privilege deterministic or probabilistic futures. While approaches such as adaptive pathways, transition management, and decision-making under deep uncertainty advocate planning for multiple futures [5, 96, 97], their integration into resilience research has been limited and their uptake in planning practice remains marginal. The absence of systematic frameworks bridging resilience theory with uncertainty approaches or institutional learning with long-term transformation has thus resulted in fragmented scholarship and practice [98], leaving planning ill-equipped to address climate uncertainty.

GAP 3: There is an inadequate understanding of how the temporal dynamics of "connected and moving" urban systems, can be harmonised with formal planning timeframes.

Compounding the above two gaps is the weak understanding and alignment between planning timeframes and the temporal dynamics of urban systems. Conventional planning approaches are known to prioritise rapid recovery and restoration of the status quo, while neglecting the longer-term transformations required for resilience [20–22]. Urban systems operate across overlapping lifecycles of construction, maintenance, renewal, and replacement-each unfolding at different speeds. *Temporal dynamics in cities refer to the rhythms and timelines across these processes, shaped by factors such as infrastructure ageing, land-use change, investment cycles, demographic shifts, and socio-political decision-making.* Planning for resilience under climate uncertainty therefore requires engaging with this full spectrum of temporal dynamics, from gradual adjustments to transformative shifts.

Climate-related disruptions, abruptly alter these rhythms and trajectories and exposing vulnerabilities. Planning that fails to integrate such temporal dynamics risks overlooking critical intervention windows, reinforcing lock-ins, and constraining adaptive capacity. Bridging this gap requires explicitly embedding temporality into planning frameworks, so that resilience is understood not as short-term fixes but as part of long-term trajectories [99].

GAP 4: Current approaches to integrated scenario development (that combine qualitative narratives with computational models) tend to oversimplify complexity and overlook planners' knowledge, reducing its policy relevance.

Scenarios, whether qualitative or quantitative, are among the few tools available to navigate uncertainty and envision long-term urban futures. A seminal contribution on PSS highlighted the importance of enabling planners to explore a wide spectrum of options when addressing complex environments [100]. Yet a persistent disconnect remains in how qualitative and quantitative techniques are integrated.

Narratives provide contextual richness by surfacing values, design preferences, and long-term uncertainties, while computational models offer analytical rigour, scalability, and the capacity to simulate thousands of futures [96, 101–104]. However, models often rely on oversimplified assumptions, rigid data requirements, and formalised procedures, producing outputs that appear abstract or detached from local realities [105]. The translation of narratives into model inputs frequently strips away nuance and yields results that planners find overly technocratic or disconnected.

This gap is particularly acute in the presence of *normative uncertainty*, about goals, values, and design preferences, which cannot be resolved through computational optimisation alone. Without systematic mechanisms for incorporating expert judgment, tacit practitioner knowledge, and spatial design preferences into computational workflows, scenario models risk reinforcing a technocratic rationality that fails to capture the messy, negotiated character of urban planning [90, 106]. This in turn reinforces the institutional risk aversion in planning, which constrains planners' capacity to respond to the complexity and uncertainty in future transformation.

A persistent challenge remains in linking policy-relevant narratives and spatial reasoning processes of planners with the analytical rigor and scalability of computational models. As a result, despite advances in models, their influence on actionable planning policies has remained limited.

Addressing this gap requires approaches that blend narratives and models in systematic, iterative, and transparent ways, where planners' perspectives, diverse viewpoints, and ability to learn from failure actively shape model assumptions and outputs. Design Thinking (DT) offers a structured method for iterative learning. However, the current implementation of Design Thinking in urban planning-particularly within long-range and strategic processes-remains fragmented and underdeveloped. This forms the starting point for the methodological framework developed in this dissertation.

1.4 Research Aim and Research Questions

The main research question that the thesis addresses is "How can urban planning be re-envisioned using resilience, temporality, and design-based methods to enable planning under climate uncertainty?" The thesis answers it through four key research questions, each corresponding to one of the identified scientific gaps:

RQ1: How can urban planning approaches and Planning Support Systems (PSS) be advanced to enable long-term climate resilience?

RQ2: How can resilience principles be systematically integrated into urban planning to address climate uncertainty across different contexts?

RQ3: How can the temporal dynamics of urban systems be conceptualised and leveraged for flexible planning processes to enhance long-term resilience?

RQ4: How can design thinking be operationalised to combine qualitative narratives and quantitative models, with experts insights, for decision-oriented future urbanization scenarios?

1.5 Research Approach and Methodological Considerations

This dissertation investigates how urban planning processes can be re-oriented to support long-term planning under climate uncertainty. It recognises also that urban resilience strategies often fail when planning structures are too rigid to accommodate context-specific risks and spatial realities [4]. The research adopts a mixed-methods approach positioned at the intersection of theory building, empirical investigation (through qualitative cross-case analysis), and methodological innovation (Figure 1.1). At its core, the research builds and refines theory through an iterative process underpinned by **Multi-Case Theory (MCT) building** [107] and the logic of **Systematic Combining (SC)** [108]. MCT provides a foundation for studying complex and evolving domains-such as urban resilience and adaptation-where prior theories are partial, fragmented, or conflicting [109]. Long-term urban planning, shaped by dynamic uncertainties, requires an approach that can capture emerging insights rather than relying solely on predefined theoretical models. *SC* enables reflexive movement between theory, data, and analysis. MCT, in particular, allows for structured comparison across cases, refining concepts and ensuring that the theoretical propositions developed in this thesis are continuously tested and enriched by empirical insights and methodological experimentation. By engaging with contrasting contexts through common research questions and analytical lenses, the findings are not idiosyncratic to one setting but speak to broader challenges of resilient urban planning under climate uncertainty. This strengthens the explanatory capacity of the research, enabling contributions not only to scholarly theory supported by practical insights from diverse planning contexts.

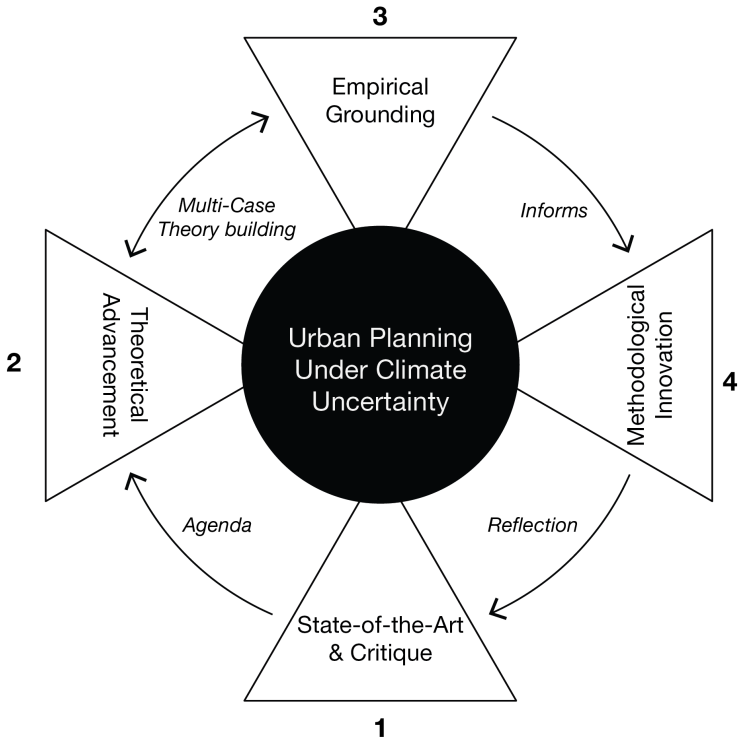

Figure 1.1: Research approach of the dissertation. The study adopts a mixed-methods research design positioned at the intersection of theory building, empirical cross-case analysis, and methodological innovation. The arc progresses from Critique (systematic review of PSS and planning approaches for climate resilience.), to Theoretical Advancement (bridging resilience and uncertainty, situating resilience within temporal urban dynamics), Empirical Grounding (application and refinement of theories and conceptual frameworks through two contrasting metropolitan case studies), and finally to Methodological innovation (design-thinking methodology to design urban futures).

The dissertation also acknowledges that concepts such as resilience are not objective or singular, but polyvocal and contested. Resilience is interpreted differently across contexts-such as Amsterdam and Mumbai-reflecting distinct climatic conditions, socio-economic dynamics, governance traditions, and cultural priorities [110]. Much resilience and adaptation theory originates in the Global North, rooted in contexts with data-rich environments and strong planning institutions. This raises questions about their applicability in the Global South, where informality, limited data, and different risk perceptions demand alternative knowledge frameworks. To address this, the research adopts an interpretivist/constructivist lens, engaging with planners' perceptions, narratives, and tacit knowledge (through case studies, interviews, and scenario narratives) to examine how resilience principles are interpreted and materialised in practice.

At the same time, the thesis is grounded in the understanding that while the impacts of climate risks on urban systems are real, our knowledge of these structures is inevitably partial and mediated through planning institutions, computational models, and cultural framings. The research explicitly seeks to uncover the underlying mechanisms-temporal dynamics, uncertainty, and interdependencies-that shape observed planning outcomes.

Arc of the Dissertation This dissertation contributes to the emerging discourse of climate urbanism by adopting a mixed-methods research design to develop a theoretically grounded and empirically tested framework that integrates resilience, temporality, and uncertainty into long-term urban planning, along with a design-driven methodology to explore future urban scenarios. It makes four interrelated contributions, tracing a coherent line of enquiry that begins with critique, to theory and conceptual deepening, supported by empirical insights, and culminating in methodological innovation (as illustrated in Figure 1.1):

1. **State-of-the-Art & Critique:** A systematic review of urban planning approaches and Planning Support Systems (PSS) in relation to climate change, identifying key conceptual, institutional, and methodological gaps in enabling long-term resilience.

2. **Theoretical Advancement:** Bridging resilience and planning-under-climate-uncertainty theories into an integrated framework, multi-case empirical grounding, and developing a novel conceptual foundation for embedding temporal dynamics in urban planning systems.

3. **Empirical Grounding:** Application and refinement of the theories and conceptual framework through two contrasting metropolitan case studies-Amsterdam (Global North) and Mumbai (Global South)-demonstrating how resilience and uncertainty are interpreted and operationalised in different institutional and planning contexts.

4. **Methodological innovation:** Development of "FutureScapes," a design-driven scenario methodology that integrates qualitative narratives with computational land-use modelling to generate adaptive, spatially explicit, and decision-relevant long-term planning scenarios.

Key Concepts

The dissertation advances the emerging discourse on **climate urbanism**. It offers a rigorous **theoretical foundation** which is iteratively refined with **empirical insights**, and a robust methodological framework. Together, these enable planners to design transformative planning strategies that embed resilience within long-term urban planning processes. The research is structured around five defining choices:

Climate Urbanism & Urban Resilience: This thesis contributes to the discourse on climate urbanism [45], which positions cities as critical sites for climate action. It examines how resilience can be integrated into planning frameworks to manage climate disruptions and uncertainty. In this study, resilience is approached not as a fixed end-state, but as a planning principle interpreted and materialised across different urban systems and temporal horizons. The focus is twofold: (i) to investigate how resilience principles translate into spatial interventions-such as greening, retrofitting, multifunctionality, and adaptive design-across domains (open spaces, buildings, networks) and timescales (short-, medium-, and long-term); and (ii) to analyse how the interpretation and implementation of resilience concepts differ across contrasting planning contexts shaped by distinct climatic risks, socio-economic conditions, and development priorities. By moving beyond abstract framings, the research interrogates how resilience is operationalised in practice, and how these practices inform theoretical understandings of climate urbanism.

The Early, Strategic Stages of Urban Planning: Urban planning encompasses a broad spectrum of activities. In the context of climate change, this ranges from problem framing and diagnostic assessment to scenario development, strategic formulation, design, and evaluation [111–113]. This dissertation focuses on the early, strategic stages, where foundational choices shape interdependencies across multiple systems. Specifically, it examines the spatial dimensions of planning as expressed through master plans and urbanisation strategies. Here, spatial planning refers to land-use policies and zoning regulations that balance socio-economic and ecological objectives.

The Metropolitan Scale: Unlike much existing research that concentrates on the city scale, this dissertation adopts a metropolitan perspective. The metropolitan scale is critical for resilience because it encompasses interconnected systems-transport networks, economic hubs, and ecologically sensitive regions-while extending beyond the urban core to include suburban expansions, peri-urban zones, and satellite cities. Examining land-use dynamics at this broader scale enables a more comprehensive understanding of interventions across spatial and temporal dimensions.

Computational Land-Use Models: Given the long-term consequences of land allocation and its path dependencies, this research employs a stochastic land-use model (**Metronamica**) to explore urban growth trajectories under climate uncertainty. At the metropolitan scale, Metronamica captures cross-jurisdictional dynamics and inter-system spillovers, quantifies interactions among land uses, and represents cumulative transitions in the urban fabric under multiple futures [114, 115]. This makes it well-suited for multi-decadal planning, where the goal is to explore sequenced development pathways and intervention windows rather than to optimise short-term operations.

In this dissertation, the model is implemented for the Metropolitan Region of Amsterdam (MRA), where data availability enables testing of spatial

outcomes against narrative assumptions, generation of suitability surfaces and transition probabilities, and comparison of sequenced pathways. For the Mumbai Metropolitan Region (MMR), modelling was initiated but excluded from final results due to data quality and format constraints. Documenting this process nonetheless provides valuable insights into the limitations of data environments in the Global South and their implications for long-range modelling. This limitation itself constitutes a key finding, highlighting the practical challenges and methodological gaps in applying advanced modelling approaches to data-sparse contexts.

Design Thinking (DT): A final gap addressed in this thesis is the limited capacity of computational models to systematically incorporate practitioner knowledge and preferences. Building on design-oriented planning approaches [44, 116], this research applies design thinking as a lens to blend practitioner expertise with computational outputs.

Within this research, DT is introduced as a theoretical and methodological lens for scenario planning. As a user-centered, iterative mode of inquiry, DT facilitates movement between practitioner preferences and model assumptions-a stance that aligns with the demands of long-term planning. DT supports early-stage ideation and the integration of stakeholder perspectives [117–119], making it well-suited to the evolving and multidimensional character of urban environments. Here, planning is not treated as a linear, problem-solving activity but as an iterative process of collective inquiry.

Compared to prior work, the novelty of this dissertation lies in four key contributions.

1. Integrates theory and empirical evidence: Demonstrates how literature-based conceptual frameworks on urban resilience and planning-under-climate-uncertainty, can be mapped into urban planning responses and that literature can be further refined through cross-case study analysis (Global North/South), highlighting convergences, divergences, and their theoretical implications for urban planning.
2. Contrasting case study insights: Uses two radically different planning contexts-Amsterdam in the Global North and Mumbai in the Global South-to expose how resilience is shaped by divergent planning systems, socio-economic conditions, and perception of climate risks. This contrast provides unique leverage to test and extend resilience theory, offering more inclusive and generalisable insights.
3. Temporal dynamics framework: One of the first studies to develop the theoretical foundation for temporal dynamics, in increasingly disrupted yet ”connecting and moving”, to extend resilience beyond “bounce back” logic.
4. A blended modelling-expert approach backed by design thinking: Proposes the **FutureScapes** methodology to develop policy-relevant future urban scenarios. The methodology embeds planners' tacit knowledge and preferences into computational scenarios.

1.5.1 Selection of Case Studies

The selection of case studies in Amsterdam (Netherlands) and Mumbai (India) (Figure 1.1) was guided by three key criteria:

1. **Scientific and practical urgency:** Both metropolitan regions face pressing climate impacts and are making major investments in either renewing aging infrastructure or building new systems;

2. **Diversity:** The cases represent contrasting contexts in geography, socio-economic characteristics, planning practices, and institutional frameworks, creating a strong foundation for comparative analysis and enhancing the transferability of emergent theories;
3. **Proximity and familiarity:** The researcher's prior engagement with both regions enabled access to data, networks, and deeper contextual insights.

MRA, located in the Global North, is a high-income, technologically advanced, and politically stable region characterised by controlled urban growth, well-maintained infrastructure, and a strong emphasis on sustainability and long-term planning. By contrast, MMR, situated in the Global South, is rapidly urbanising, with a young population, medium per capita income, and ongoing industrialisation. It faces challenges such as high-density settlements, informal housing, and inadequate infrastructure from unregulated expansion. While MRA focuses on renewing aging systems, MMR is investing heavily in new infrastructure to meet the demands of growth.

Planning frameworks further reflect these differences. MRA operates within a structured and relatively predictable environment that historically evolved under low-risk conditions, though sea-level rise and heatwaves now pose urgent challenges. MMR, in contrast, operates in a fragmented and reactive context shaped by frequent and severe risks including flooding, heatwaves, and cyclones. These contrasting risk profiles underscore the differing capacities and strategies of each region in managing climate disruptions.

Both regions are actively addressing climate change, though the scale and scope differ. MRA has developed a comprehensive adaptation strategy at the regional level, while MMR's climate action remains largely confined to Mumbai city. This reflects the broader challenge of scaling climate policy across metropolitan areas in resource-constrained contexts, in contrast to the centralised and well-funded efforts of MRA.

The deliberate inclusion of one case from the Global North and one from the Global South addresses a critical gap in resilience and planning research. Much existing literature is rooted in Global North experiences, often overlooking the unique dynamics of Global South cities. By testing theories across these divergent contexts, this study refines their relevance for non-Western planning systems and contributes to debates on the Global North-South divide in resilience knowledge production [120, 121]. Although MRA and MMR are not representative of all cities in their regions, they embody key characteristics of urbanisation and governance that provide meaningful variability for comparative research.

Accessibility and researcher engagement also supported case selection. The researcher's position at TU Delft facilitated proximity to MRA and access to regional practitioners. Prior professional experience in MMR, as a native of the region and graduate of a local planning programme, enabled access to institutional knowledge and on-the-ground insights. Additional support came from TU Delft's involvement in the Delft Global Initiative, and mentorship from the Coalition for Disaster Resilient Infrastructure (CDRI) and the C40 Cities Women4Climate initiative.

Although theoretical and empirical analyses were conducted for both case studies, the final computational land-use modelling was undertaken only for MRA. In MMR, barriers related to data availability and format proved prohibitive: many required datasets were either inaccessible, inconsistent, or demanded extensive manual processing. While initial vectorisation

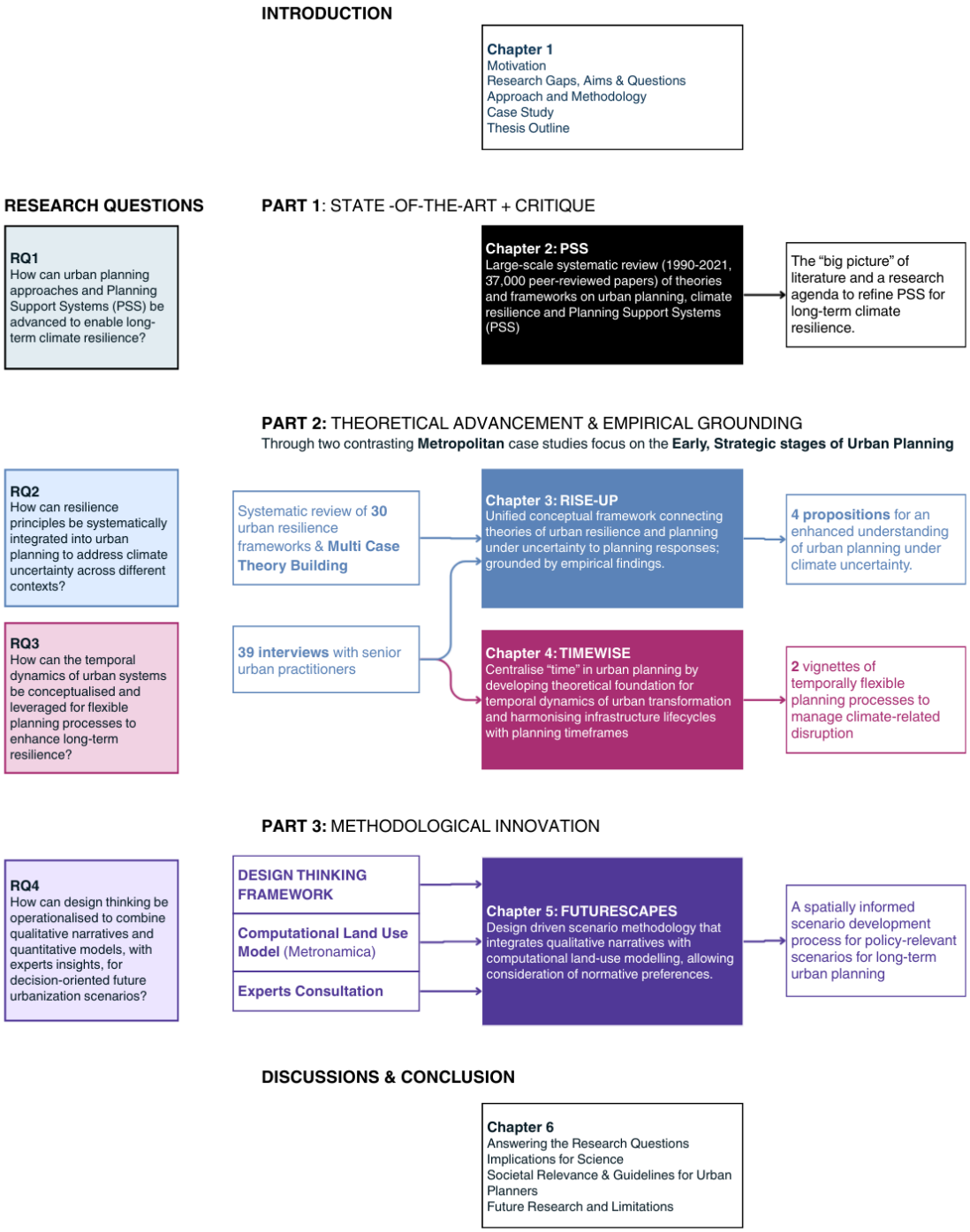

Figure 1.3: Visual abstract of the thesis: Part I addresses RQ1, Part II focuses on RQ2 & RQ3, and Part III covers RQ4.

and corrections were attempted, validation standards could not be met. Consequently, the modelling component for MMR was excluded from the final analysis. Nonetheless, this process was carefully documented [122] and presented at the International Conference on Resilient Systems (ICRS) 2023, contributing to broader discussions on data limitations and methodological constraints in Global South contexts.

1.6 Thesis Outline

The thesis is structured into four chapters, each corresponding to a research gap and research question. Figure 1.3 presents a visual abstract of the thesis.

Chapter 2

Critique and State-of-the-Art (answers RQ1)

This chapter undertakes a large-scale systematic review (1990-2021, 37,000 peer-reviewed papers) of theories and frameworks at the intersection of urban planning and climate resilience, with Planning Support Systems (PSS) as the focal entry point. It identifies how the literature has conceptualised planning responses to climate change, maps trends across four knowledge streams (climate pressures, driving forces, planning responses, and resilience characteristics), and highlights the limitations of PSS in addressing integrated, long-term resilience. The chapter concludes with a research agenda to reframe PSS and priorities for advancing them to support long-term climate resilience.

Chapter 3: Theory Building + Empirical Grounding (answers RQ2)

This chapter develops the first theoretical contribution of the dissertation: a unified conceptual framework that connects urban resilience principles with approaches to urban planning under climate uncertainty. The framework is empirically evaluated through two metropolitan case studies-Amsterdam (Global North) and Mumbai (Global South)-drawing on official planning documents and semi-structured interviews. The analysis assesses how resilience principles and uncertainty approaches are translated into planning responses, what spatial scales they operate at, how rigidity and flexibility are viewed and how climate goals are integrated in different contexts. By answering **RQ2**, the chapter refines resilience theory, approaches to urban planning under climate uncertainty and demonstrates how systematic frameworks can better guide planning under climate uncertainty.

Chapter 4: Conceptual Deepening (answers RQ3)

This chapter advances the theoretical foundation for incorporating temporal dynamics into urban resilience planning. It conceptualizes urban regions as assemblages of overlapping lifecycles - of construction, maintenance, renewal, replacement - disrupted by climate shocks and stresses. Addressing **RQ3** (on temporal dynamics) identified earlier, the chapter introduces the original concept of"arrhythmias" to describe the misalignments between planning horizons and infrastructure lifecycles

that constrain adaptive capacity and long-term resilience. It proposes and illustrates innovative approaches ("vignettes") for incorporating temporal flexibility in planning processes and how that may be applied in different planning contexts. Drawing on evidence from Amsterdam and Mumbai, it proposes a framework for harmonising planning timeframes with the temporal dynamics of urban systems. By making time an explicit analytical dimension, the chapter extends resilience theory and contributes to emerging debates on complex adaptive systems and phase-based planning in the context of climate change.

Chapter 5: Methodological Innovation (answers RQ4)

This chapter presents a stepwise methododology to develop future urban scenario that blends qualitative scenario narratives with stochastic computational land-use models - guided by design thinking principles. FutureScapes systematically incorporates planners' tacit knowledge, design preferences, and spatial insights into computational workflows, generating spatially explicit and decision-relevant scenarios for long-term planning. Applied to Amsterdam, the method demonstrates how blending narratives and models produces richer, policy-relevant futures that avoid oversimplification, reduce technocratic abstraction, and enhance planning's capacity to design under uncertainty. By answering **RQ4**, the chapter shows how integrating narratives and models enhances both the scientific and policy relevance of scenario planning for long-term urban futures and also reflects on initial feedback from practitioners on FutureScapes' usefulness.

Planning Support Systems
for Long-term Climate Resilience: A Critical Review

2

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As climate change is becoming a reality, there is an increasing demand to improve urban resilience. Planning Support Systems (PSS) enable climate-informed planning. However, previous research confirms difficulties in the uptake of PSS due to their resource-intensive nature and lack of awareness of their usefulness. This chapter aims to make headway in understanding research priorities and gaps that need to be addressed for PSS to address climate resilience in the long run. To this end, we review the emerging body of knowledge in academia and practice, by conducting a text-mining analysis of academic (n = 36,405) and non-academic (practice) (n = 86) literature on urban planning and climate resilience. We extract trends in climate pressures, infrastructure drivers, and planning approaches. A key finding from the academic literature is that long-term planning continues to be limited to a few fixed scenarios and places a strong focus on single-sector strategies. Practice documents continue to be designed to inform high-level policies, but not spatial plans that require integrated thinking. Our analysis concludes with a research agenda for improving PSS to (1) identify and integrate the full range of variables in the long term; (2) support the selection of appropriate planning responses across multiple infrastructure systems; and (3) improve flexibility in planning by a deeper understanding of temporal aspects such as planning timeframes.

Keywords: *urban resilience, planning support systems, uncertainty, urban knowledge systems, long-term planning, urban climate adaptation, machine learning, literature review, topic modeling, academic publishing*

2.1 Introduction

Cities are making concentrated efforts to improve their climate resilience. Significant work is being undertaken on resilience frameworks, bioclimatic urban design, nature-based solutions, blue-green masterplans, multifunctional urban spaces, and sector-specific strategies. To improve long-term resilience, urban planning must adapt to rapidly changing constraints and be flexible to continuously integrate evolving insights [123]. However, changing demands on cities mean that planning is increasingly characterized by uncertainty and complexity that aren't solvable by using conventional methods [2]. In the context of climate change, long-term planning must consider a scope of 30-100 years which is especially complex since cities must constantly manage unforeseen events that require both incremental and structural changes in the planning process [124]. Cities currently develop largely 'fixed' masterplans for 5-20 years which focus on immediate development needs. Thinking beyond 20-30 years is a procedural and financial challenge despite the availability of climate projections. This is why climate projects are often isolated as small or

medium-scale initiatives that are not integrated with larger development goals hindering long-term resilience. Hence, the motivation among planners to adopt a long-term planning perspective and use a PSS that enables it has been missing [125].

Long-term planning requires the identification of changing insights and connecting them with decision-making windows within urban planning timeframes. Planning Support Systems (PSS), such as large-scale urban models and visual tools, provide applications to navigate this complexity, deliberate on issues collaboratively [75] and capture the behavior of urban systems under changing conditions [2, 76, 126]. However, compared to the advances in the domain, the uptake of PSS in planning has been low due to their resource-intensive nature and inability to acknowledge the constraints of its end-users [89, 127]. Moreover, in the planning process, there is a lack of balance in combining the objectivity (formalism) of large-scale PSS models with the experience and intuitive knowledge of urban planners that guide decisions [90, 106].

In this study, we make headway in understanding research priorities and gaps that must be addressed for PSS to address climate resilience in the long run. To this end, we review the emerging body of knowledge in academia and practice, by conducting a text-mining analysis of literature on urban planning and climate resilience. The results are analyzed to identify similarities and variations in consideration of climate and environmental pressures, infrastructure sectors, planning approaches, and understanding of resilience. We precede this with an examination of the merits and demerits of existing PSS applications in climate and resilience to assess overall trends and what areas require work. As compared to previous work, we present a comprehensive overview of the knowledge landscape in academia and practice to highlight how both areas can work collaboratively to improve PSS. We conclude with a research agenda for designing an improved PSS that is useful in accounting for long-term resilience goals.

2.2 Background

Planning has traditionally promoted the creation of fixed plans for the 'here and now' which prioritizes development needs in a 5-20 year timeframe [128–130]. Investments made in this single planning cycle create path dependencies that have far-reaching impacts on infrastructure, land use, and overall urban growth. The dichotomy is that most practitioners would consider a 20-30-year timeframe to be significantly long since rapid unanticipated changes could change the direction of development. However, a timeframe of 5-20 years also provides little incentive for planners to bring in the integration and flexibility required for long-term climate resilience [29]. Hence, there is a dilemma as well as a gap in methods that can assist planners in accounting for long-term changes and incorporating them within the standard planning cycle.

Due to a large number of stakeholders in the planning process, planners also seek a 'negotiated certainty', which divides the urban problem into different manageable modules or sectors [131]. Hence, the role of PSS is automatically steered towards sector-specific tools and tools on 'communication and collaboration' as opposed to decoding complexities of planning itself [90].

The tendency for sector-specific PSS applications also comes from the need to present successful proof of concept. For instance, for blue-green infrastructure, there is the *Adaptation Support Tool (AST)* [77], SUSTAIN [132] and EPA's National Stormwater Calculator [133]. For transport, there is *Infrastructure Planning Support System (IPSS)* which is used to assess the long-term success of roads by analyzing costs and benefits for climate adaptation. However, it does not account for local knowledge of inundation that causes disruptions [83]. For energy, there is E-GIS which is used for site selection for low carbon urban energy systems [134] and [84] which presents a method for site selection for renewable energy systems. The single-sector focus does not lend well to an integrated planning approach that must account for path dependencies with other sectors.

PSS are also designed to work with a few fixed scenarios. For instance, the Dhaka Metropolitan Development Planning Support System (DMDPSS), demonstrates the benefits of using land-use planning and scenario modeling to manage climate issues, both useful for long-term thinking. However, it constructs two fixed development scenarios and does not discuss the roadblocks in using multiple scenarios [29]. To manage uncertainties, [78] advocates for a PSS with a higher degree of contextual awareness ('sentience') that allows planners to adjust variables and constraints based on a context. There is a gap in systematically identifying and interpreting evolving variables and constraints for planning [33, 135].

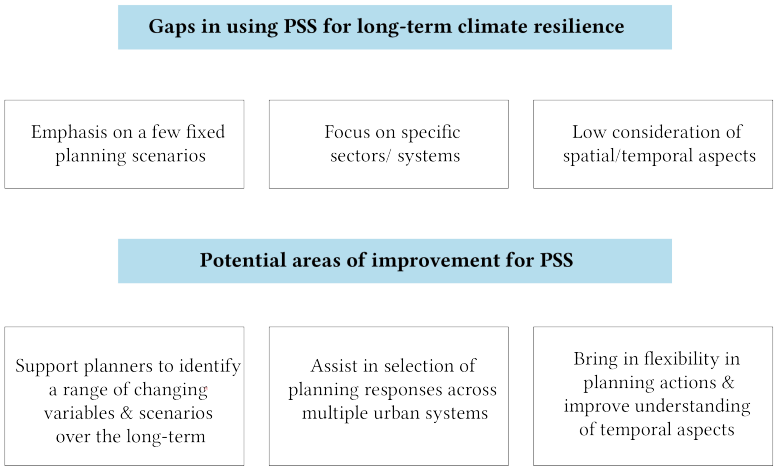

Figure 2.1: Gaps in using PSS for long-term climate resilience and potential areas for improvement.

However, urban planning, especially long-term planning, is characterized as a 'deep uncertainty' problem, which cannot necessarily be solved by identifying an exhaustive range of variables that impact planning. There is no definite method to evaluate the plan outcomes [136]. Uncertainties may originate from climate stresses (sea level rise, precipitation, temperature) and shocks (storms, flash floods, heatwaves) and may be compounded due to interactions with socioeconomic, environmental, and political variables [102] as well as the scale of the urban form itself [137].

Building a robust plan towards uncertainties requires bringing flexibility into the planning process and understanding inherent flexibility in urban systems [12, 138]. For instance, road networks, occupation patterns, ecosystems, etc., have their own lifecycles and adaptation rhythms which help determine actions to adapt, retrofit or renew. A systematic understanding of these temporal aspects becomes central in determining planning actions for changing conditions, and identifying trade-offs

and lock-ins to promote resilience. Urban resilience practice hasn't yet presented methods to account for temporal scale resilience trade-offs [6]. Model-based decision support tools like Dynamic Adaptive Policy Pathways (DAPP), have proven useful for setting long-term policies and short-term actions. But they do not capture the spatial complexity required to inform masterplans [56]. Methods such as the *Urban layers approach* [81] are enabling the classification of urban systems based on their lifecycles and properties. However, these are at an early stage and PSS can make a valuable contribution in mainstreaming these spatial and temporal aspects into planning. Based on the above review, PSS applications for long-term resilience must potentially fulfill three key requirements (Fig Figure 2.1):

1. Manage complexity [79]: PSS must support planners to identify multiple variables from climate, socio-economics, environment, etc. that are constantly changing - and select them in a manner that is feasible for implementation.
2. Support selection of planning responses: PSS can assist planners in selecting combinations of planning responses across multiple sectors to scale up resilience goals.
3. Bring in flexibility: Long-term planning calls for a deeper understanding of the temporal aspect of the planning. PSS can help systematically understand planning timeframes as well as lifecycles of components within a plan to work on long-term climate goals within relatively short-term masterplans [92].

2.3 Methodology

The study aims to suggest improvements for PSS to become useful for long-term urban planning for resilience. The methodology comprises two main components: (1) Derive an understanding of emerging themes and trends in the literature on urban planning and climate resilience by conducting a systematic text mining analysis of academic and non-academic (practice) documents (Figure 2.4); (2) Draw comparisons between the two areas to establish research priorities and conceptual gaps in the implementation of resilience goals. Understanding variations is interesting because we can find areas of synergy and dissonance and how those can be addressed to push boundaries in research and practice. It allows us to reflect on how PSS can play a bigger role in bridging process and knowledge gaps on urban climate resilience.

The PSS domain encompasses a large number of urban components, sectors, and planning approaches. Understanding its knowledge landscape requires a common language to assess these components and identify links between them. In order to do this, we rely on a widely accepted framework used by planners known as the DPSIR framework which stands for *('Drivers-Pressures-State-Impact-Response').* The DPSIR is a constantly evolving framework that is used to represent the origin and consequences of environmental problems using nodes and causal links [139]. It has been useful in conveying simplified information to a broad range of stakeholders and has been applied for the assessment of coastal areas, biodiversity, etc., by the European Environment Agency (EEA), Organisation for Economic Co-operation and Development (OECD), and Dutch National Institute for Public Health and the Environment (RIVM) [140].

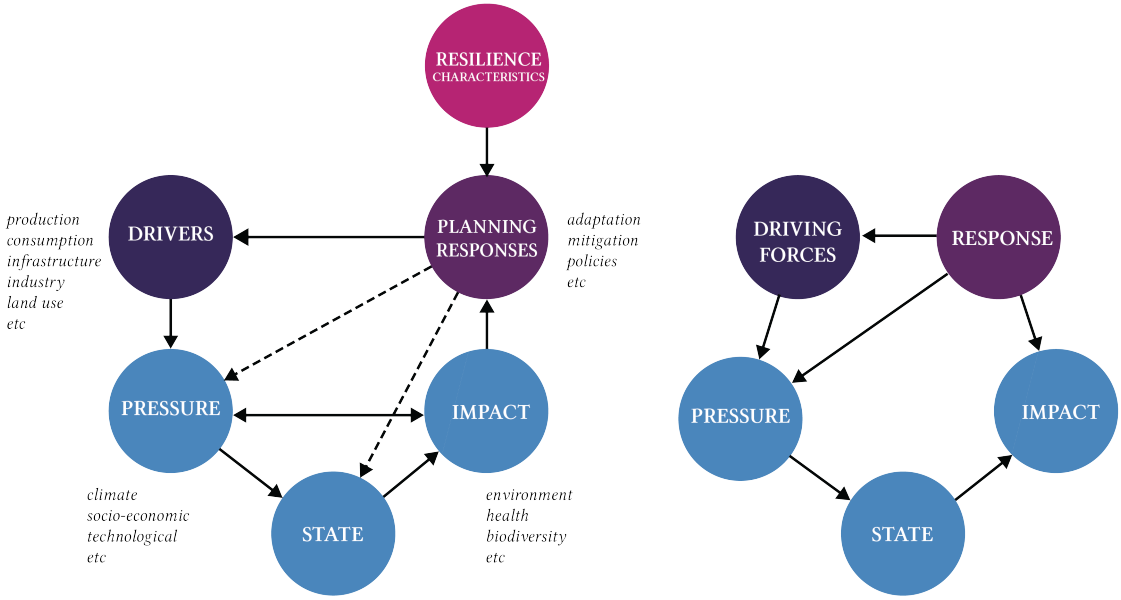

Figure 2.2: Deriving a common language to analyze academic and practice literature using the DPSIR Framework (right). DPSIR helps in categorizing results of text-mining analysis into knowledge categories (streams) representing urban systems, external pressures and causal links between them [141]

DPSIR has evolved from three main information categories: *Driving Forces* (economic and infrastructure sectors, human activities), *Impacts* (On ecosystems, human health and functions) and *Responses* (plans, prioritization, target setting, indicators) which are adapted based on the area of the study. Two additional categories added later are *Pressures* and *State* that are closely related to *Impacts*. For instance, urbanization leads to deforestation leads to air pollution and health Impacts. The cause and consequence can be multiple or be interrelated to each other. For this study, we combine these three under one stream. Studies on DPSIR present indicative lists of terms that can be included under each category [141]. We acknowledge the complexity of the real world and that it cannot be classified into simple categories. However, for the purposes of this study, we set out the following knowledge streams for analysis (Figure 2.2):

1. **Stream 1: Pressures, State and Impacts** (climate triggers, environmental impacts, air quality).
2. **Stream 2: Driving forces** (production, consumption, infrastructure).
3. **Stream 3: Planning Responses and Approaches** (actions, policies, tools).
4. **Stream 4: Resilience characteristics** (self-organization, diversity, flexibility, redundancy). We introduce a fourth stream to explicitly focus on resilience terminology in literature. This is related to Stream 3 but has been analyzed separately [38, 142, 143].

Data Collection

This section describes methods of data collection adopted for academic and non-academic literature.

Table 2.1: The search string used to build the academic corpus on Scopus [144]. In addition, some simpler groups of words were used including: *"urban resilience", "urban plan(ning)*" AND climate, [(climate OR resilience) W/15 "urban informatics"], [(climate OR resilience) AND "planning support system"].*

X	**urban**	**plan**	**climate**
Concepts: combine with AND	*urban* OR city OR cities OR spatial*	*strateg* OR vision OR framework OR "land use" OR method* OR scenario* OR variable* OR adapt* OR tools OR models*	*climate OR risk* OR hazard* OR resilien* OR uncertain* OR "climate change" OR future OR long-term OR vulnerab* OR "climate adapt*"*

Academic Literature: We developed a search strategy using the following three groups of words: (a) urban planning, (b) climate, and (c) frameworks, and support systems. For each group, we enlisted an exhaustive set of synonyms, and similar terms and combined them into a final 'search string' (Table 2.1) which we ran on the online database Scopus [144]. The resulting corpus included publications ranging from urban planning strategies, and support systems for climate adaptation to climate frameworks covering risks and uncertainties published between 1900-and 2021. We filtered these to include four publishing avenues: peer-reviewed journals, conference proceedings, book chapters, and reviews. We excluded unrelated domains such as infectious diseases, manufacturing, nanoscience, archaeology, and computational biology. This amounted to a corpus of 37,745 publications (Figure 2.3).

Non-academic literature: The urgency among cities to plan for climate change has led to a steadily increasing number of publications by governments, businesses, multilateral development banks, United Nations agencies, etc., on building resilience in general and in specific regions and sectors. These are in the form of guidelines, action plans, strategies, and frameworks which are closely connected to how PSS can be utilized. For a comprehensive overview, it was essential to include this grey literature in our analysis as it constitutes a rich and complex source of information. However, there is no rigorous search method for grey literature or a comprehensive database for publications on urban resilience. Moreover, there is no mandated structure or format for such documents, hence the level of detail shows a vast variation. To make our search manageable but intuitive, we adapted the search method developed by [145]. Our search plan consisted of a combination of terms similar to that used for academic literature. However, these had to be adapted into multiple shorter combinations of words as databases often had different filters and nomenclature for documents. For instance, we used *policy brief urban resilience, urban climate framework, resilience knowledge network, urban climate adaptation* and *center for resilience.* In order to minimize the risk of omitting important documents, we incorporated three strategies:

1. **Databases**: We searched prominent databases that publish in the domain of urban resilience and climate adaptation. This included the Open Knowledge Repository of World Bank Group [146], Rockefeller Foundation [147], Asian Development Bank Institute [148], Urban Resilience Hub - UN Habitat [149], Climate Adaptation Knowledge Portal [150], PreventionWeb - UNDRR [151], EU Science Hub [152], 4TU Resilience Engineering [153], IIHS Knowledge Gateway [154], etc.
2. **Targeted websites**: We made a list of resources and agencies that publish practitioner-focused documents and guidelines for the implementation of urban resilience. This is a hand-searching method based on the existing knowledge of the authors and recommendations from colleagues in the domain. Websites included those of ICLEI – Local Governments for Sustainability [155], Asian

Cities Climate Change Resilience Network [156], Global Center On Adaptation [157], The Energy and Resource Institute [158], World Resources Institute [159], etc.

3. **Customized Google search**: We searched for documents on the Google search engine using multiple combinations of search terms. As this is a very vast resource, we decided after initial search runs to only review the first 30 to 40 links per search term to keep our work feasible and ensure consistency. Here, we relied on the relevancy ranking of Google and screened the title and short text underneath to decide if it is relevant for further review.

As an emerging research area, a vast body of literature needed to be screened. In addition to the thematic focus, we set inclusion and exclusion criteria to make the analysis feasible (Table 2.2). The final corpus had 86 documents covering 6 continents including 31 global/general documents, 41 location-specific documents, 11 sector-specific documents, and 3 special projects. A comprehensive list of resources and search terms may be accessed on this link:
`https://github.com/supadupa09/cupum2021_KAC` (Figure 2.3).

Table 2.2: Inclusion and exclusion criteria used for selecting the corpus of non-academic (practice) documents for analysis, adapted from [145].

Inclusion criteria	Exclusion criteria
▸ English. ▸ Open Access. ▸ Action-oriented document written by governments including policy briefs, planning. guidelines, action plans, frameworks, etc. ▸ Documents written with an urban focus targeting practitioners. ▸ Overall resilience and climate adaptation planning at a city, regional, country scale.	▸ Books, Webpages ▸ Documents focusing on specific aspects such as financing, governance, community resilience, social protection etc. ▸ Broad conceptual frameworks or very short flyer-style documents. ▸ Specific case study or summary of case studies. ▸ Focus on a single type of risk like heat, flood, etc.

Analysis

The earliest academic publication extracted was for 1956, but the volume of publications rose significantly from 1990 which we consider as the starting point for the analysis. Our tool to analyze the corpora was LiTCoF (Literature Topic Co-occurrence and Frequency), a collection of open-source Python libraries used for text mining analysis of large and unstructured bodies of text [160]. We chose LiTCoF for the following abilities:

1. **Topic Modelling (TM)**: To retrieve main topics that emerge from literature.
2. **Term Frequency (TF)**: To extract frequently occurring terms.
3. **Term Evolution (TE)**: Analyze the evolution of selected terms over several years. Here, **Relative Frequency (RF)** is used to quantify the importance of a term in the corpus. LiTCoF adjusts the frequency of occurrence based on the length of the document.

LiTCoF requires data on *Titles, Abstracts, and Year of Publication* in a *.csv* format for analysis. Due to the non-standard format of non-academic literature, we extracted the detailed executive summary/ introduction instead of *Abstracts*. LiTCoF provides inbuilt packages to reformat, process the data, and define a list of overused or unrelated words we can exclude from the analysis. This required running LiTCoF

on the corpus iteratively to calibrate the dataset for final analysis. Details on the pre-processing along with full datasets may be accessed at https://github.com/supadupa09/cupum2021_KAC.

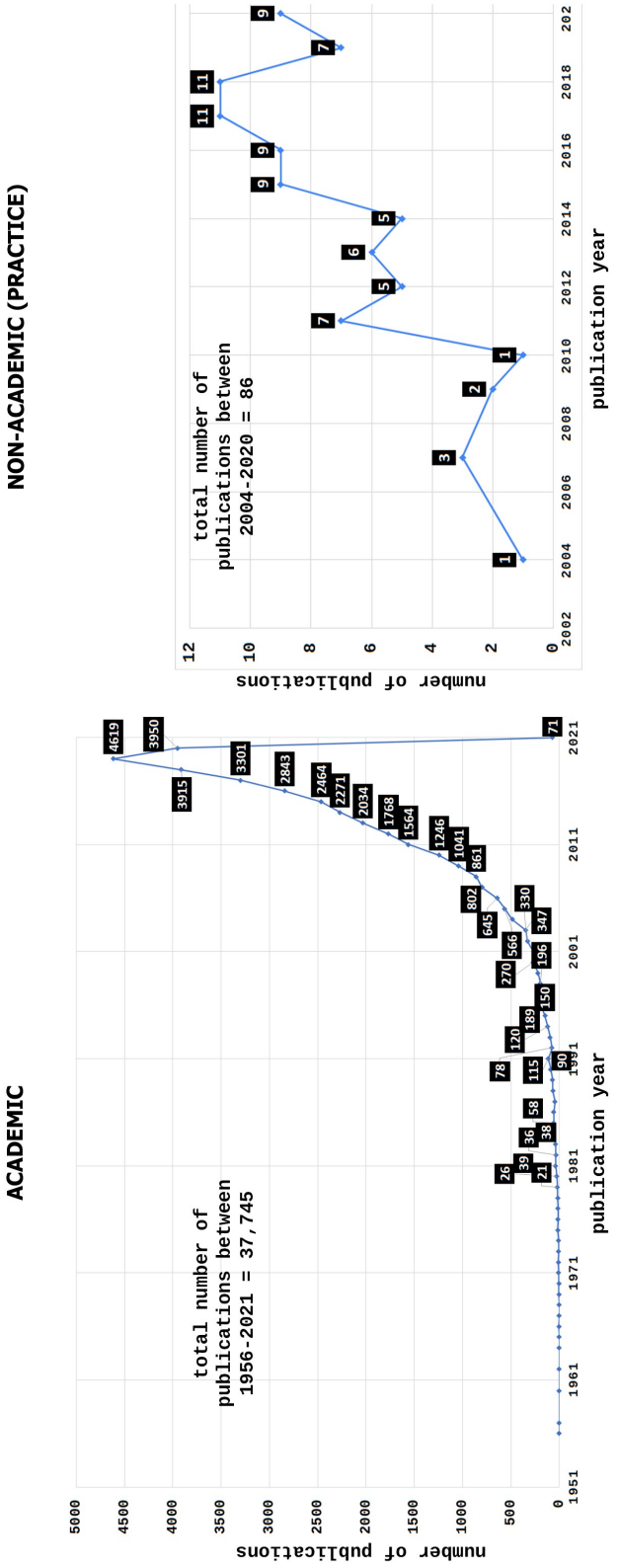

Figure 2.3: Total number of academic (1990-2021, n= 37,745) and non-academic (2004-2020, n= 86) publications extracted.

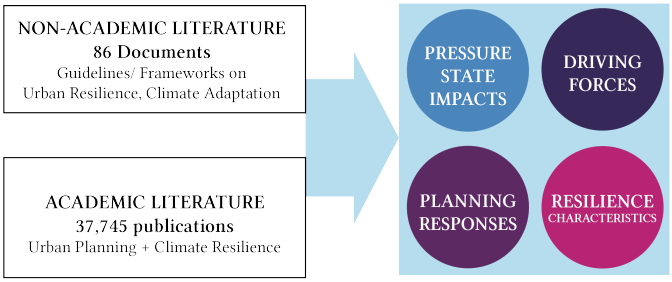

Figure 2.4: The total corpus of academic and non-academic (practice) literature along with the four knowledge streams used for the analysis identified in Figure 2.2

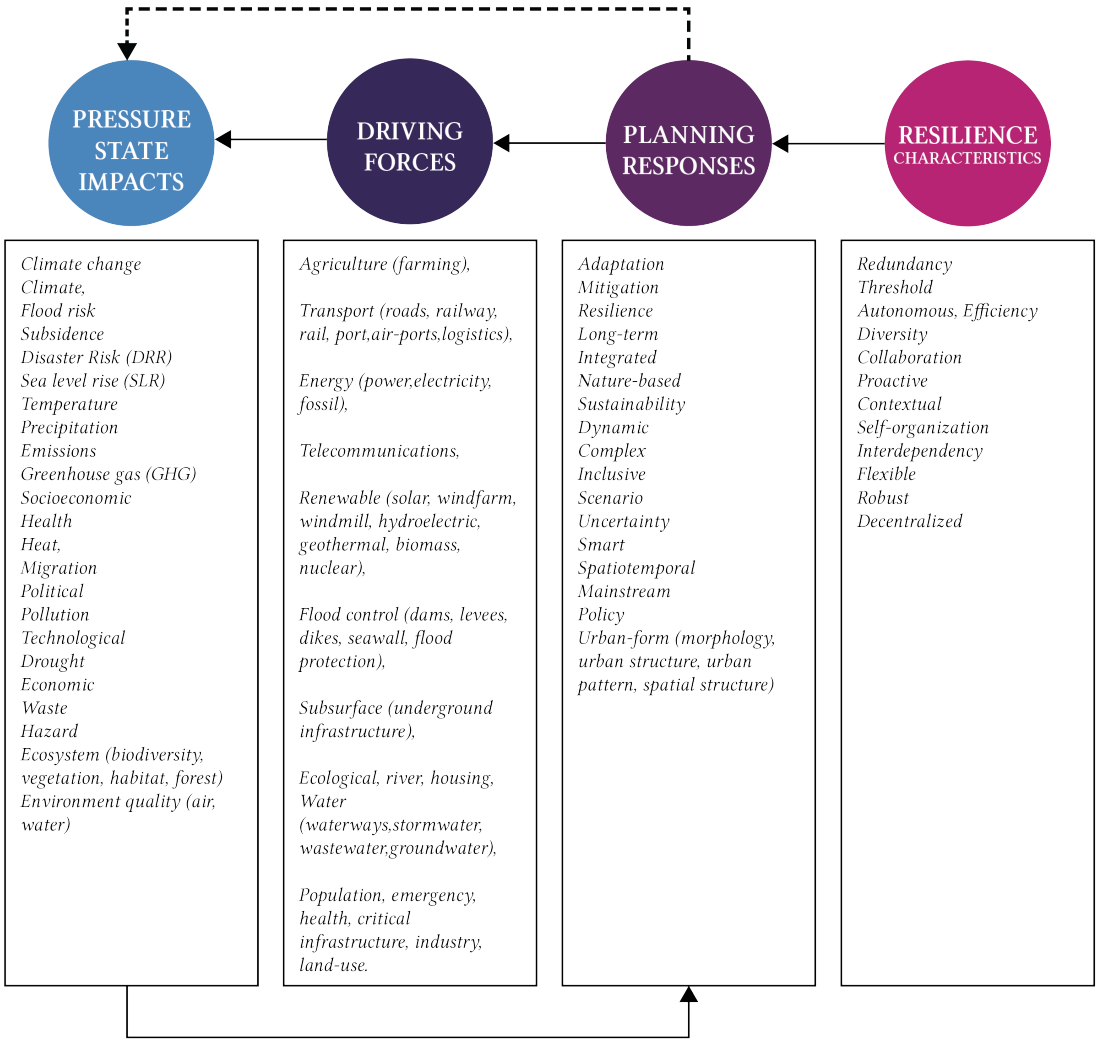

Figure 2.5: Terms enlisted under the four knowledge streams derived from the DPSIR framework (Figure 2.2). We will use LiTCoF to analyse the evolution of these terms between the years 1990-2021. These terms are shortlisted based on results of *Term Frequency (TF), Topic Modeling (TM)* as well as literature on DPSIR framework and urban resilience)

2.4 Results

Topic Modelling (TM)

We used Topic Modelling (TM) to extract 50 and 40 topics from academic and non-academic literature respectively. The number of topics selected was based on a low perplexity score (a measurement of good model performance in LiTCoF) (Figure 2.3). TM is a useful indicator of themes and trends that represent the corpus. For instance, academia sees a dominance of *vulnerability, flood risk, precipitation, uncertainty, models, land-use, regional (scale), and sustainability.* Non-academic corpus sees terms on *adaptation, disaster-risk, community, local government, stakeholders, health, environment, and transport.*

Term Frequency (TF)

In both corpora, the top 100 most frequently occurring terms include the following (Figure 2.5):

- **Stream 1: Climate (and related) Pressures, State and Impacts:** *Flood risk, climate change, temperature, precipitation, health, pollution, emission, traffic, damage.*
- **Stream 2: Driving Forces:** *Agriculture, transport, energy, water, health, ecological.*
- **Stream 3: Planning Responses and Approaches:** *Adaptation, resilience, policy, integrated, sustainability, long-term.*
- Miscellaneous: *Evaluation, indicators, parameters, assessment, simulations, performance, stakeholders, decisions, coordination.* There are not many terms on **Resilience characteristics**.

Figure 2.7, Figure 2.8 and Figure 2.9 illustrate comparative trends of terms in academic and non-academic literature. In **Stream 1**, both corpora place an emphasis on *climate, climate change, flood risks, population and vulnerabilities* but practice places emphasis on *disaster risk, sea level rise and heat stress.* In **Stream 2**, both corpora include terms on major infrastructure systems and economic drivers. However, 'practice' illustrates more nuanced systems like *food, green infrastructure, river and waste management.* **Stream 3** indicates a separation of trends where practice places a high emphasis on *local action, community engagement, strategies and adaptation* and academia emphasises broader concepts such as *uncertainty, sustainability, spatial development, models, and the future.*

Term Evolution (TE)

Term Evolution (TE) is an indicator of changing priorities in research and practice and may help deduce new directions for study. We examine the Relative Frequency (RF) of terms over the period of analysis for the four knowledge streams identified in Section 2.2. We enlist terms under each stream based on results from Topic Modelling (TM) (Section 2.4) and Term Frequency (TE) (Section 2.4), as well as literature on DPSIR framework and urban resilience. The results are discussed below:

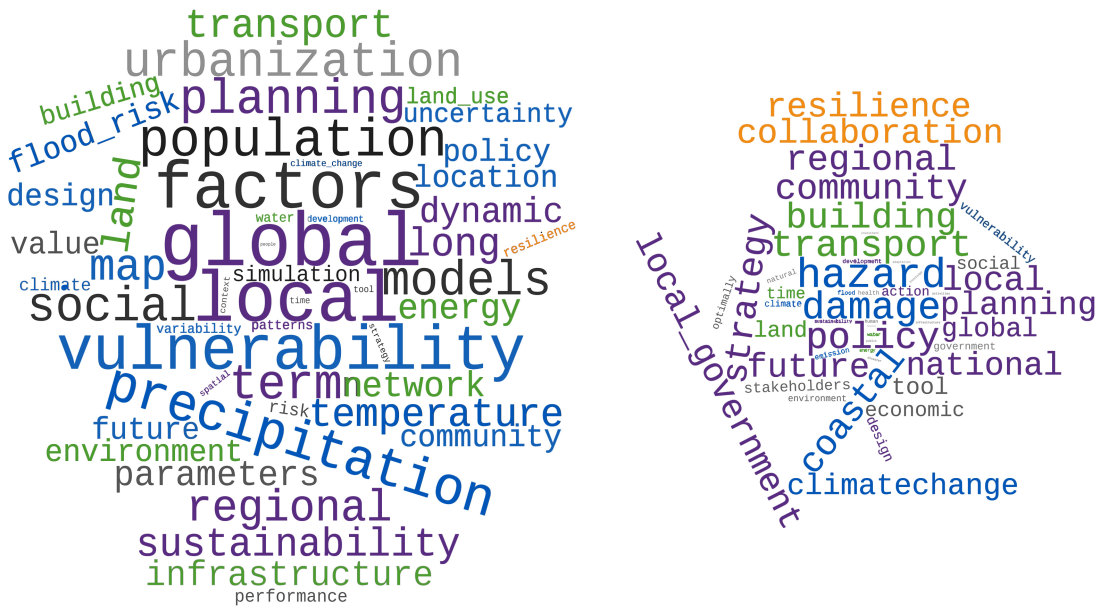

Figure 2.6: Wordclouds depicting results of Topic Modelling (TM); highlighting emerging terms in academic (left) and non-academic corpora

Stream 1: Climate (and related) Pressures, States and Impacts (Figure 2.10)

Academic literature: Occurrences of *climate and climate change* have risen steadily over 31 years. 1991 and 1999 saw a surge of publications with keywords on urban climate, housing, climate variability, water resources, etc. *Flood risk* has emerged as a consistently strong theme in literature which may be a direct outcome of the number of cities that are suffering losses from flooding [161]. *Temperature and precipitation* see a moderate RF, whereas *heat and drought* which are emerging as high-impact risks have a low RF. This is backed by literature that cites a lack of sufficient studies and comparable data on heat [162]. *Health and population* occur consistently, so do *migration and politics.* Environmental variables such as *pollution and emissions (carbon, greenhouse gas)* find significant mentions. *Technological* disruptions due to electric vehicles, autonomous driving, smart highways, etc., seem to be rising but not significantly.

Non-academic literature: Climate variables are dominated by hydro- meteorological stresses from *precipitation, sea-level rise, storm surges, inland/-coastal flooding and subsidence. Heat stress* is discussed but continues to be underrepresented. California is one of the few regions that presents a dedicated strategy for heatwaves [163]. Geophysical risks from *landslides and volcanoes* find mentions. There is a relatively higher representation of *socioeconomic* aspects of development including *health (stress, disease,*

mortality), population, politics, and *environmental aspects* (*emissions, waste and pollution*). As implementation-oriented documents, climate variables are represented using extreme scenarios like 'identification of 15 worst events that should never happen' [164] or as a set of guiding national scenarios [165].

Stream 2: Driving Forces (Figure 2.11)

Academic literature: *Water* emerges as the strongest sector with a steep increase after 2010 concerning publications on water supply, rainwater harvesting, stormwater, wastewater, watershed management, etc. *Energy and ecological systems* see a steady upward swing. The year 1998 saw a jump in *energy* with one of the first papers on decisions in energy planning [166] followed by highly cited publications on consumption, water-energy-food nexus, energy transition, global energy management and, energy-climate policy. However, RF of *transport and agriculture* are seeing a downward trend. The unusually low RF for *transport* could be attributed to a dedicated transport domain that conducts research independent of urban planning. *Renewable* (energy), *flood control* infrastructure and *blue green infrastructure* see a low RF, possibly because they see intensive research in specific regions of the world. *Subsurface* infrastructure, which plays a critical role in determining infrastructure layouts, renewal, sustainability measures and even energy transition has a very low RF.

Non-academic literature: Like academia, 'practice' continues to see a high RF for *water* and *transport* sectors. In line with planning practice's tendency to formulate 'response-based measures', we see high occurrences of *emergency preparedness, disaster risk management and community engagement. Housing* is mentioned in publications with a focus on affordable, low-income, and sustainable housing. *Agriculture, housing and telecommunications* also find mentions in several documents. Contrary to academia, *energy* has a medium RF which could be attributed to independent initiatives in this sector that aren't integrated in planning documents. *Land use* regulations which play a key role in scaling up resilience and adaptation measures have a low RF [113, 167, 168].

Stream 3: Planning Responses and Approaches (Figure 2.12)

This stream investigates scientific concepts and practical processes on planning for climate. Non-academic literature served as a starting point to shortlist terms being used by cities [12, 102].

Academic literature: Occurrences of *sustainability* and *resilience* have risen gradually from 1990 and sharply after 2010. 2013 was the year the Rockefeller Foundation institutionalized the 100 Resilient Cities Framework which may explain a high interest in the urban resilience domain since then [147]. *Adaptation* has a rising RF as compared to *mitigation* which could be explained by increased scientific and practical interest by cities on climate adaptation. *Mitigation* is mentioned concerning hazards, disaster risks, greenhouse gas emissions, public transport, etc. The small corpus of 71 documents for the year 2021 already sees 31 and 20

publications with keywords on sustainability and resilience respectively including research on shifting from sustainability to resilience, critical infrastructure and water stress.

Concepts such as *complex, integrated, dynamic, long-term* see a varying but consistently medium RF whereas *smart* sees a rise around 2016. *Circular economy, scenarios and nature-based solutions*, which are recurrent in non-academic documents finds low mentions in academia. *Spatio-temporal* did not make it to the list due to its low RF, though we see selected publications on air pollution, heat islands, temperature and environmental modelling. However, the study of spatio-temporal dynamics for urban resilience sees limited work.

Non-academic literature: There is a strong trend towards *resilience and adaptation* but a rather low RF for *uncertainty* and dealing with changing constraints. *Long-term* planning is recognized through *long-term adaptation and resilience* actions. Low to medium RF is observed for *integrated, sustainable, inclusive* development and for the term *smart*, which is used in the context of smart spatial combinations in planning [169] and climate-smart agriculture [165, 170]. Spatial and temporal aspects are insufficiently addressed with most documents providing policies and checklists with no concrete timelines. Exceptions to this are the *Bangladesh Delta Plan* [171], *Netherlands Adaptation Strategy* [165] and *Thames 2100* [172] that set out detailed scenarios and short-term, medium-term and long-term phasing plans.

Stream 4: Resilience Characteristics (Figure 2.13)

We introduced this additional stream of knowledge to observe how resilience characteristics are represented in the literature on urban planning.

Academic literature: Of the 36,405 abstracts, 922 documents are indexed by keyword *resilience*, and, only 174 mentions *urban resilience*, with the first mention in 2005. With regards to resilience properties, *robust and efficiency* see the strongest presence. *Robustness* was initially used for control systems in the 1990s, followed by modeling economic effects in the 2000s, and finally sectoral applications in water, climate assessment, and information technology starting in 2003. Application of robustness principles in urban growth was first seen in 2010 [173] followed by long-range transportation plans, road network robustness [174], flood risk analysis, and spatial climate scenarios [175]. *Efficiency* is predominantly used for energy with limited mentions for water use, economics, and transport.

Terms showing dispersed mentions are *diversity*, in relation to biodiversity, culture, and more recently spatial and functional diversity. *Flexible* is used for transport [176], architecture, long-term decisions, adaptive management and infrastructure [177] with emphasis on water [178]. Recently, flexibility has been investigated in planning through *flexible city* [179] and flexible planning processes for climate [180]. *Interdependency* became an area of investigation starting 2013 with rising awareness of cascading effect in disasters including infrastructure interdependencies during earthquakes, floods and risk assessments of critical infrastructure [181, 182].

Non-academic literature: 20 out of 30 documents specify a definition of resilience with the most popular being the definition presented by Arup and Rockefeller Foundation [147]. World Bank's *CityStrength Diagnostic framework* sets out qualities of resilient systems [183] whereas the resilience of spatial development is explained in *Netherlands Climate Adaptation Strategy*. *ASEAN Guidebook* provides a resilience checklist [165, 167]. A high RF is observed for *collaborations, diversity and efficiency*. A medium to high RF is seen for *flexibility* (plans, processes, water use, management), *redundancy* and *interdependency* (infrastructure, cascading failures). *Robust* is used for applications including spatial structures, energy, telecommunication, flood protection and land use.

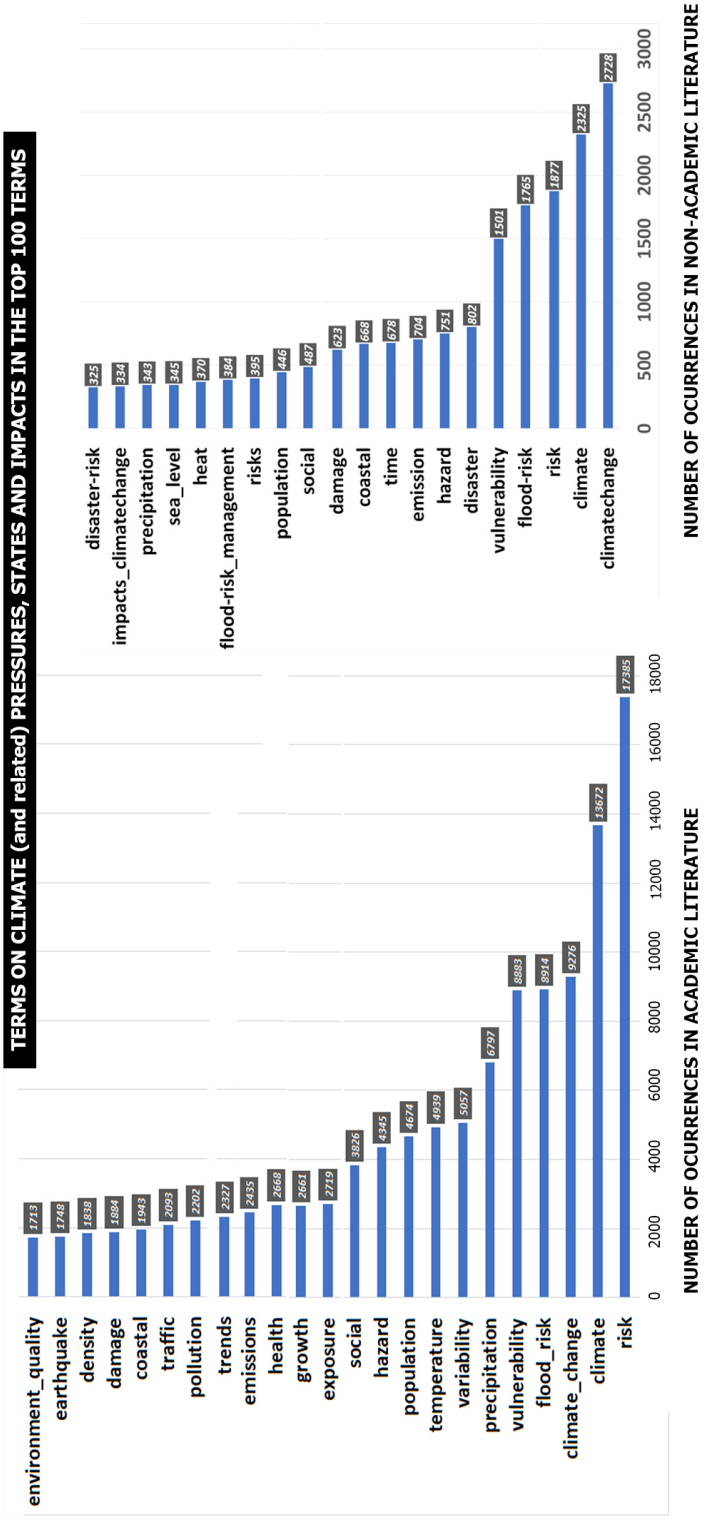

Figure 2.7: The most frequently occurring terms related to **Climate Pressures, State and Impacts** in academic (bottom) and non-academic literature (extracted from the top 100 terms).

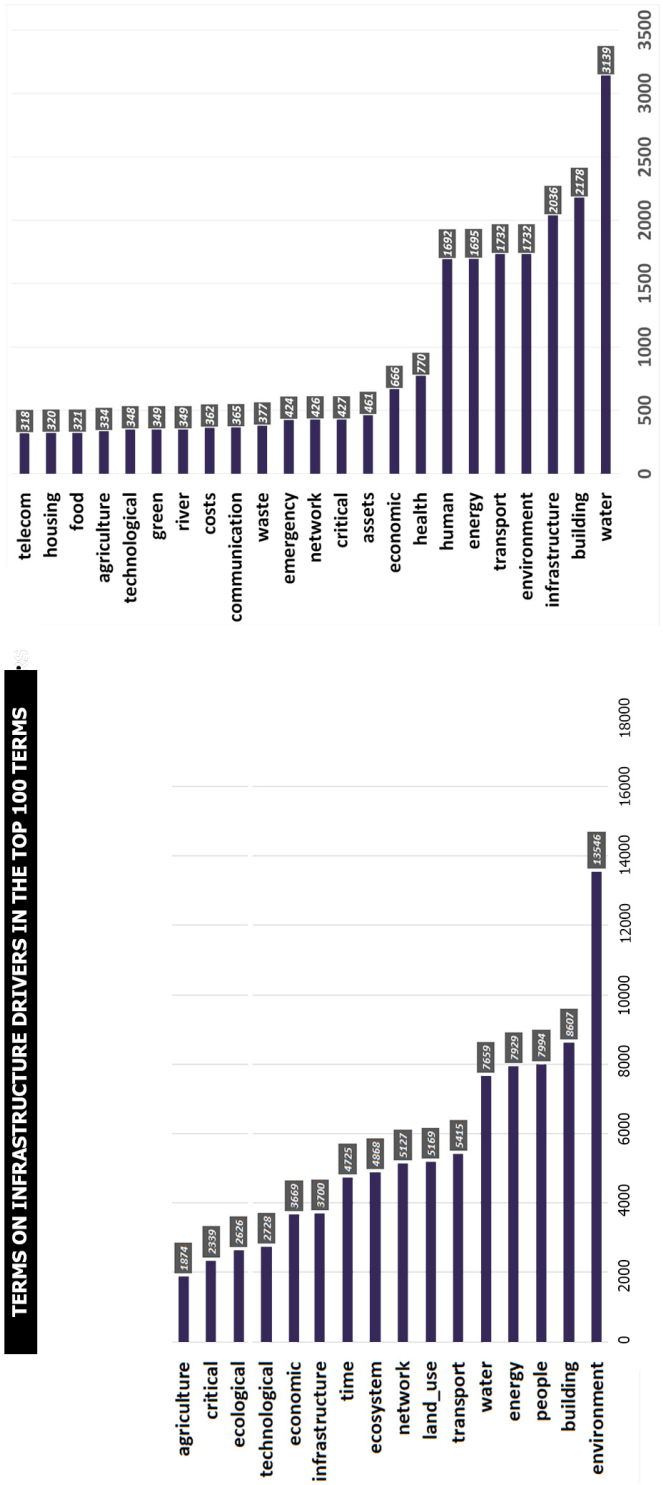

Figure 2.8: The most frequently occurring terms on **Infrastructure Drivers** in academic (bottom) and non-academic literature (extracted from the top 100 terms)

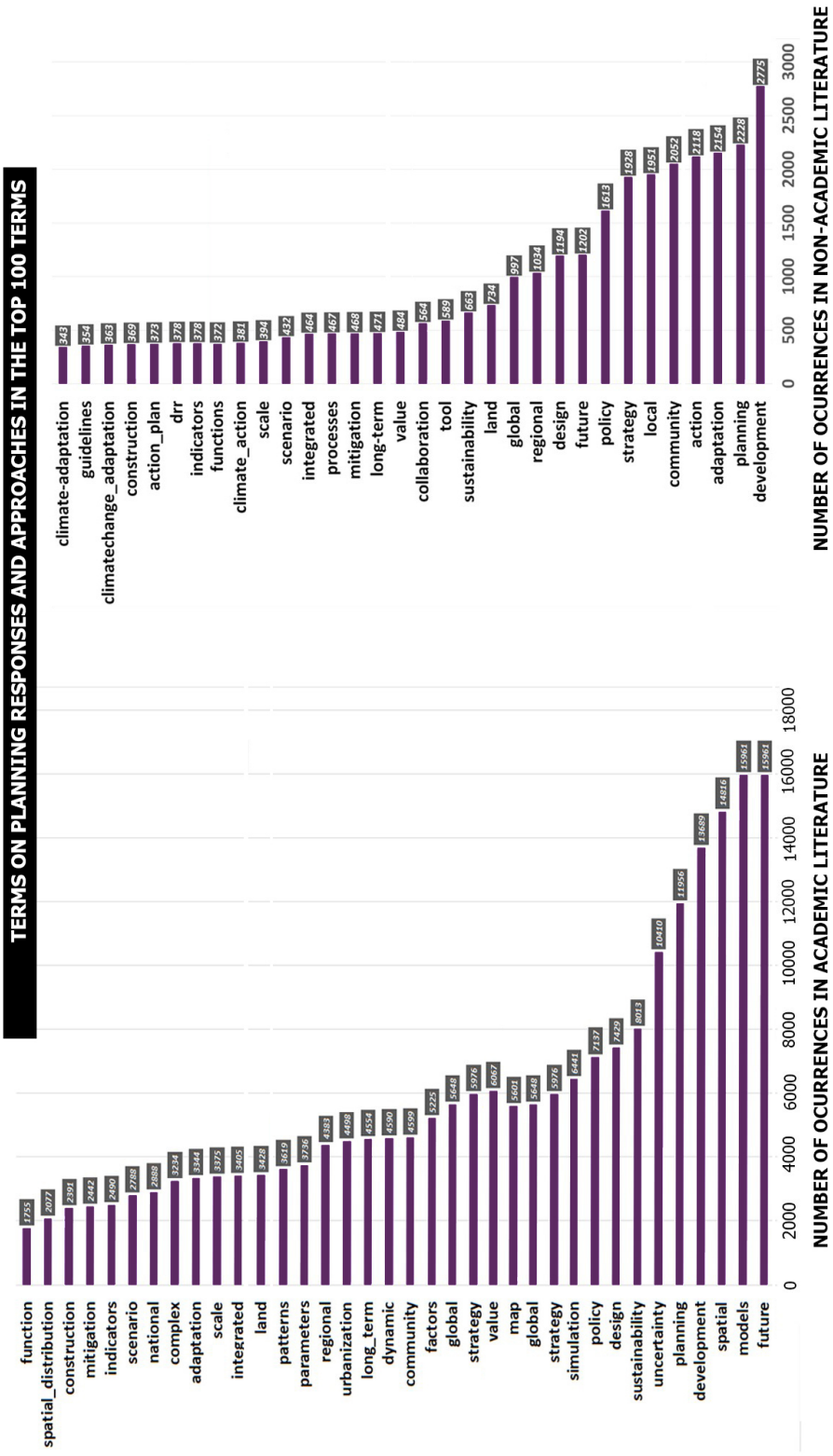

Figure 2.9: The most frequently occurring terms on **Planning Responses and Approaches** in academic (bottom) and non-academic literature (extracted from the top 100 terms)

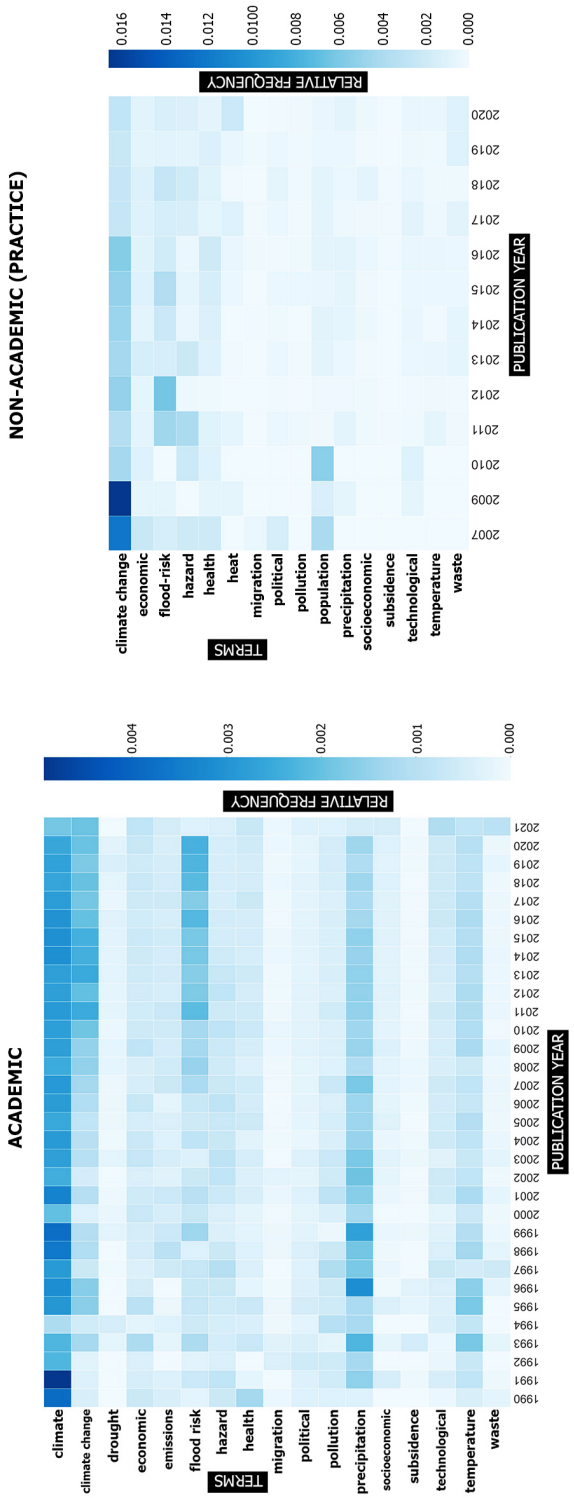

Figure 2.10: Stream 1: Evolution of Terms (TE) related to **Climate Pressures, State and Impacts** between 1990-2021 (academic, bottom) and 2007-2020 (non-academic).

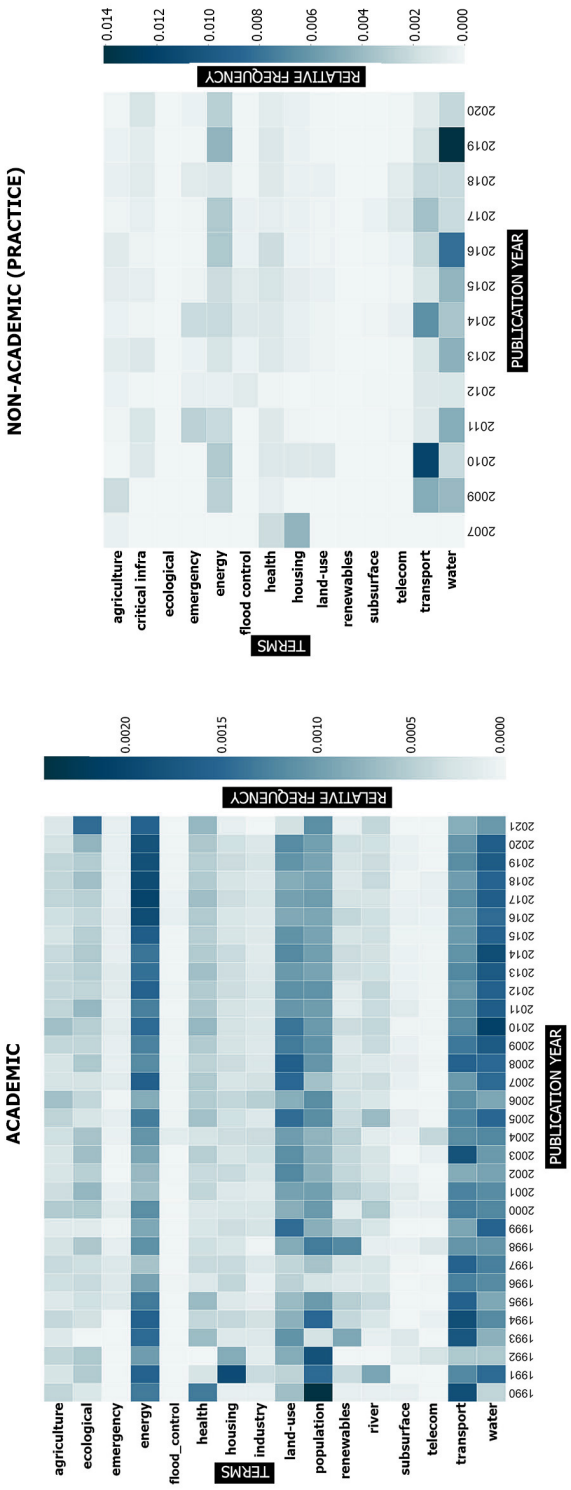

Figure 2.11: Stream 2: Evolution of Terms (TE) related to **Driving Forces** between 1990-2021 (academic, bottom) and 2007-2020 (non-academic).

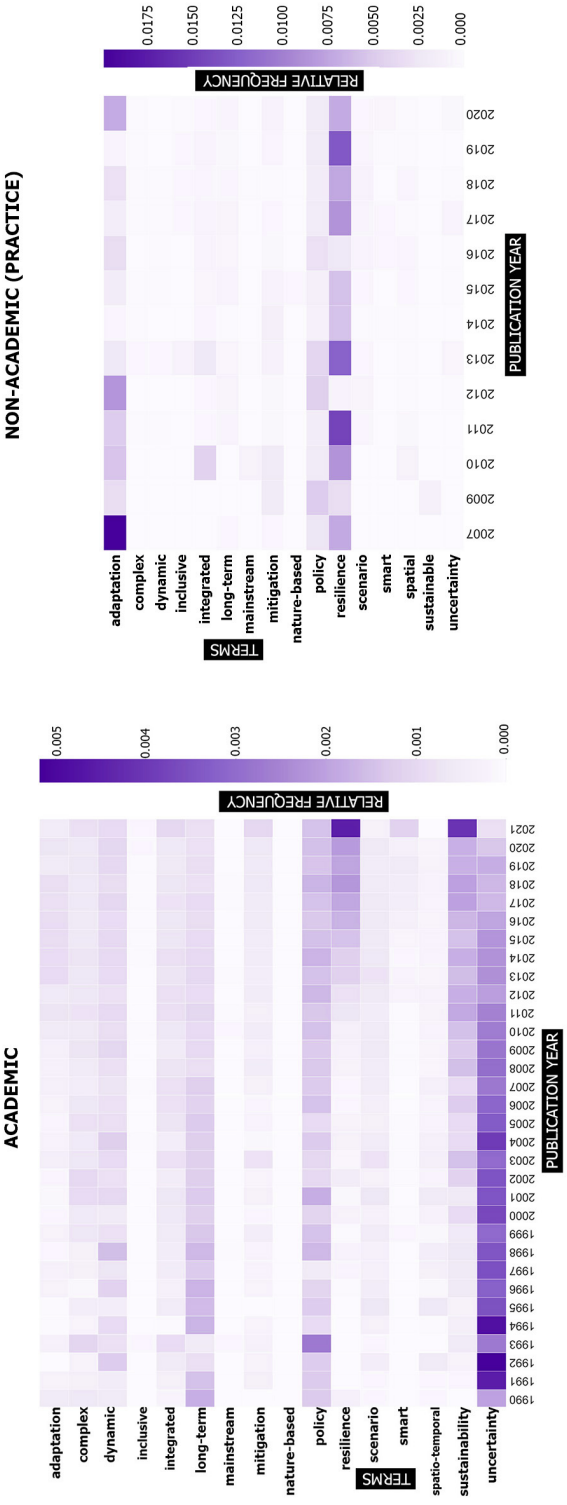

Figure 2.12: Stream 3: Evolution of Terms (TE) related to **Planning Responses and Approaches** between 1990-2021 (academic, bottom) and 2004-2020 (non-academic).

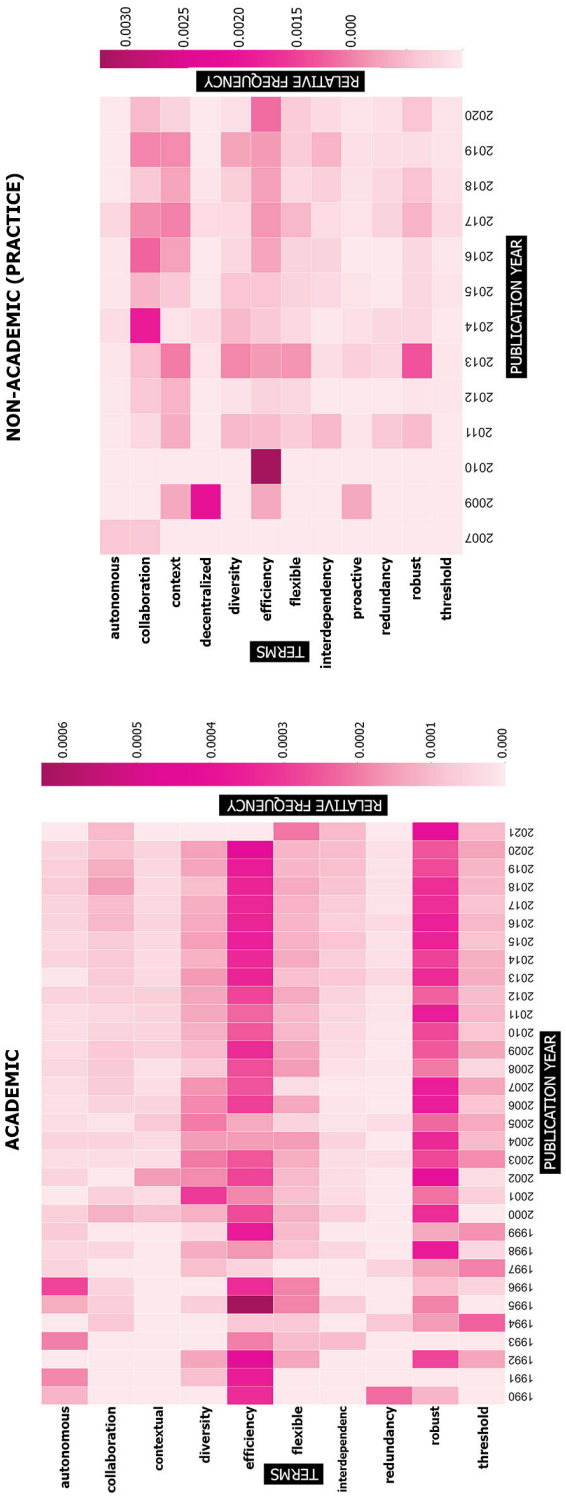

Figure 2.13: Stream 4: Evolution of Terms (TE) related to **Resilience Characteristics** between 1990-2021 (academic, bottom) and 2004-2020 (non-academic).

2.5 Conclusions and Discussions

In this study, we set out to develop a research agenda to improve PSS for long-term climate resilience. We presented an overview of applications of PSS in the climate adaptation and resilience space where we identified three important issues that hinder long-term resilience thinking including (a) Emphasis on a few fixed planning scenarios; (b) Focus on individual sectors, and; (c) Less consideration of spatial and temporal aspects in planning. Based on these, we suggested three potential areas of improvement for PSS (Figure 2.1). We also observe that cities make urban plans for timeframes of 5-20 years which has proven insufficient to account for long-term climate projections as most investments made in that period will last much longer and suffer intense impacts from climate. With advances in long-term climate projections, mapping, monitoring, the fast pace of technology - plans that are made for 20 years are fast becoming outdated even before they are published. There is a clear dichotomy between how practitioners and researchers perceive 'short-term' and 'long-term' timeframes for planning. Recalibrating what constitutes as 'long-term' can assist in better scoping resilience objectives, which can improve understanding of temporal aspects of planning.

In order to further investigate the knowledge landscape of urban planning and climate resilience, we conducted a text-mining analysis of 36,405 academic and 86 non-academic publications in this domain (Section 2.3). We analyzed and classified the results along four knowledge streams: **S1:** Pressures, State and Impacts; **S2:** Driving forces; **S3:** Planning Responses; and **S4:** Resilience Characteristics. In the following sections, we will discuss two aspects: (1) the findings derived from text-mining analysis; and (2) the procedural challenges in conducting this study.

Findings derived from text-mining analysis

The results of the text-mining analysis reinforce two of the three issues with PSS that we identified including the heavy focus specific sectors and the low consideration of spatial and temporal dimensions (Figure 2.1). The drivers of climate risks are covered well in both academia and practice, especially *flood risks* and *environmental aspects*. Almost all non-academic documents address climate risks though the level of detail varies from outlining all possible variations of risks to using 'risk' as an umbrella term. As compared to academia, 'practice' seems to place a higher emphasis on *socio-economic aspects, health & disease, migration, poverty, etc* (Figure 2.7).

The infrastructure sectors highlighted in the non-academic corpus are also a representation of sectors that attract heavy investments or those that stimulate bottom-up initiatives such as *water and energy* (Figure 2.8). The role of digital infrastructure, *telecommunications* and *critical infrastructure* that have visible widespread impacts are discussed, although *interdependencies* between infrastructure sectors are not addressed sufficiently. Though some work is available, a significant gap in both areas is the potential of subsurface (underground) infrastructure that can guide long-term resilient urban form [184, 185].

Spatial aspects find a place in the top five most recurrent terms in academia concerning land use and building regulations (Figure 2.9). But, non-academic guidelines continue to be written to inform theoretical policies,

not spatial actions. Though the benefits of long-term planning are recognized, terms on implications of policies in space or mainstreaming risks in planning do not find mentions. Non-academic literature places a heavy focus on climate adaptation and disaster risk while mitigation measures are limited to the reduction of greenhouse gas and carbon emissions. Resilience building requires combining both measures to capitalize on their co-benefits, which requires further investigation in academia. Non-academic documents do discuss spatial impacts for small-scale projects such as flood-prone urban spaces, rainwater harvesting on rooftops, etc. Academia can play a major role in developing methodologies to bring in a spatial perspective and guide the development of a PSS that enables scaling up measures. This can snowball into more research on spatial diversity especially to address flexibility and diversity of functions for planning resilience.

Procedural challenges in conducting this study

While the study set out to be a comparative analysis between academic and non-academic literature, a fair comparison was not possible due to the stark imbalance in the number of publications (Figure 2.2). Despite a focused search plan, the number of relevant non-academic (practitioner-focused) documents remained low. This points to the lack of comprehensive databases on urban planning and climate. Moreover, as many such documents are being written for the first time by governments and independent agencies, the format and nomenclature vary vastly. A document that is tasked with communicating implementation strategies for climate resilience can go by the names of *resilience frameworks, climate action plans, adaptation strategy* or take the names of the programs that fund them such as the *'citystrength framework'* [183] and *'making cities resilient'* [168]. While an 'urban masterplan' has an associated recall value and definition of what it is expected to contain, a 'resilience guideline' continues to be open to interpretation. This made the search and analysis challenging.

Future Directions

As discussed in Section 2.2, urban planners currently lack the incentive to think long-term [29]. A PSS can play a critical role in bringing in a concrete long-term perspective for climate resilience. The takeaways from the text mining analysis present specific insights on how to materialize the suggested improvements in a PSS (Figure 2.14). Firstly, a PSS should support planners in identifying and integrating constantly changing variables such that they can anticipate and prepare for emerging risks. Secondly, for long-term decision-making, a PSS should assist planners in selecting appropriate planning responses across multiple infrastructure sectors. A key sector that a PSS should target is the underground (subsurface) infrastructure that forms the literal backbone of city utilities and has a huge role to play in sustainable transitions. Thirdly, a PSS can play a role in improving understanding of infrastructure dependencies. Based on the context, it can help identify complementary urban systems, that can be clubbed together for decision-making and to reduce negative dependencies. Lastly, it becomes important to draw upon the resilience properties of urban systems such as functional diversity, flexible functions, emergence, etc., that can directly inform planning responses for the long term (See Box 2). These are related to the lifecycles of infrastructure

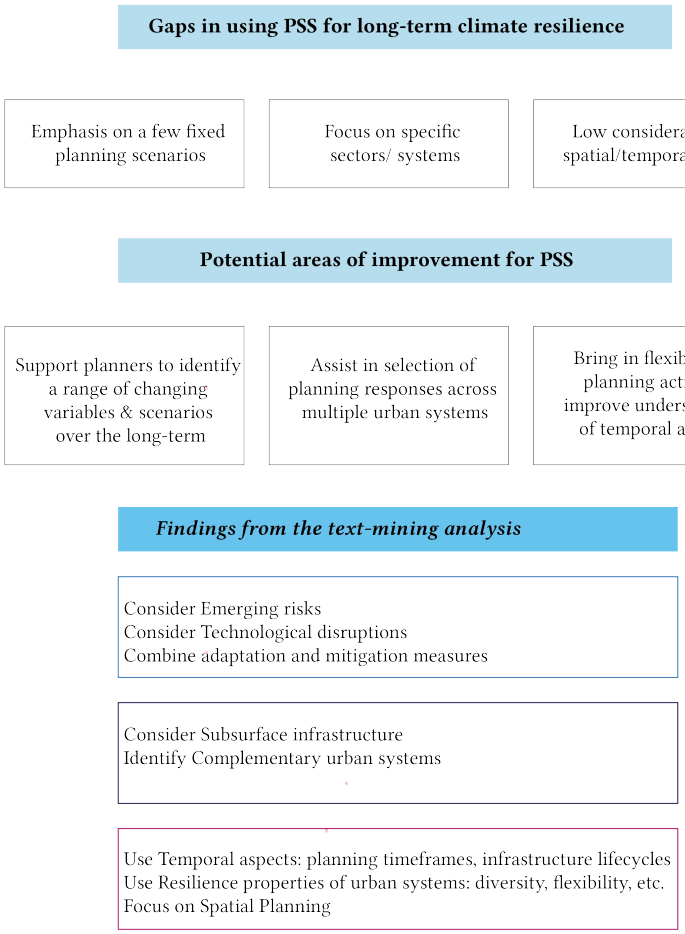

Figure 2.14: Conceptual framework indicating three potential areas for improving PSS applications for long-term climate resilience building upon Figure 2.1. It also indicates detailed findings from text mining analysis as direct inputs to each area (see Boxes 1 and 2).

systems and thus can improve our understanding of temporal dimensions of planning.

Through this study, we acknowledge that the analysis of terminology is not a direct indicator of the extent of inclusion or impacts in the domain. However, it allows us to scope the priorities of the domain and present a starting point to steer further research. In further work, LiTCoF should be used to analyze more detailed streams of knowledge and a larger corpus of non-academic literature. Finally, we should augment this desk analysis by interviewing planning practitioners to reflect on the processes and knowledge gaps in building long-term resilience. Our ultimate goal through this study is to push the boundaries of urban planning to move from a 'static' towards an 'uncertainty-oriented' approach for building resilience.

RISE-UP:
Resilience in urban planning for climate uncertainty

3

Published as:

Krishnan, S., Aydin, N.Y. and Comes, T., 2023. RISE-UP: Resilience in urban planning for climate uncertainty-empirical insights and theoretical reflections from case studies in Amsterdam and Mumbai. *Cities*, 141, p.104464.

Climate change is one of the main drivers of uncertainty in urban planning, but only a few papers systematically address these uncertainties, especially in the long term. Urban resilience theory presents principles to manage uncertainty but largely focuses on individual urban systems rather than complex interdependent dynamics. Further, most planning and resilience theory originates from the Global North and is unsuitable for capturing the dynamics of the Global South. This study uses an exploratory multi-case analysis towards developing an enhanced understanding of urban planning for climate uncertainty. We argue that long-term urban planning for climate uncertainty can benefit from systematically integrating resilience principles. We use a two-step qualitative research approach: (1) To propose a conceptual framework connecting urban resilience principles, approaches to urban planning under uncertainty, and planning responses in urban systems. (2) To use the conceptual framework to analyse climate-related planning responses in two contrasting case studies in the Global North (GN) and Global South (GS) (Amsterdam and Mumbai). We conclude with four propositions towards an enhanced understanding of urban planning for climate uncertainty by drawing upon the empirical insights from the two case studies.

Keywords: *Urban resilience, long-term urban planning, uncertainty, qualitative research, cities, case study*

3.1 Introduction

"The complexities and uncertainties associated with climate change pose by far the greatest challenges that planners have ever been asked to handle" [186].

In its recent chapter on 'Urban Areas,' the Intergovernmental Panel on Climate Change (IPCC) highlighted the importance of promoting the resilience of urban areas as a central policy consideration [187]. Especially for long-term urban planning, climate change brings significant uncertainty compounded by environmental, societal, and economic drivers. To manage uncertainties, urban resilience theory presents several principles to guide appropriate planning responses [9–12]. Despite integrating these principles, planning responses remain largely incremental and emphasize *"bouncing back"* [24, 188]. They focus on individual urban systems (buildings, open spaces, highways) for a single future scenario [20–22].

The need to navigate uncertainty has also led to the emergence of approaches such as decision-making under deep uncertainty [96], transition management [5], agile planning, storylines approach [97], and the *adaptive-modeling-managerial* perspective in infrastructure planning

[189]. While these approaches advocate planning for multiple futures, they do not see a wide application in urban planning because they usually work with probabilistic or fixed futures. This is unsuitable for urban systems with multiple spatiotemporal dynamics and path dependencies that must be accounted for in a planning timeframe [190].

Urban planning under climate uncertainty requires expanding existing planning approaches and theories to systematically modulate responses based on disruptions or new insights. While the literature on resilience and uncertainty individually offer principles and approaches to manage disruptions, they have drawbacks that impede their application in long-term urban planning. Combining the field of urban planning with theories on urban resilience and urban planning under uncertainty may, therefore, have great potential.

In this study, we take the first steps towards an enhanced understanding of urban planning for climate uncertainty. . The study is positioned in the early stages of urban planning, where strategic decisions are made in multiple urban systems. It adopts a rigorous methodology where a conceptual framework that ties together resilience and planning under uncertainty are systematically connected to planning responses. We use this framework as a basis for empirical research in using a combination of Multi-Case analysis [107] and Systematic Combining [108].

The paper is structured as follows: First, we examine academic literature to develop our conceptual framework connecting the literature on resilience and planning under uncertainty, and exploring how they can together determine planning responses (Section 3.2). Second, we use the conceptual framework (Figure 3.2) as the basis to analyze two case studies from the Global North (GN - Metropolitan Region of Amsterdam (MRA)) and Global South (GS - Mumbai Metropolitan Region (MMR)) (Section 3.3). The cases are selected to reflect the inherent variability in planning processes in the GN and GS and not to generalize findings for the GN and GS.

Using official planning documents and extensive semi-structured interviews, we assess to what extent the cases integrate resilience and address approaches for planning under uncertainty when proposing climate-related planning responses (Section 3.4).

Third, we formulate four propositions using our empirical findings to reflect on the current gaps in urban planning for climate uncertainty. Each proposition is substantiated using comparative insights from the two cases, such as narrative accounts and structural findings that characterize the planning process. We use the insights to make the first steps towards an enhanced understanding of urban planning for climate uncertainty (Section 3.5).

3.2 Background

In this section, we provide the theoretical background for our work. First, we analyze academic literature on urban resilience, focusing on planning frameworks that provide guiding knowledge for implementation (Section 3.2). Second, we discuss approaches for urban planning under uncertainty (Section 3.2). Although closely connected, there is no definitive theory connecting urban resilience and urban planning under uncertainty. The following section delves into both theories to highlight gaps and consolidate learning from the two streams into a conceptual framework for

urban planning for climate uncertainty that forms the basis for analyzing the case studies. Table 3.1 presents a list of terminology and definitions used in this study.

Table 3.1: Definitions of key terminology used in this study

Concept	Definition
Urban Resilience	*Urban resilience is the ability of an urban system to maintain or rapidly return to desired functions in the face of shocks or stresses [14].*
Urban Resilience Principles	*They are specific mechanisms and behaviors that make an urban system resilient, such as flexibility, multifunctionality, etc. [11].*
Planning Response	*In the context of resilience, Planning Responses refer to the full range of measures or initiatives undertaken to prepare, absorb, recover, and adapt to climate-related disruptions [48–50]. These may target single or multiple urban systems and include actions such as preserving ecological zones, improving engineering standards, or introducing new urban functions.*
Conceptual Framework	*A structure that highlights and links key concepts from literature and their application area [191]. In this study, we connect Urban Resilience Principles, Approaches to Urban Planning under Uncertainty, and Planning Responses.*

Urban Resilience Principles

Integrating resilience into urban planning requires planners to identify disturbances such as precipitation and heatwaves (*resilience to what?*) that a region may face and propose planning responses to ensure that urban systems (*resilience of what?*) remain in a functional state [192].

To identify urban resilience principles, we broadly assessed urban resilience frameworks in academic literature in the context of climate change. We conducted a systematic search in the online database Scopus using the terms:

> ((urban OR city) AND climat*(e) AND (resilience OR adaptation) AND framework)

We expanded the search string to include urban climate adaptation, sometimes used interchangeably with urban resilience. From the 1460 results, we screened the titles and abstracts to select 51 papers that explicitly discuss the implementation of resilience in urban planning. We then conducted a detailed consolidated review of 20 papers focusing on urban resilience 'planning frameworks.' These papers specify *Resilience Principles*, which provide guiding knowledge that planners can implement through design and planning responses. The final list of papers we analyzed and the resilience principles they mention are in (Appendix).

Figure 3.1 presents a selection of recurring *Resilience Principles* from the literature that is widely applied through certain Planning Responses in the urban environment .

They include *Adaptivity, Buffer, Connectivity, Diversity, Flexibility, Modularity, Multifunctionality, Multiscalarity, Redundancy, Robustness,* and *Self-organization* (Section C.2). While there is no single accepted set of principles, several frameworks use principles under different conceptual denominators to inform similar planning responses [50]. Figure 3.1 therefore also highlights how the resilience principles can be applied through common *Planning Responses*, also derived from literature. In Section 3.2,

we elaborate on the principles and later assess their relation to concrete planning responses in our two case studies Section 3.3.

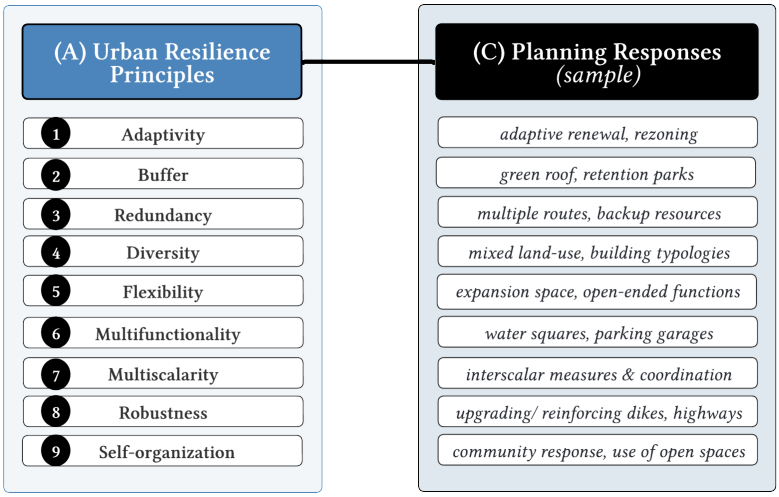

Figure 3.1: A selection of recurring *Resilience Principles* from academic literature that is widely applied through certain *Planning Responses* in the urban environment. A principle can inform multiple planning responses, and a response can be impacted by more than one principle.

Principle 1: Adaptivity, involves adjusting urban systems to changes using responses such as adaptive renewal, reuse, and rezoning [189, 193, 194].

Principle 2: Buffer, absorbs disturbances by creating reserve capacities [38, 194, 195]. Greening is a popular strategy to improve the latent potential of urban spaces to absorb excess rainfall [9] through responses such as water retention parks in low-lying regions and compartmentalizing regions using water channels.

Principle 3: Redundancy, keeps systems operational during crises by offering functional alternatives [38, 194, 195]. It includes strategies like multiple access routes to critical facilities such as train stations and hospitals, and setting up energy backups. Enhancing accessibility and risk absorption through denser urban fabric land divisions increases redundancy [196].

Principle 4: Diversity is managing multiple risks or spreading risk impacts across different urban systems to minimize damages. Spatial diversity can be achieved through mixed land-use functions and distributing critical amenities to avoid simultaneous impacts [10, 197–199].

Principle 5: Flexibility, is a system's ability to *leave things open* to manage changes [38].

It can be achieved using open-ended functions to respond to multiple futures. Flexibility is restricted due to space scarcity, competing for spatial claims, unequal distribution of resources [54] or reliance on heavily engineered responses like dikes that create an artificial sense of stability.

Principle 6: Multifunctionality, draws from the concept of polyvalent spaces [10]. It uses preemptive design such that the same space can serve different uses without significant physical changes [81]. Planning responses include public water squares that double up as playgrounds, floodable parking garages, and schools as temporary shelters.

Principle 7: Multiscalarity, involves understanding interactions across spatial scales to determine planning responses [14, 200–202]. In practice, it includes policies to ensure coordination between the local, regional and national levels and determine trade-offs between scales to minimize

negative impacts and reduce regional imbalances when a major city is made resilient at the cost of surrounding regions. Multiscalarity can also enable understanding the speed of change at different scales to set short and long-term responses [203].

Principle 8: Robustness, is the potential to resist the negative impacts of disturbances by anticipating potential system failures and reducing damages by over-dimensioning the capacities of the system [203]. Planning responses include designing flood defence infrastructure to withstand a very low probability of floods. In the short-term, robustness has proven adequate to manage risk impacts. However, as climate impacts become increasingly dynamic and extreme, robust systems with inherently low flexibility can suffer catastrophic damage.

Principle 9: Self-organisation, implies maintaining an urban system's internal structure, function, and organizational patterns during a disturbance without significant external institutional interventions. A self-organizing system can preserve overall functionality by making changes at faster scales in its subsystems [204]. Planning responses include community-led responses and aid distribution centres, schools as temporary shelters, and using water-based transport during a flood.

Approaches to Urban Planning under Uncertainty

The central idea for urban planning under uncertainty is *'maintaining a fit'* of an area under changing dynamics [205]. This involves updating planning responses based on a changing environment such that systems can avoid or reduce undesirable lock-ins, keep the plan functional, reduce negative impacts and adjust urban configurations based on changing risks.

Conventional approaches for addressing uncertainty, such as performance monitoring and assessment, have successfully solved probabilistic uncertainties that can be predicted based on (past) statistics [102]. Examples are growth trends or frequently re-occurring weather phenomena. However, long-range climate uncertainties are so-called *deep* uncertainties, which cannot be defined by probabilities [136]. They are conventionally addressed by adaptive planning or scenario approaches, for instance, in projects such as the Dutch Delta Program [206].

However, there is no widely accepted and comprehensive set of responses that addresses uncertainty [94] across complex urban systems and over long time horizons. Hence, responses rely heavily on practitioners' intuition, experience, and preferences. To address this gap, we assess the available theoretical approaches to inform decisions in overall urban planning for uncertainty. We draw from the literature on deep uncertainty [96, 207], sustainable urban futures [5], infrastructure management, and complexity in urban planning [94] and synthesize four approaches to manage uncertainty in urban planning.

Type A: Pragmatic approach is the dominant approach that targets planning responses for individual urban systems such as roads, buildings, and parks. It is perceived as a feasible approach that commits to short-term actions while keeping options open for the future. However, it relies on the most probable risk or "best guess" future for that system based on conventional cost-benefit assessments that restrict the scope of alternatives and are not viable for the long-term [189, 207].

Figure 3.2: Conceptual Framework for urban planning for climate uncertainty that is used to analyse the case studies. It illustrates that: (A) Urban Resilience Principles; and (B) Approaches to Urban Planning Under Uncertainty; together determine (C) Planning Responses; that impact (D) Urban Systems.

Type B: Nomocratic/ Procedural approach includes broad regulations to reduce exposure to risks and negative impacts from uncertainties. The approach focuses on prohibitive rules such as 'no-development zones' and restrictive building codes. It works on the premise that it is easier to avoid negative actions than to formulate positive actions that are resource-intensive and are eventually not used by planners [205].

Type C: Methodological approach considers a full range of possible, plausible, and unlikely future climate scenarios. It works on the premise that coping with uncertainties requires moving beyond linear predictions and historical trends. Scenarios that present undesirable lock-ins or interference with large complex systems, including those that are *prima facie* unlikely to happen, such as extreme climate trends, must be considered [94].

However, in practice, even cities with well-developed planning processes are limited to considering a few fixed planning or climate scenarios in decision-making.

Type D: Integrated approach includes consideration of a range of societal values and normative issues that are related to or will impact responses to the main uncertainty being tackled [208]. Planners must consider state-sponsored ambitions for economic prosperity, democracy, policy preferences and other innovations that impact larger goals for climate risks and urban transitions. Responses include integrated area development plans, and finding clever sectoral combinations like the water-energy nexus.

A Conceptual Framework for long-term urban planning for climate uncertainty

We propose a conceptual framework (Figure 3.2) that connects the two prevailing theoretical streams shaping urban planning discourse for climate uncertainty discussed above – *Urban resilience principles* (Section 3.2) and *Approaches to urban planning under uncertainty* (Section 3.2). The intersection of these literature streams illuminates differing, yet fundamental, thought processes that underpin the formulation and scaling up of climate-related planning responses. Together, resilience principles and approaches to planning under uncertainty can provide a framework to analyse how specific planning responses are selected and implemented by considering the historical risk exposure and institutional planning structures in any region. *Planning Responses* are the common denominator to

assess how the two streams interact and manifest in space and impact single or multiple urban systems.

As discussed in Section 2.1, urban resilience theory presents principles that can be applied through planning responses to managing the impacts of climate change. Despite integrating resilience, there is a tendency to propose planning responses for fixed short-term risks [209]. Some climate objectives may also require the implementation of principles that may have the opposite impacts on space (such as robustness v/s flexibility), which restricts the ability of urban systems to respond and adapt to evolving uncertainties in the long-term [190, 210]. Hence, urban planning for climate uncertainty requires integrating resilience and expanding existing planning processes to systematically modulate responses based on new insights.

To systematically assess how resilience and uncertainty impact urban systems, we use a classification offered by the *Urban Layers Approach (ULA)*. ULA classifies urban systems into five groups based on their spatio-temporal characteristics, i.e., the spatial scale and the lifecycle over which the system tends to change [211]. Understanding this change window enables planners to propose appropriate planning responses to integrate resilience to uncertainty.

The five urban systems or layers with their spatio-temporal lifecycles: *Layer 1: Unplanned/ Open spaces (1-10 yrs)*, *Layer 2: Occupation/ Buildings (3-20yrs)*, *Layer 3: Focal Points (5-20yrs)*, *Layer 4: Networks (20-100+yrs)*, and *Layer 5: Natural Resources (20-100+yrs)*.

We illustrate the application of the conceptual framework using the example of highways that see heavy investments in urban regions [212]. From resilience literature (Section 3.2), we derive that **Highways *(Layer 4: Networks)***, become resilient by integrating principles such as *Redundancy (3), Flexibility (5), Robustness (8)*, and *Self-Organization (9)*. These can be achieved through planning responses such as alternate routes, reserving spaces for future vehicle volume, better engineering standards, and preempting self-organization behaviour in a crisis. Resilience must be integrated over the highway's lifecycle to manage long-term uncertainty. Using the *Type-B: Nomocratic Approach*, and *Type-C: Methodological Approach* for planning under uncertainty (Section 3.2) may ensure performance standards to minimize failure under extreme climate scenarios. Use of *Type-D: Integrated Approach* would involve reserving space required for future energy goals and the advent of autonomous vehicles that will significantly impact its use.

The conceptual framework is used for analyzing two case studies. The framework serves as the common basis to map and analyze how these two theoretical streams inform Planning Responses and how each planning response impacts one or multiple Urban systems in a region. These impacts influence the longevity of responses and their role in long-term uncertainty.

3.3 Methodology

This section elaborates on our research approach, case study selection, and data collection and analysis.

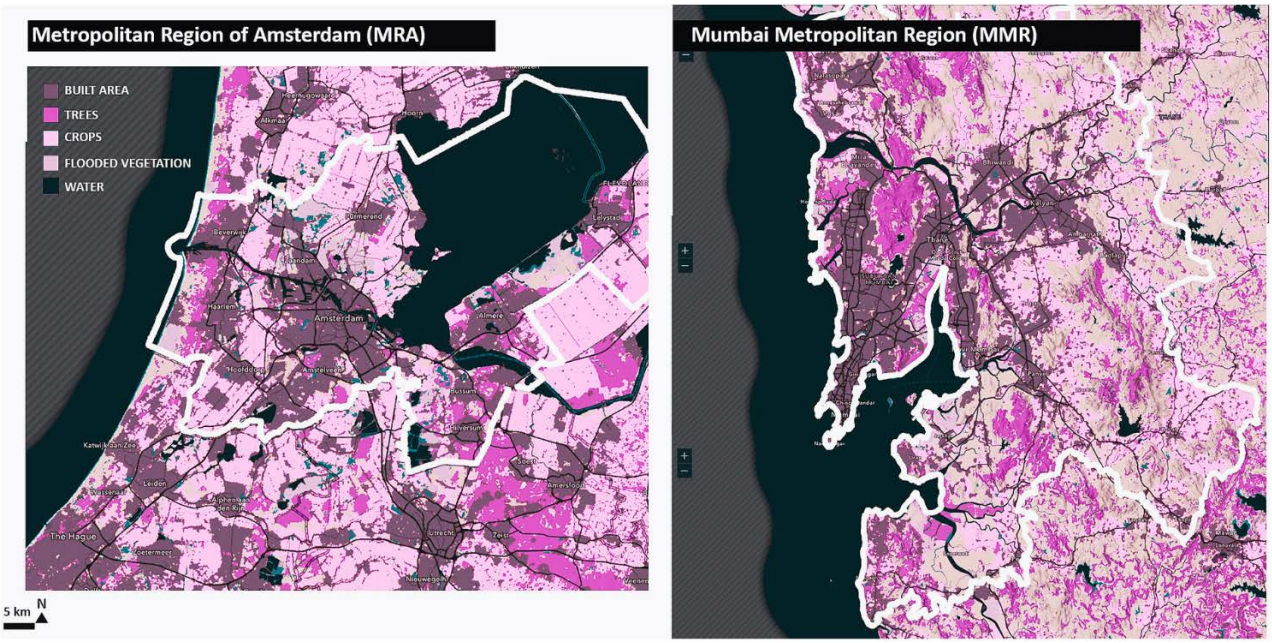

Figure 3.3: Selected Case Studies: Metropolitan Region of Amsterdam (MRA - left) and Mumbai Metropolitan Region (MMR) (Source: Sentinel-2 10-Meter Land Use/Land Cover)

Research Approach

This study aims to make the first steps towards towards an enhanced understanding of urban planning for climate uncertainty. The objective is to understand, through empirical insights from contrasting case studies, how cities are formulating climate-related planning responses and how these planning responses relate to urban resilience theory and planning approaches under uncertainty.

We use a multi-case analysis [107] together with Systematic Combining [108]. The multi-case approach allows us to assess contextual variability in the case studies. We use *Systematic Combining* to develop the findings of the case studies through the interplay between the conceptual framework (theory world) and the empirical findings (real world) [108]. A requirement for *Systematic combining* is clear boundaries for assessing empirical data, without which the research may expand (or shrink) based on each case and distort analysis to inform a common theory. We rely on the conceptual framework as the common reference to analyze the two case studies and identify gaps and missing links. Subsequently, we present four propositions to reflect on the current gaps in long-term urban planning for climate uncertainty.

Selected Case Studies

The conceptual framework is applied to two case studies. To contrast the Global North (GN) and Global South (GS) and investigate the divide in planning and resilience literature [120], we opt for one case study in each of the two contexts (Figure 3.3). Further, the case study cities are selected based on the following requirements: (1) cities that have strong planning ambitions to address climate change; and (2) cities that invest in a large volume of new infrastructure or systematically renew ageing infrastructure.

Based on these requirements, we selected two urban regions: the Metropolitan Region of Amsterdam (MRA) in the GN and the Mumbai Metropolitan

Region (MMR) in the GS. Both regions are their respective countries' economic and cultural centres but have different planning processes and institutional structures. Both recognize the urgency to meet climate-related goals and are drafting spatial strategies that frame the opportunity to derive diverse insights.

While these are not the only 'types' of cities in the Global North and South, they exhibit major urbanization characteristics that presented the variability required for this study. Amsterdam exhibits characteristics of a developed GN economy with high per capita income, technological advancement, and political stability but an ageing society and ageing infrastructure. Mumbai, on the other hand, can be characterized as a developing GS economy with medium per-capita income, in the process of industrializing, with a majority youth population and investments in new infrastructure.

Case Study 1: Metropolitan Region of Amsterdam (MRA)

The Metropolitan Region of Amsterdam (MRA) in the Netherlands is an agglomeration of 32 municipalities housing 2.48 million people. MRA has a polycentric structure with Amsterdam as the dominant core, supported by eight sub-centres. Amongst one of the highly developed areas in the world, MRA is characterized by a mature spatial planning approach with well-coordinated public investments, consensus-driven political processes, and robust urban planning structures [111].

MRA's economic attractiveness has resulted in high inward migration and outward expansion of the urban footprint, which has led to a significant housing crisis. This has added immense pressure on its mobility systems and meeting sectoral goals like energy transition.

MRA's vulnerability stems from the fact that large areas lie below sea level and are protected by engineered dikes. Around 70% of MRA's area is threatened by one or more risks that it must respond to extreme heat periods, rainfall, prolonged droughts, and sea-level rise. In addition, the region faces labour shortages and increasing socio-economic disparity.

Planning is driven by a regional urbanization strategy (*verstedelijkingsstrategie*) supported by city-level Structural Vision (*structuurvisie*, detailed urban plans (*bestemmingsplan*), and thematic documents on mobility, environment, energy, and climate. From a climate perspective, MRA is critiqued for its highly regulated planning process, limiting its flexibility to absorb fluctuations and make constant adjustments.

Case Study 2: Mumbai Metropolitan Region (MMR)

The Mumbai Metropolitan Region (MMR) in India is the fourth-largest urban agglomeration globally, consisting of 8 municipal corporations, nine municipal councils, and houses over 22 million people. MMR has a polycentric structure, with Greater Mumbai as the dominating core supported by several densely populated sub-centres.

MMR's economic attractiveness has led to high inward migration. Its urban growth has rapidly increased to crushing densities adding immense pressure to its urban infrastructure systems. Formal planning could not meet the requirements of the growing population, which is why more than half the urban population lives in informal settlements. The region

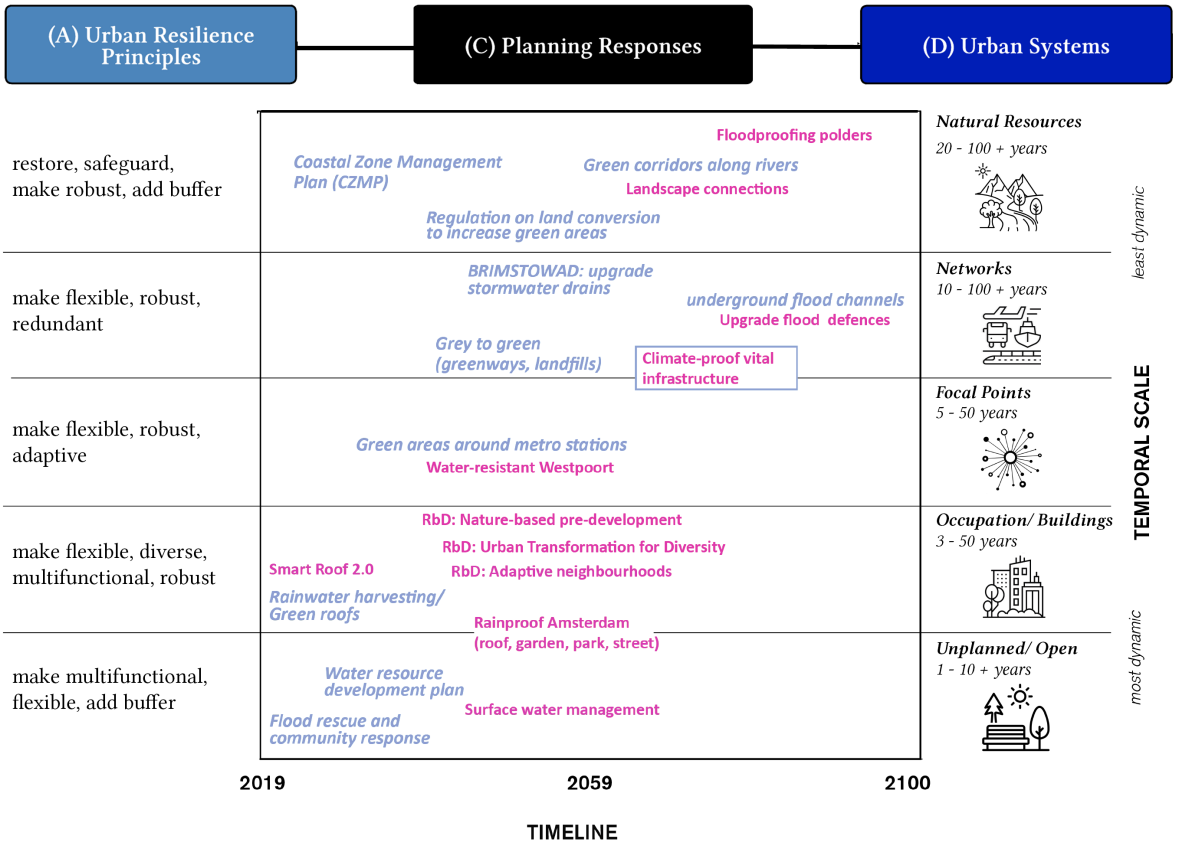

Figure 3.4: Mapping climate-related Planning Responses for MRA (in red) and *MMR (in blue and italics)* to the Urban Systems they target. Each Urban Layer has a recommended resilience principle to make it most effective in managing climate uncertainties [81]. ('RbD' indicates projects proposed as part of MRA's Resilience by Design programme) [214]

is now making high-value investments in roads, high-speed rail, metro, and coastal roads.

MMR is vulnerable as the city is built on reclaimed land, and large portions along the coast lie below the high tide level. The city must have planning responses to chronic flooding, inadequate civil infrastructure, outdated stormwater systems, and insufficient open spaces.

MMR's official planning is guided by the Regional Plan (RP) supported by the municipal corporations' Development Plans (DP). The RP presents guidelines for growth across infrastructure, socioeconomic, and environmental sectors, and the DP presents more detailed zoning and building regulations. These plans are augmented by a state-level action plan for climate change and a city-level disaster management plan guiding response and recovery measures. MMR's planning documents are critiqued for being overtly prescriptive, regulatory, and prohibitory instead of building integrated visions. They do not identify entry points for climate-related goals but stick to broad recommendations [213].

Data Collection and Interview Design

The analysis is based on two data collection processes. For both case studies, we first assessed grey literature in the form of primary planning documents and how they discuss climate-related planning responses (Section C.2). In the context of resilience, *Planning Responses* planning,

preparatory, and recovery measures that target single or multiple urban systems (Table 3.1). Hence, we selected official planning documents for both cases, such as development plans, urbanization strategies, regional plans, climate action plans, and disaster management strategies, to extract the full range of climate-related planning responses.

Second, we conducted 39 semi-structured interviews with senior practitioners and scholars directly involved in the development and implementation of urban plans. The interviews were conducted over one year (2020-21), and each interview was approximately 60 minutes long and conducted online using Zoom/Teams calls due to travel restrictions during the Covid-19 pandemic.

The interview protocol was framed to dive into the thinking processes for climate-related planning and to what extent they are guided by theories of resilience and planning under uncertainty. The interview questions were structured into four main sections: Climate-related planning responses and sectoral focus; Long-term thinking (beyond current planning timelines); Knowledge gaps and institutional challenges; and Planning variables and values. A semi-structured protocol allowed us to vary the sequence of questions and ask follow-up questions to enable richer discussions. Appendix Section C.2 presents an indicative interview protocol. A detailed protocol with a consent form may be accessed here: `https://github.com/supadupa09/TFG_Interviews.git`.

The authors used their professional networks to identify participants in a 2-step process. A list of 20 experts was made for each case, which was expanded to approximately 200 using snowballing sampling, personal referrals, and social media. The objective was to select between 17-20 participants per case, which is the suggested sample size saturation in empirical research using interviews [215]. Short introductory conversations were conducted based on the research's intent to arrive at a combined list of 39 experts to ensure a reasonable representation of sub-domains - 20 for MRA and 19 for MMR. Participants came from four sub-domains that play crucial roles in planning: urban planners, strategic/policy advisors/bureaucrats, academic researchers, and specialists in sustainability, environment, and engineering (Table 3.2).

Table 3.2: Combined Participants grid for MRA (P1–P20) and *MMR (P21–P39)* classified based on their role in the urban planning process and their domains of expertise. 'X' indicates that we did not receive responses from the right participants from that domain.

Domain	Role in the urban planning process			
	Strategic/ Policy Advisors/ Bureaucrats	Academic Researchers	Sustainability/ Climate/ Environment/ Engineers	Urban Planners
Urban Planning, Geography	P1, P2, *P26, P30, P33, P38*	P11, P20, *P34, P35, P36*	P3, P15, P18, *P27*	P4, P5, P17, P19, *P21, P22, P37, P39*
Climate and disaster risks, environmental planning	P6, P7, P9, *P24, P28*	P10	P12, *P31*	P8, P13, *P23, P25*
Infrastructure	P14, P16, *P29*	X	*P23*	X

Data Analysis

The goal of the data analysis was to (1) Analyse grey literature to map climate-related planning responses for different urban systems; and (2) Analyse interview content for the application of urban resilience principles, planning responses, challenges, and approaches for planning under uncertainty.

To analyze interviews, we developed a corpus of the 39 interviews by transcribing recordings and combining memos written during the interviewing process. Interviews for each case were analyzed separately using systematic qualitative coding on *Atlas TI*. Qualitative analysis of interviews was conducted in three steps [216].

In *Step-1*, we used open coding to extract broad findings on integrating climate goals, planning approaches, urban systems, values, and challenges. The coding scheme was derived from findings from the literature review in Section 3.2. In *Step-2*, we used selective coding to extract findings in four categories to focus on the research gap: Application of urban resilience principles, planning responses, approaches to uncertainty, and associated challenges (Figure 3.5). As there was a heterogenous participant group, there was significant variation in terminology between interviews. Table 3.3 and Table 3.4 enlist the dominant resilience principles discussed for MRA and MMR, respectively, together with terms that were grouped and sample quotations.

Finally, in *Step-3*, we revisit the coded data for both cases to conduct a cross-case analysis to observe similarities and dissimilarities in resilience principles applied in both contexts, variations in planning responses, and approaches to uncertainty. The following section elaborates on the findings for each case.

3.4 Results

Findings from grey literature

In Figure 3.4, we map proposed and 'in-progress' climate-related planning responses for both case studies. In the context of resilience, *Planning Responses* may include planning, preparatory, and recovery measures that target single or multiple urban systems (Table 3.1). Hence, we assessed a selection of official planning documents for both cases, such as development plans, urbanization strategies, regional plans, climate action plans, and disaster management strategies, to extract the full range of climate-related planning responses (see Section C.2).

We connect the responses to *Urban Systems* they target and describe *Resilience principles* that are relevant for each system (see Section 3.2). Standard planning responses include rainwater harvesting, upgrading and streamlining stormwater drains, reinforcing landscape connections, and climate-proofing vital infrastructure.

MRA's planning documents recognize climate adaptation as a key goal and include a conceptual strategy for 2050. Responses target all five urban systems with a heavy emphasis on building resilience to manage excess water and climate-proofing assets. Hence, *Adaptivity* and *Robustness* emerge as the dominant resilience principles. Rainproof Amsterdam is a well-developed project targeting *Layer 2: Occupation* and *Unplanned/Open Spaces* to capture excess water (see Figure 3.4 in red). In addition, the MRA is taking concrete steps through the *Resilience by Design* initiative that proposes demonstration projects for climate adaptation, including an adaptive tree plan, adaptive neighbourhoods, and urban transformation for diversity [214]. While the projects apply multiple resilience principles like *Adaptivity, Diversity* and *Flexibility*, most are targeted at the scale of buildings.

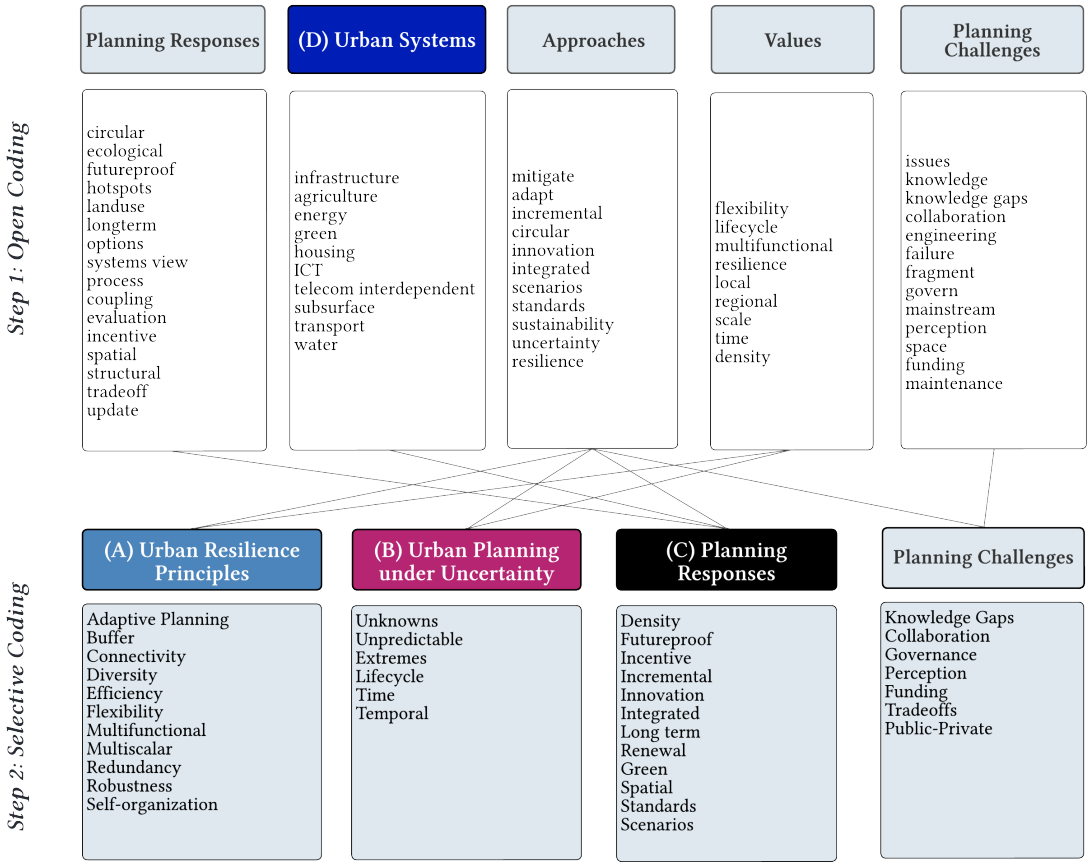

Figure 3.5: Final coding scheme for the content analysis of interviews for MRA and MMR. Categories were utilized to identify components of the conceptual framework including Urban Resilience principles, Planning Responses, Urban Systems, and Approaches to Uncertainty; as well as Challenges in Long-term Planning.

Climate-related goals in the MMR are heavily reactive and focused on building resilience to urban flooding through community response and recovery. Planning is incremental and prescriptive, with most actions focused on upgrading infrastructure. BRIMSTOWAD is an ongoing long-term project to expand the capacities of stormwater drains. In the absence of a formal climate program while writing this paper, MMR (see Figure 3.4) integrates climate into several scattered projects where it becomes a secondary objective. With a scarcity of open spaces, MMR emphasizes restoring and expanding natural *Buffer* using green corridors along rivers, regulating land conversion, and a Coastal Zone Management Plan (CZMP). MMR enforces norms for rainwater harvesting only in new greenfield developments.

Findings from Interviews: Case Study 1 (MRA)

Dominant Resilience Principles with high application

The dominant resilience principles discussed by participants are to manage risks using *Adaptivity, Buffer* and *Multiunctionality* and to resist risks by increasing *Robustness. Adaptivity* is widely applied at the *Layer 2: Occupation* as adaptive neighbourhoods, adaptive tree plans, and nature-based development. Participants criticize the lack of an empirical foundation

or proven planning instruments in applying adaptivity *(P1, P2, P13)* and note that it relies on its thematic popularity rather than the urgency to act *(P8, P17)* (Figure 3.6).

MRA adopts the *'retain-store-drain'* strategy for flood management used in the Netherlands and implements it in planning (P10). Due to MRA's space scarcity, most participants endorse the use of *Buffer* in conjunction with *Multifunctional* urban spaces to create water squares, floodable parking garages, and retrofitted rooftops *(P10, P13, P15)*. The 'Amsterdam Rainproof' program applies these actions to improve urban capacity to manage rain. It has led to policies that require every area to retain a rainfall volume of 60mm/hour *(P8, P13)* [217].

The popularity of applying *Multifunctionality* has made it a convenient answer to integrated resilience irrespective of its small spatial scale and relatively short-term impact *(P1)*. Hence, '*Greenwashing*' dominates planning responses, especially at the plot level. Making spaces multifunctional also affects their living quality if not maintained well (like, parking lots that do not drain well). Additionally, *Multifunctionality* for larger urban systems such as *Layer 2: Occupation* and *Layer 3: Focal Points*, requires managing changing demographic demands and there may be *"a potential misalignment between the structure and the expected function" (P1)*. For instance, the building occupants change every few years, but the function of the building changes much slower. Understanding these change frequencies and *Flexibility* will be vital to introducing new functions into existing buildings.

Finally, *Robustness* emerged as a recurrent principle to resist risk while also being criticized for making the MRA less flexible to changes. Planning in the Netherlands is highly regulated and focused on definitive outcomes [111]. This has counter-intuitively made the MRA vulnerable to uncertainties as the system is presumed to be fail-proof, and expansion continues on land that could be flooded from dike breaches *(P8, P10)*. *P21* explains that *"If (MRA) gets flooded, the government is held responsible. Therefore, we offer one of the highest levels of protection in the world"*. Hence, MRA's extensive network of dikes and sluices against flooding are continually upgraded until they reach their tipping points.

Dominant Resilience Principles with low application

The principles discussed due to low applications are *Flexibility, Diversity, and Multiscalarity.* MRA's lack of flexibility was attributed to an inflexible water system and an over-reliance on engineered dikes *(P7)*. *P7 & P14* critiqued the heavy focus on rainfall, which is 'ready to solve' and hampers the development of regulations for emerging, lesser-known risks from heat and prolonged drought. Planners critiqued the master planning instrument as *"being tightly wound blueprints that offer no flexibility" (P14)*. *P2* emphasized that zoning plans are flexible at the plot scale but not at a larger scale. Participants proposed updating the master plan every ten years or less based on changing needs. P1 proposes a ratio of *"one-third structure two-thirds diversity"* in master planning to keep it flexible, to adapt or diversify as needed. Participants from different domains conceded the need to *"think about flexibility at the conceptual stage"* to avoid undesirable lock-ins and higher re-investment costs *(P8, P9, P10)*.

On *Multiscalarity*, the urban planners and climate specialists discussed the regional scale as ideal for long-term planning *(P2, 12, 13)* as most urban

Table 3.3: Case Study 1 (MRA): Dominant resilience principles discussed by participants, with the number of mentions and sample quotations. (+) and (–) indicate principles with high and low application respectively.

S.	Resilience Principles	Terms included	Mentions	Participants	Example Quotes
1	*Adaptivity* (+)	adaptable, adaptation, agile, accommodate, adjust	180	ALL	*"Greenwashing is synonymous to climate adaptation" (P2)* *"Big decisions on where to plan... is not taking climate adaptation or future uncertainties into account" (P8)* *"We need to try to not make big investments, where we later regret it. We need to find a way to make progress, but keep different adaptation options open." (P7)*
2	*Buffer* (+)	retention, infiltration, storage, garden, green roof	31	1, 2, 5–20	*"The 'retain-store-drain' strategy in the Netherlands is translated into a multi-level flood protection strategy." (P10)* *"We have spatial plans on a local level, where you can include requirements for new buildings..., increase infiltration/buffer capacity of roads and not immediately discharge it to the sewers." (P6, P12)*
3	*Multifunctionality* (+)	alternate, water square, mixed use	17	1, 5, 9, 10, 14, 16, 17	*"The water square is only a solution to one issue. I don't know anyone who likes to live at the water square." (P1)* *"Different elements in a city have different frequencies. The user that occupies a building changes every few years, but the function changes slower." (P1)*
4	*Robustness* (+)	strong, reinforce, maintain	29	1–3, 5–10, 12–14, 16–19	*"A redevelopment offers a moment of renewed interest and gives us the opportunity to review what we wrote down 10 years ago and make a new perspective where we integrate climate adaptation." (P5)* *"Can you use a small percentage of your maintenance projects to test new techniques?" (P14)*
5	*Diversity* (–)	diverse, various, range, multiple	16	1, 2, 5–7, 10, 17	*"By spreading the risk to 1000 planning options, there's always one that works." (P1)* *"There is an optimal balance between structure and diversity in an ecosystem, in order to be resilient." (P1)*
6	*Flexibility* (–)	frequency, updating	60	1–3, 5–14, 17–19	*"It's not very flexible because of the lack of space." (P6)* *"We have to skip the blueprints." (P14)*
7	*Multiscalarity* (–)	scale, local, regional, community, neighbourhood, scalar	108	all except 4 and 9	*"If you really want to work on climate adaptation, you have to do it on a regional scale." (P2, P13)* *"Scale is connected to types of climate. You cannot cope with sea-level rise in the design of your urban areas. Cities are limited by their administrative boundaries." (P12, P16, P18, P19)*

systems with long lifecycles are planned on that scale *(P1)*. However, most climate-related planning responses are targeted towards *Unplanned/Open Spaces* and *Occupation/Buildings* where it is effective to introduce small-scale fitted solutions. Urban designers find the local scale feasible *(P6)* and find regional planning futile for climate *(P3)*. Multi-scalar thinking is essential as different climate risks can be addressed effectively at different scales. For instance, municipalities are *"limited their administrative boundaries"* and cannot make strategies to cope with a sea-level rise at their scale *(P12, P16, P18, P19)*. Urban planners *P17 & P8* emphasized matching the spatial scale with the risk to form viable business cases for investing and avoiding roadblocks.

Implication for Urban Resilience theory and Planning under Uncertainty

Resilience: *Redundancy* and *Self-organisation* find no mentions in interviews, possibly because both principles typically emerge or are applied in systems that are constantly exposed to risks and must continually adjust [218]. In the recent past, MRA has offered a relatively safe environment except for prolonged drought and extreme heat days for which localized energy and water backups are arranged. Creating a redundancy of trans-

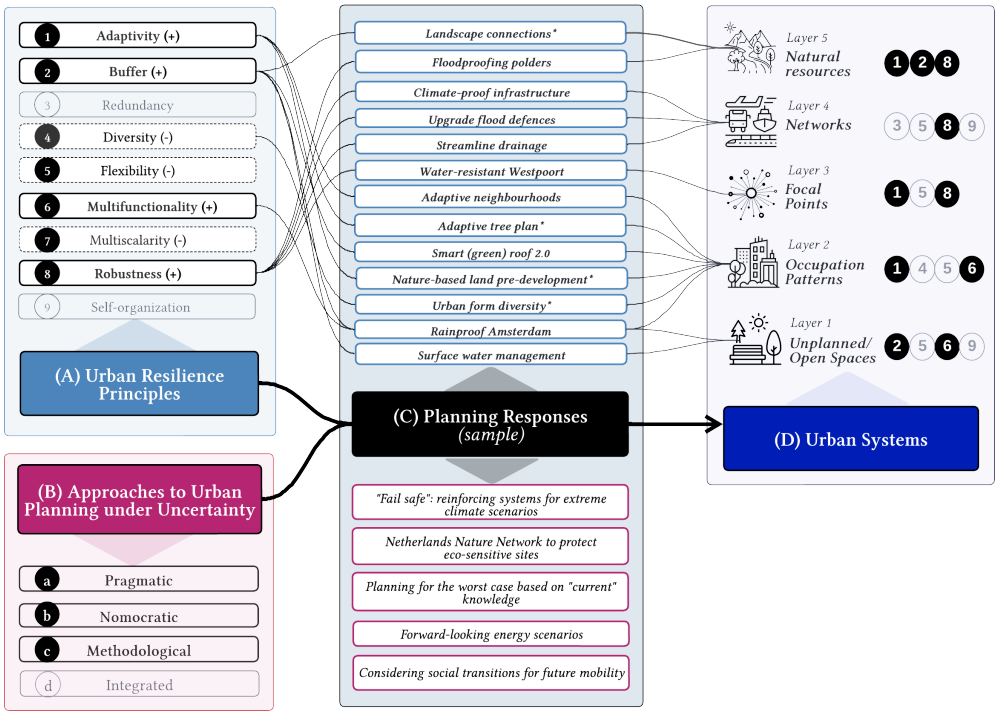

Figure 3.6: Case Study 1 MRA: Assessing climate-related planning responses using the Conceptual Framework (Figure 3) and findings from interviews to highlight: (A) Dominant Urban Resilience Principles; ((+) and (-) indicate principles with high application and low application, respectively.); (A) Dominant Approaches to Urban Planning under Uncertainty; (C) How 'A' and 'B' together determine Planning Responses; and their impact on (D) Urban Systems.
(Grey box indicates no mentions. Dotted lines indicate terms mentioned but not discussed in detail in literature or interviews. (*) indicates proposed Planning Responses.)

port networks and water sources for low-probability events like flooding does not receive any attention, though it can cause significant damage.

Uncertainty: MRA's approaches to planning under Uncertainty emerges from a risk-resistant attitude where planning responses are designed to resist failure [8, 218]. A risk-resistant system is planned in a fail-safe manner where its inherent variability is suppressed, and it becomes less resilient to sudden changes [219]. Participants also blame an over-reliance on flood-protection engineering for cultivating a culture of planning for the worst case without accounting for emerging risks like winter storms, heavy rains, or prolonged drought in the detail that they should be.

In theory, MRA's planning incorporates all four approaches to planning under uncertainty with varying degrees of application (see Section 3.2). The dominant approach is *Pragmatic*, where responses are targeted toward individual urban systems like reinforcing flood defenses, climate-proofing energy networks, and improving the buffer capacity of open spaces. *Nomocratic* approach is seen in regulations to protect ecological and cultural sites. *Methodological* approach can be partially observed in MRA's use of forward-looking scenarios for energy and mobility systems. It also benefits from four well-researched, predictive national climate scenarios for climate risks. P9 emphasizes that *"MRA plans within these plausible scenarios and dealing with outliers, extremes and emerging risks are where things go wrong."* While MRA discusses different scenarios for its sectors, alternative urbanization strategies are not thought of. P9 proposed a robustness analysis of the urban plan to identify long-lasting urban systems and use a mix of uncertainty approaches accordingly.

Table 3.4: Case Study 2 (MMR): Dominant resilience principles discussed by participants, with the number of mentions and sample quotations. (+) and (–) indicate principles with high and low application respectively.

S.no.	Resilience Principles	Terms included	Mentions	Participants	Example Quotes
1	*Adaptivity* (-)	adaptation, agile, accommodate, tipping, rapid, adjust	30	21, 22, 24, 25, 28, 27, 30, 31, 33, 38	*P28: "Urban adaptation schemes elite-driven. You see a major role for transnational corporations, and the projects cater to urban middle class"* *P21: "Adaptation is perceived as a cop-out for governments because they have failed to limit emissions."*
2	*Buffer* (+)	retention, infiltration, store, garden, green, permeate, park	28	21, 22, 26, 27, 30, 31, 33, 35	*P22: "A lot of land designated for public purposes like parks eventually became a slum."* *P30: "Buffers are hard to achieve when the city is 97% built-up"*
3	*Flexibility* (-)	frequency, update	29	22, 27, 29, 30, 31, 33, 35, 36	*P27: "We have to make a master plan every year to cater to the current trends. It is the only instrument and can be very flexible and be allowed to change as we move along.* *P33: "What we should freeze is ecological areas which will remain permanently as no development zones. The other areas should be very flexible to expand and absorb intense construction."*
4	*Multi scalarity* (-)	scale, local, regional, community, neighbourhood, context, ward	110	21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39	*P34: "You have to look at at least 30-50 years and think regionally for climate resilience".* *P29: "The Metro will last for 200 years. That kind of (scale) will change the whole city's life. So projects with long-term impacts must be given a special consideration in the planning process, which is not happening.* *P36: "Follow a flexible approach for macro level planning. Use local area plans for micro level urban development by following a market driven logic to enable equitable distribution of land."*

Findings from Interviews: Case Study 2 (MMR)

Dominant Resilience Principles with high application

As MMR does not have a dedicated program on climate action, resilience does not find many mentions but is integrated into different planning projects and policies. The dominant principles discussed by participants are to manage urban flooding using *Adaptivity* and *Buffer* and the need to bring in more *Flexibility* and *Multiscalarity* in planning to manage uncertainty (Figure 3.7).

Due to Mumbai's chronic flooding, improving *Robustness* of stormwater drains is a significant project *(P31).* The State of Maharashtra's Action Plan on Climate Change also presents system-specific strategies for transport, energy, and ecosystem-based adaptation actions *(P24)* [220]. The transport sector is considered to be most effective in improving *Adaptivity* given the heavy future investments and high traffic volume (P33). However, a robust, data-driven understanding of adaptation, including the implications of maladaptive planning and undesirable tradeoffs, does not exist *(P21).* For instance, Mumbai's metro rail construction requires acquiring land preserved under natural resources. But, the tradeoff between the mitigating properties of public transport versus the adaptive properties of damaged natural ecosystems is not assessed. P21 criticizes that *"Adaptation is viewed as a cop-out action when the urban planning mechanism fails."*

Buffer is widely applied in MMR across spatial scales. New development schemes are mandated to harvest rainwater onsite at the building level. A buffer is introduced at the neighborhood/ward scale through land reservations and assigning recreation areas as 'no-development zones.' There are policies to protect mangroves, wetlands, and other natural

ecosystems at the city scale, which act as a sponge for coastal flooding. A city-wide blue-green network was initiated but not completed as Mumbai has few large open spaces to capture rainwater within urban limits *(P30,33)*. In addition, Mumbai is considering developing an underground floodwater channel similar to Tokyo to store surplus water.

Unlike MRA, what hinders the application of *Multifunctionality* is that public spaces are viewed purely from a consumption standpoint to cater to a large existing population *(P31)*. It is challenging to find synergies as the planning responses are not tied to a common climate strategy, which brings in competing priorities in a hyper-dense region.

Dominant Resilience Principles with low application

On lack of *Flexibility*, more than half the participants criticized existing planning instruments for being overly regulatory. Rigid norms for land reservations and a moderate Floor Space Index (FSI) encourage illegal expansion in a city facing intense land scarcity. *"Instead of anticipating changes, the planning instruments are prescriptive and go into (unnecessary) details"* which impedes inherent Flexibility *(P22, P36)*. Like MRA, MMR participants also recommend that the Development Plan (DP) be updated every 5-10 years to cater to changing trends *(P27, 31, 33). P33* recommends developing adaptation pathways and scenario planning for Mumbai not to be locked into blueprints.

On *Multiscalarity*, the role of the correct spatial scale was discussed extensively. Participants recommend multi-level engagement but recognize the regulatory challenges of coordinating between scales. For instance, the Regional Plan is not binding upon the local wards and has a lower legal standing in the planning process *(P22)*. Moreover, the mix of formal and informal growth and massive peri-urban expansion establishes a standardized planning template for inter-scalar coordination. Hence, the city adopts tactical planning responses to manage risks at the project-level or plot level. *P29* points out that the planners must give infrastructure projects like the Mumbai Metro special consideration due to the long lifecycle and impacts on the region's economy. However, the climate is not fundamental to its planning.

MMR's local flood response capacity points to a mature level of *Self-organization* illustrated by a strong community response in flood rescue and sheltering. The disaster management plan also presents guidelines to develop *Redundancy* plans during a crisis through alternative transport routes and energy and communication backups.

Implications for Urban Resilience and Planning Under Uncertainty

Resilience: While the urgency of climate change is recognized, it is not integrated into urban planning *(P24). Diversity, Redundancy, Robustness*, and *Self-organization* find little to no direct mentions in the interviews. From a resilience perspective, Mumbai's annual urban flooding becomes an agent for resilience-building and self-organizing since each flooding event leads to small to medium-scale disruptions that allow urban systems to readjust. This has led to the emergence of a diverse set of coping strategies and high inherent *Adaptivity* [221]. However, planning responses have not systematically tapped into the usefulness of *Multifunctionality*

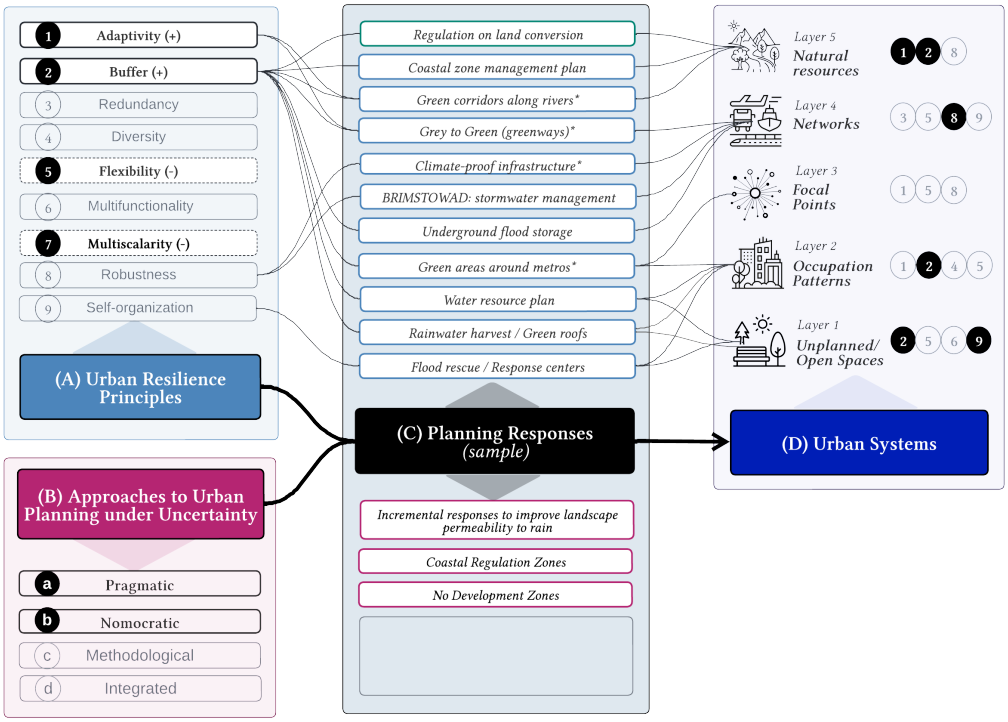

Figure 3.7: Case Study 1 MMR: Assessing climate-related planning responses using the Conceptual Framework (Figure 3) and findings from interviews to highlight: (A) Dominant Urban Resilience Principles; ((+) and (-) indicate principles with high application and low application, respectively.); (A) Dominant Approaches to Urban Planning under Uncertainty; (C) How 'A' and 'B' together determine Planning Responses and their impact on (D) Urban Systems.
(Grey box indicates no mentions. Dotted lines indicate terms mentioned but not discussed in detail in literature or interviews. (*) indicates proposed Planning Responses.)

or *Robustness* to use space efficiently and absorb the recurrent impacts of flooding.

Uncertainty: MMR's approaches to uncertainty emerge from the experience of a region that faces recurrent flooding and is forced to embrace it as an environmental dynamic. Due to limited resources and a complex urban fabric, the region has not realized intensive engineering responses like underground flood channels to manage floods. However, it relies on reinforcing natural ecosystems to absorb risks. Only two participants explicitly discussed uncertainty and pointed to the urgency of introducing it to planning *(P33, P35)*. Given the expanding urban footprint of the MMR, participants propose *"decentralized planning as an antidote to uncertainty"*. This implies empowering local decision-makers to experiment with new strategies to manage flooding, pollution, and urban heat islands. This reflexive approach may help fulfill market demands to utilize land efficiently to manage changing risks *(P36)*.

MMR dominantly uses the *Nomocratic* and *Pragmatic* approaches Section 3.2. Nomocratic approaches can be seen in blanket regulations to conserve green areas and reinforce green corridors. This has proven insufficient to manage floods from fluctuating rainfall patterns and inadequate civic infrastructure. *Pragmatic* approaches are targeted towards increasing *Open Spaces* and regulating the density of *Occupation/Building*. No system-wide strategy exists for resilience of *Focal Points* and *Networks*.

From a *Methodological* perspective, MMR plans for a single future scenario, relying mainly on past trends and fixed predictions. *P22* emphasizes that

"Mumbai is stuck with the impacts caused by the 2005 deluge - a 1 in 100-year flooding disaster. Most policy documents, as well as academic studies, are written considering the impacts of that single event" [222]. Participants acknowledge that the formal planning framework does not recognize uncertainty or the need to consider 'what-ifs' to plan for alternative scenarios. For instance, infrastructure and building codes consider flood levels from 2-3 decades ago.

Cross case analysis

This section conducts a cross-case assessment of findings from MRA and MMR to examine similarities and dissimilarities in applying urban resilience principles, planning responses, and approaches to uncertainty.

Similarities

From a general planning perspective, both MRA and MMR foresee growth that must balance new development and several renewal projects. Both cite a scarcity of space as a roadblock to implementing climate-related projects like expanding stormwater drains or adding buffers. Participants in both cases confirmed the ease and cost-effectiveness of implementing climate-related projects on public land as they have more control *(P2, P6, P8, P14, P22, P28)*. Introducing measures on private land or expropriation of land was recognized as a significant barrier to scaling up climate-related responses.

On resilience principles, participants explain the lack of *Flexibility* as a critical barrier to long-term planning. While MRA's lack of Flexibility came from a heavily regulated planning system, MMR deals with significant capacity gaps that do not allow it to consider a flexible planning regime. *Multiscalarity* emerged as a common goal, but its implementation was also a common point of conflict in both cases. Climate specialists and strategic planners made solid arguments supporting top-down, centralized planning, especially for large-scale decisions where multiple infrastructure systems must be coupled together *(P7, P21, 22, 33)*. On the other hand, urban planners and bureaucrats who implemented detailed plans endorsed bottom-up, decentralized planning at the local scale to manage climate risks *(P3)*.

Both participants acknowledge that uncertainty is not part of the formal thinking process. Planning responses are *Pragmatic*, low-regret *(P3, P7)*, and emphasize incremental actions in individual urban systems. A common conflict for both regions is prioritizing incremental over transformative planning projects.

Both cases successfully use *Nomocratic* planning to manage uncertainty. For instance, MRA preserves natural areas under Netherlands National Ecological Network (NEN) [223]. Similarly, MMR has a Coastal Zone Management Plan to conserve ecologically sensitive zones [224].

Dissimilarities

The first dissimilarity between the cases is urban development and the maturity of planning instruments. MRA has fulfilled its basic urban infrastructure needs but needs to transform standards for emerging risks. On the other hand, MMR must manage a significant infrastructure deficit

while meeting climate goals. MRA has a mature spatial planning system that primarily uses a combination of top-down and community-based planning. MRA benefits from national policies on climate adaptation and well-researched climate scenarios as benchmarks for long-term planning. MMR has a hybrid planning approach where top-down formal plans are supported by tactical responses, especially for growth outside the purview of formal regulations. MMR's planning for climate risks is mainly reactive, and open-ended, and relies on feasible short-term targets. In the absence of detailed climate scenarios, planners consider only high-level assumptions, and plans are designed to absorb forecasted growth.

Second, the capacity gap in MMR hinders an integrated approach to long-term planning in MMR. MRA has a solid regional authority to develop and implement climate programs. Hence, planning responses address all five urban systems, and it is possible to have a template to propose resilience principles and predict planning outcomes. Climate programs in Indian cities are outsourced to independent consultancies or international agencies due to a lack of internal capacity, leading to fragmented projects, generic responses, and inequality *(P23)*.

3.5 Propositions towards an enhanced understanding of urban planning for climate uncertainty

This study analyses two case studies to build an enhanced understanding of long-term planning under uncertainty by combining concepts from urban resilience and urban planning under uncertainty. Despite the contrasting planning contexts, participants in both cases - MRA and MMR - confirm the lack of a systematic way for planning to manage climate impacts. This section presents four propositions developed using findings from theory and empirical insights from the interviews to reflect on the current gaps in adopting long-term planning and where theory can play a role in filling this. Each proposition is substantiated using comparative insights from our two case studies and 39 interviews. We present narrative accounts and structural findings that characterize the long-term planning process. We further present propositions on four themes: planning processes, urban resilience, planning under uncertainty, and types of planning responses, towards an enhanced understanding of long-term urban planning for climate uncertainty (Figure 3.8).

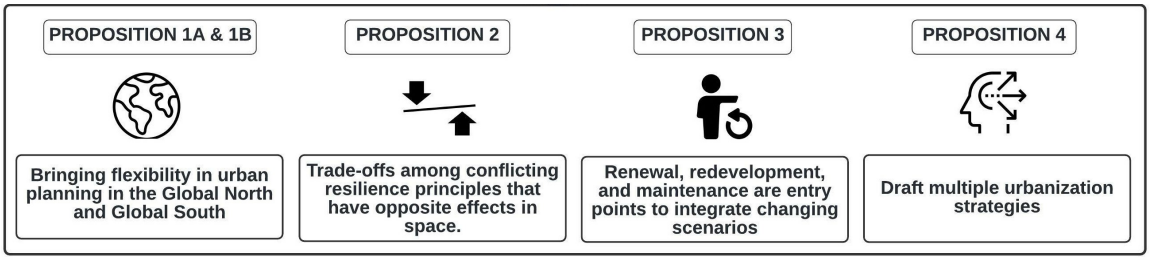

Figure 3.8: Four propositions towards an enhanced understanding of urban planning for climate uncertainty, using theoretical reflections from literature and empirical insights from case studies.

Proposition 1: On Urban Planning Processes

Proposition 1A. *Bringing flexibility in urban planning is a pivotal way Amsterdam (MRA) and Mumbai (MMR) can develop a process to continuously integrate changing variables essential for planning for climate uncertainty.*

One of the key findings of this study is the dissimilarity in planning and resilience capacities in the MRA and MMR. MRA and MMR must manage major long-term transitions under climate change, but the approach differs based on their position on the development spectrum. It is widely known that developed regions like MRA are expected to not prioritize climate due to high inherent adaptivity [225]. However, several recent events like hurricanes, tornadoes, and prolonged droughts have caused significant losses in industrialized regions of the Global North due to damages to existing protection structures.

MRA must deal with locked-in risks because of the massive investments made in the past, which today face more extreme hazards than intended. It must ensure that future climate-related responses do not disturb the well-functioning status quo. On the other hand, MMR must address the dual goals of meeting its fundamental infrastructure deficit while ensuring resilience. However, planning processes in MMR face significant institutional and capacity gaps, which leaves little incentive for substantial long-term thinking (P25, 32, 35).

Proposition 1B. *The lack of flexibility in planning in Amsterdam stems from rigid outcome-oriented planning regulations, and in Mumbai, stems from insufficient planning structures.*

MRA has made steps to integrate climate into formal urban planning instruments, but it is applied only to small-scale pilot projects based on fixed variables. Conceptually, the value and interpretation of flexibility in planning remain ambivalent as it could improve resilience and provide unfair development advantages based on market forces [226]. MRA participants, especially the strategic planners, criticize its overtly regulated, outcome-oriented planning for impeding its flexibility to integrate new information. The lack of flexibility in the planning process hinders applying other resilience principles and uncertainty approaches that demand integrating emerging variables.

MMR is yet to develop and implement actions based on a strategic understanding of the interaction between climate and development priorities [227]. It relies on conservative measures like reinforcing green spaces and reactive measures such as emergency response and rescue to manage disasters. This makes it challenging to have long-term planning trade-offs to improve resilience [228]. MRA participants view open-ended planning systems, like the one in MMR, as advantageous to integrating unprecedented changes to build resilience. From an uncertainty perspective, not having definite outcomes is a mark of a flexible system open to change. Participants in the MMR criticize that Mumbai's open-ended approach has led to a high tolerance to risk, recurrent infrastructure damage, and low trust in the government to protect it.

A second important planning highlight is that urban growth in the MMR spreads beyond formal physical and institutional boundaries. While there are some ways to characterize informal growth, managing unprecedented changes is challenging as planning responses may not have the expected outcome.

Proposition 2: On Urban Resilience Principles

Proposition 2. *Conventional thinking assumes that different resilience principles mutually reinforce each other's impacts. However, transformative long-term urban planning requires resolving trade-offs among principles with opposite impacts in space. Three such conflicting combinations that emerge in discussions of the cases are Robustness versus Flexibility, Structure versus Diversity and Redundancy versus Efficiency.*

Section 3.4 discussed how resilience principles like *Buffer* and *Multifunctionality* are used in combination to improve urban capacity to manage rain. However, participants from both cases emphasize that long-term planning requires applying principles that have opposite impacts in space [229]. Implementing conflicting principles creates a deadlock in spatial decisions.

An overarching planning conflict that emerged in MRA (See Propositions 1B) was maintaining its fixed planning structure with a robustly engineered water system versus making it flexible to future changes. A risk-based conflict also arises when a city must manage prolonged droughts while increasing green cover to mitigate the impacts of urban heat islands. A thematic dispute arises between meeting goals for climate adaptation and energy transition when *"Buildings with rooftops must find a trade-off between using the roof space to store water from rainfall or to install solar panels to generate energy"* (P3).

MMR participants recommended striking a balance between flexibility and rigidity, like imposing strict regulations to protect natural resources but a flexible approach for all local areas to absorb growth. Counter-intuitively, P36 emphasized that increasing flexibility in local area plans will only benefit private developers in a hugely market-driven economy. Hence, planners must prioritize the land's endemic and endogenous potential before setting flexible norms.

In urban morphology, a conflict arises in decision-making for increasing density versus adopting low-impact, medium, or low-density. Dense centers are known for their Efficient urban form for better transport accessibility and lower energy consumption which is desirable for building resilience (P27) [12]. However, the same density increases concentrations of the at-risk population leaving less space for rainwater infiltration and increasing susceptibility to urban heat islands [121, 230]. Several MMR participants endorse medium-density ecological planning to offset the impacts of a dense urban footprint around existing business districts. Few participants strongly argue against this, since loosely regulated ecological planning leads to uncontrolled urban sprawl. Practitioners recommend making clever connections between urban systems to use opposing responses to advantage and avoid undesirable temporal trade-offs and deadlocks. P2 proposes a balance of *"one-third fixed structure two-thirds diversity"* in an urban plan to keep it responsive to changes.

Proposition 3: On Planning Under Uncertainty

Proposition 3. *Renewal, redevelopment, and maintenance of urban systems present an entry point to integrate or align with emerging risks and to change scenarios - through iterative learning. These entry points are essential to overcome the aversion to uncertainty planning prevalent in existing practice.*

Long-term planning requires responding to a changing environment. Participants emphasized the need to integrate climate goals at the conceptual planning stages rather than bearing high re-investment costs later (P8,9,10). However, new and greenfield development opportunities are limited in urban regions already built up, like in the MRA, or are incredibly dense, like in the MMR. A planning challenge for MRA was *"to replace the entire City of Amsterdam"*, referring to a large stock of urban infrastructure waiting to be renewed that can potentially become resilient (P14). Similarly, MMR's routine planning is dominated by redevelopment projects which present a lucrative opportunity to review old regulations and adopt a new perspective to manage uncertainties expected in the lifecycle of a system (P5, P34). However, MRA and MMR participants critique that planning encourages experimentation and empowers errors essential to nurturing innovation (P7, P33). Hence, renewal, redevelopment, and maintenance of projects or individual urban systems become entry points to integrate new variables and standards.

Proposition 4: On Overall Planning Responses

Proposition 4. *Mainstreaming climate in long-term urban planning requires that cities present multiple urbanization strategies within formal planning documents that can proactively adapt based on changing scenarios.*

The *Methodological* approach to urban planning under uncertainty proposes consideration of the full range of future scenarios to manage unforeseen changes and offer appropriate responses (Section 3.2). Variations in strategies may include reconfiguring and recombining planning responses for different urban systems that require different degrees of 'transitional,' 'incremental,' and 'transformational' changes.

MRA adopts this by proposing multiple strategies for individual urban systems like water, energy, and transport, anticipating future changes. However, the final urbanization strategy that brings these systems together is one master plan. The fixed master planning regime does not possess the flexibility to update plans for multiple degrees of 'transitional,' 'incremental,' and 'transformative' changes [6]. MRA also benefits from well-researched climate scenarios, leading to a single climate adaptation strategy.

MMR plans for a single scenario without anticipating any variation, which goes against long-term thinking as an evolving process open to changes. Long-term planning under climate change will require considering changing futures and their impacts on different urban systems based on their lifecycles. These can be developed using a combination of *Predictive (forward-looking)* and *Normative (inverse-looking)* approaches to planning. For instance, cities can adopt predictive approaches to plan for changing capacities of *Networks* like energy and mobility. Normative approaches can be adopted to preserve *Natural Resources* in the same state for the future.

3.6 Conclusion

The need to plan for uncertain futures has led to the realization that planning theory must present methods to systematically integrate rapidly

changing insights. In this study, we take the first steps towards an enhanced understanding of long-term urban planning for climate uncertainty. We develop a conceptual framework (Figure 3.2) that bridges two critical streams of literature essential to future urban planning: *Urban Resilience Principles* (Section 3.2) and *Approaches to Urban Planning Under Uncertainty* (Section 3.2). To develop the conceptual framework, we draw upon the sprawling academic literature on urban resilience and the limited literature on planning approaches under uncertainty. We connect the two theories by systematically assessing how they manifest in space through *Planning Responses* and their impacts on *Urban Systems*.

We use the conceptual framework to analyse two case studies .

We use an exploratory approach to derive insights from 39 interviews with senior practitioners across two contrasting case studies from the Global North (Metropolitan Region of Amsterdam (MRA)) and Global South (Mumbai Metropolitan Region (MMR)) that offer contextual, theoretical, and geographical variations to address the gap in planning. An exploratory approach provides initial insights into planning patterns and formulates propositions for future investigations into other case studies. We then use systematic analysis to unpack the thinking processes behind climate-related planning responses, challenges, opportunities, and planning values that are similar and dissimilar.

To connect theoretical and empirical findings in a scientifically robust manner, we use a Multi-case analysis together with Systematic Combining. It enables deriving detailed insights on the knowledge and procedural aspects of using resilience theories and approaches for planning under uncertainty (See Figure 3.6, Figure 3.7).

The cross-case analysis illustrates the need to integrate long-term climate goals at the regional scale. Participants in both cases criticized the lack of flexibility in the planning process and the low mentions of uncertainty. The dissimilarities lay in the level of maturity of planning, capacity gaps, the absence of well-researched climate scenarios, and the debate between outcome-oriented and open-ended planning.

Based on theoretical and empirical findings, we formulate four propositions to reflect on the current gaps for a theory on long-term urban planning under climate uncertainty that focus on:

- Bringing flexibility in planning processes to integrate changing variables for long-term planning continuously.
- Resolving spatial trade-offs among resilience principles that have opposite impacts in space for long-term urban planning strategies to work (such as between achieving Robustness versus Flexibility).
- Renewal, redevelopment, and maintenance of urban systems as an entry point to integrate or align with emerging risks.
- Drafting multiple urbanization strategies within formal planning documents that can be proactively adapted based on changing scenarios.

Implications for Urban Resilience and Planning Under Uncertainty. Participant P17 mentions that *"As an operative notion, resilience is extremely useful because it forces you to embrace complexity and unpredictability in urban planning."* Although resilience theory has evolved into a global discourse, most literature continues to emerge from a Global North point of view that has benefited from a well-structured, standardized approach

to planning [120]. In conclusion, we hope this study contributes to advancing the conceptual understanding of resilience and uncertainty using place-based research in the Global North and South.

Future research. The study's exploratory nature is a starting point to formulate broad propositions that can be used to investigate other case studies using the conceptual framework. The study acknowledges that each planning context is unique and requires different resilience and uncertainty approaches, enabling researchers to test further the propositions presented in this study and to reinforce a theory for long-term urban planning. Expanding this study to more case studies will be necessary to arrive at a generalizable understanding of integrating resilience in urban planning for climate uncertainty. Concerning planning for uncertainty, a key line of inquiry is temporal dynamics in urban planning and how that differs between the GN and GS to enable strategies and implementation of long-term goals. An additional line of work would be to dive deeper into spatial aspects using long-term urban scenario building, combining theoretical and real-world insights. This can enable the drafting of dynamic urbanization strategies that can adapt over time.

TIMEWISE
Temporal Dynamics for Urban Resilience

4

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Increasing frequency of climate-related disruptions requires transformational responses over the lifecycles of interconnected urban systems with short- and long-term change dynamics. However, the aftermath of disruptions is often characterised by short-sighted decision-making, neglecting long-term urban shifts. In this study, we present a first attempt to develop the theoretical foundation for temporal dynamics for increasingly disrupted yet "connecting and moving" cities that can be used in planning for urban resilience. Using the lens of climate urbanism, we conceptualise the interplay of temporal dynamics to empirically examine how planning practice perceives and addresses temporality in two regions - Amsterdam, the Netherlands, and Mumbai, India. Our findings reinforce that disruptions do not inform long-term planning. Endogenous and exogenous dynamics of change are not viewed together nor used to embed short-term planning goals within long-term resilience visions. To address the lack of systematic planning approaches that can leverage temporal dynamics, we propose two options for temporally flexible urban planning processes.

Keywords: *Urban dynamics, urban planning, resilience, cities, global south, uncertainty, disruptions, temporalities, urban and infrastructural rhythms.*

4.1 Introduction

The IPCC's 6th Assessment Report emphasizes the urgent need for cities to adapt to climate change and prepare for extreme events, especially in developing regions [231]. Hence, urban environments have become the focus of climate policy and implementation of resilience goals [232]. In this study, we refer to urban resilience as [14, 16] *"the ability of an urban system to maintain or rapidly return to desired functions in the face of disruptions, shocks or stresses"*. Currently, resilience research has two main streams: (1) emphasizing urban transformation and adaptation through substantial changes of infrastructure systems and services [15]; (2) focusing on rapid recovery from disruptions [233]. Despite interest in leveraging disasters for long-term transformation [3], evidence suggests that they do not lead to policy change [234]. We hypothesize that the inability to leverage disaster response for adaptation and urban resilience transition is due to the disconnect between the associated timescapes/ temporal dynamics in the urban environment.

The need for urban transformation under climate change is uncontested. For instance, addressing the IPCC's warnings to limit global warming within a decade [187] requires transformational responses over the lifecycles of interconnected urban systems [235]. Planning for urban resilience

becomes challenging as cities must reconcile changes and disruptions across the short-, medium- and long-term [236]. While the field of urban studies has made progress in understanding the temporal dynamics of cities [237–239], it is primarily focused on the lifecycles of urban (infrastructure) systems that impact their design, implementation, maintenance and renewal. While urban lifecycles span several decades, planning theory has remained conservative, wherein formal decision-making timeframes are short-term (around 20 years), linear and fixed. Pressing urban issues tend to be quick-fixed by planning authorities using interventions [200] that inadequately account for long-term change dynamics and disruptions [237].

Given the short-term focus of urban planning, responses to disruptions mainly prioritize rapidly restoring the status quo ante, ignoring the need for a broader transformative agenda. This is because urban systems are influenced by temporal path dependencies or regimes that are predetermined by planning authorities (such as regional governments and municipalities), which are often resistant to changes and focus on *"bouncing back"* [24, 188, 238]. As a result, short-sighted and siloed planning interventions lead to lock-ins that jeopardize long-term goals. Failure to grasp these dynamics leads to fragmented planning and undesirable investments that could result in cascading risks [240] and become a roadblock to achieving resilience and sustainability goals [241, 242].

For cities to manage resilience and sustainability transitions while responding to intensifying disruptions [187], urban planning must be considered a function of multiple timescapes of change. Understanding the inherent temporal dynamics of urban systems is key to leveraging disruptions to transform short-term planning responses into long-term solutions. However, currently, a disconnect exists between literature on disaster recovery and the field of adaptation and transition, resulting in a lack of systematic planning approaches to leverage and integrate the time dimension into decision-making [15, 243].

To address this gap, the objective of this research is to make the first attempt to develop the theoretical foundation to conceptualise major temporal dynamics for increasingly disrupted, yet "connecting and moving" cities such that it can be used in planning for urban resilience. Our three research questions are: (1) How can we synthesise diverse temporal urban dynamics to plan for urban resilience? (2) How do existing urban planning approaches account for the different temporal dynamics? (3) How can we design temporally flexible planning processes that consolidate an understanding of the different urban timescapes? By addressing these questions, ultimately, this study aims to provide arguments supporting a shift in urban planning and policy-making to account for multi-level temporal dynamics.

We follow a three-step qualitative process. First, we provide the theoretical background using three lines of inquiry. We follow it up by conceptualising the interplay between two dimensions of temporal dynamics in urban planning (endogenous lifecycles and exogenous drivers). Finally, we investigate planning approaches against the backdrop of these two dynamics.

Second, we use multi-case analysis [107] to examine the associated dynamics within the context of urban planning in two contrasting case studies. The research acknowledges that urban resilience research has focused on cases from the Global North [17, 244], resulting in limited approaches tailored for the fast-growing cities in the Global South. To

provide a more balanced perspective, we work with the following cases: the Metropolitan Region of Amsterdam (MRA) and the Mumbai Metropolitan Region (MMR). The resulting insights can subsequently inform the design of theory and approaches that can be tested, validated, and applied in a broader range of settings in the Global South and North. As such, even though the findings are grounded in the contexts of Amsterdam and Mumbai, they aim to contribute to a broader understanding of urban temporality.

Third, we design vignettes of temporally flexible urban planning processes that consider major temporal dynamics of urban systems. We demonstrate how planning timeframes could be adjusted to align with different timescapes and facilitate forward-looking decisions under climate disruptions.

Three lines of Enquiry to conceptualise temporal urban dynamics

Urban systems are driven by two major dimensions of temporal dynamics: *Endogenous lifecycles* (such as speed & duration of change, rhythms of urban systems including their renewal and decay) and *Exogenous drivers* (extreme climate events, disasters, economic shifts). Understanding the two dynamics with very different timescapes for decisions requires approaches to harmonise both within the formal timeframes of urban planning (typically spanning up to 20 years.

The theoretical starting point for endogenous dynamics is Wegener's theory of urban change [245]. It characterizes temporal dynamics based on the *Speed* and *Duration of change* [246]. *'Time geography'* concept describes human activity, using geometries such as cubes and prisms representing the scale and speed of change [247]. *Urban DNA* [248, 249] deciphers or shapes cities based on spatial form, growth speed [250] as well as velocities of infrastructure flows, lifespans, ageing, and seasonal demands. [239].

Next, Blumenfeld's theory of spatiotemporal dynamics was one of the earliest contributions that described urban growth as waves [251] - vital to understanding rhythms and lifecycles in urban expansion. Social scientists further built upon the notion of rhythms[252] to conceptualize spatiotemporal cycles of change using *Chronotopes* that link places to recognizable dynamics [253]. Next, Lefebvre's *Rhythmanalysis* focused on repetitive rhythms in cities [254] and described three modalities of rhythms: *Repetition* of periodic tasks, *Cycles* of decay; and *Periods of "birth, growth, peak, decline and end."*

Finally, an urban environment is *polyrhythmic*, It consists of nested fast-changing behavioural rhythms resulting from live-work patterns [255] and slow-changing physical rhythms [256]. Importantly, as is true for other social or social-ecological systems [142], urban systems that change slowly set the conditions within which faster and smaller behavioural rhythms emerge. Yet, research suggests that over 90% of urban investments are incremental and often overlooked in research[257], which hinders the consideration of mid-cycle corrections and changes crucial for long-term resilience [258].

Exogenous drivers

Exogenous drivers include climate change disruptions and disasters that accelerate or impede the speed of urban change [257]. The low points of resilience created by disruptions reveal windows to bring in abrupt but transformative changes in urban systems [15, 258, 259]. Yet, especially in the aftermath of disruptions, planning and policy conventionally become trapped in the '*tyranny of urgency*' [260], focusing on rapidly re-establishing the status quo ante instead of pursuing long-term agendas. Exogenous drivers also come in the form of disruptive technologies (like electric vehicles, sharing economy, ICT) which drive rapid reconfiguration of conventionally slow-changing urban systems. *Catastrophe theory*, [261, 262] explains non-standard urban changes such as rapid emergence of places, real estate bubbles, depopulation of cores, and rebuilding cities post disasters. However, no systematic planning approach has leveraged disruptions as intervention points that can be consolidated ex-post with long-term transformative goals.

Planning under climate change requires combining incremental and transformative planning responses [263] across the short-, medium- and long-term. Currently, planners use formal planning timeframes spanning between 5-20 years. Within this timeframe, planners identify changing insights and align them with decision-making windows for different urban systems [263, 264]. The timescapes for formal planning and decision-making for urban systems are often conflict ('arrhythmia'), leading to deadlocks in decisions [265]. The disjuncture in dynamics is further reinforced by capacity and knowledge gaps.

Fig. 1 illustrates the interplay of two major temporal dynamics in urban planning that must be aligned and harmonised for achieving long-term resilience goals. The X-axis is *Time* representing *Urban planning timeframes of up to 20 years* in which decisions must be made for multiple urban systems. Y-Axis represents *Endogenous lifecycles* of five major urban systems, i.e. the period over which an urban system decays or can be renewed. It also illustrates Exogenous drivers and disruptions that impact urban systems (red). To account for the temporal heterogeneity of urban systems, we use the *Urban Layers Approach (ULA)*, which classifies urban systems into five groups based on their lifecycles [81, 211]:

1. *Layer 1: Unplanned/Open spaces*: Retention parks, traffic intersections, parking lots (1-10 yrs).
2. *Layer 2: Occupation*: buildings, neighborhoods (3-50yrs).
3. *Layer 3: Focal Points*: multi-model hubs, train stations, airports (5-50yrs).
4. *Layer 4: Networks*: highways, railways (10-100yrs).
5. *Layer 5: Natural Resources*: wetlands, national parks (20-100+yrs).

Fig. 1 also shows that urban systems are in different stages of their lifecycles at any given time. However, conventional planning decisions are focused at the beginning or endpoint of the lifecycles of urban systems where they have decayed or fulfilled their functions [266]. Mid-course corrections or modifications are challenging to account for within planning timeframes, where such decisions have to be made for multiple systems with different temporal dynamics. Hence, they remain disconnected from the overall plan. For instance, *Planning Timeframe A (black)* includes the beginning or ends of lifecycles of several urban systems (both short and long-lived). The lifecycles present windows to integrate new insights. Whereas *Planning Timeframe B (grey)* includes the beginning or ends of

only a few short-lived urban systems, subsequently offering few opportunities for change. Further, restrictive formal planning timeframes (up to 20 years) hinder adapting to abrupt disruptions crucial for transitioning to long-term climate-resilient futures, even if these disruptions affect all urban systems (red in Fig. 1).

Table 4.1: Synthesizing and summarizing commonalities and differences between the findings for the two cases: Metropolitan Region of Amsterdam (MRA) and Mumbai Metropolitan Region (MMR).

Results	Commonalities	Differences
Finding 1: Short-lived urban rhythms and tactical urbanism dominate in the face of lock-ins, rendering long-term planning futile	Both regions prioritize alleged "quick wins" through incremental responses in urban systems with short lifecycles. Both have fixed timeframes for planning.	MRA recognizes the long-term transformation process and the importance of incorporating multiple nested temporal frames within a single planning timeframe. However, the underlying master plan remains static, limiting its adaptability to change. MMR participants do not discuss long-term strategies, as there is a lack of adherence as well as significant delays in the implementation of master plans.
Finding 2: Disasters fail to inform transformative urban change	Both cases acknowledge the role of disasters as catalysts for change	MRA's approach to planning for resilience after disasters and outlier events remain erratic and abstract MMR develops concrete interventions for disaster management, but is highly reactive, and not aligned with risk-informed plans or policies.
Finding 3: Overtly structured planning approach in MRA and the prescriptive approach in MMR are restricting temporal flexibility in planning.	Both cases discuss the dynamics of urban renewal, maintenance and transformation as temporal windows to integrate resilience.	A history of structured planning in the MRA has created inertia in existing planning and policy-making, hindering their ability to adapt or respond effectively to disruptions despite ample future projections. MRA engages in concrete planning approaches incorporating urban layers, enabling tangible strategies. MMR's approach is conservative, prescriptive, and mechanical, relying on past metrics and market forces and exhibiting limited flexibility to change.

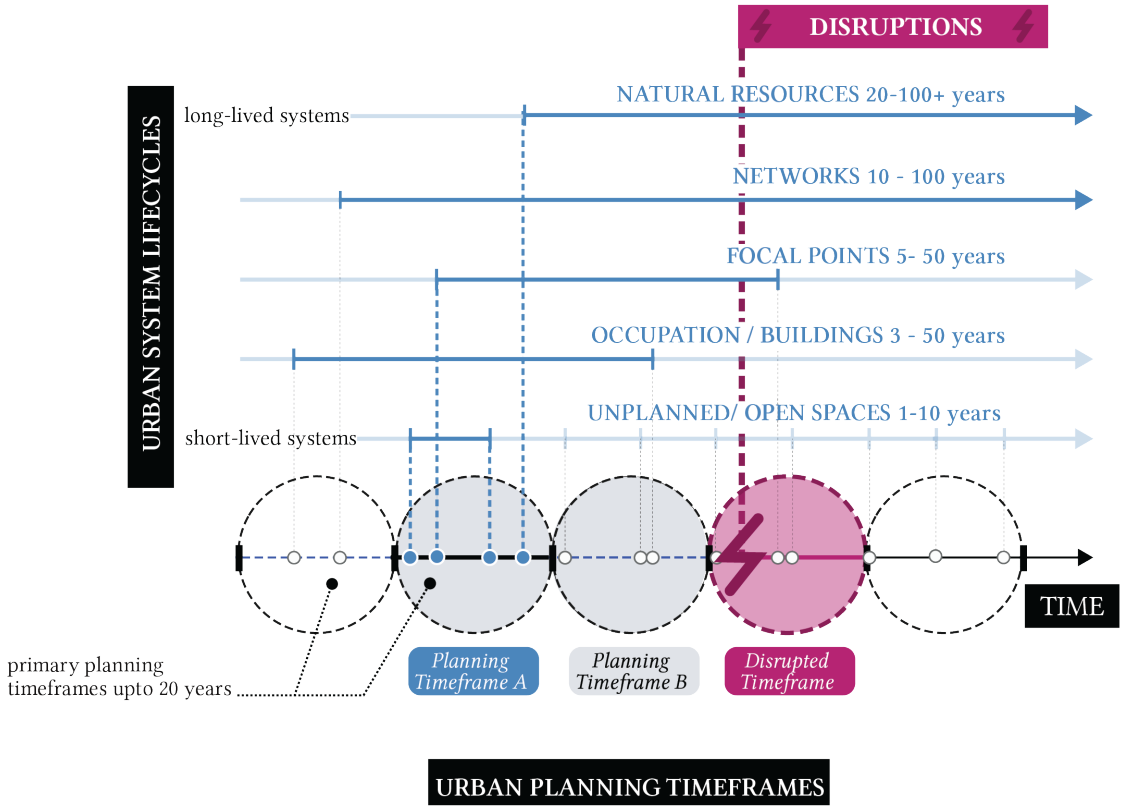

Figure 4.1: Conceptualising the interplay of two major temporal dynamics in urban planning that must be aligned and harmonised for achieving long-term resilience goals
(1) X-axis: TIME - representing *Urban planning timeframes of up to 20 years* in which decisions must be made for multiple urban systems.
(2) Y-Axis: *Endogenous lifecycles* of five major urban systems, i.e. their lifecycles of renewal and decay (various colours); and
Exogenous drivers and Disruptions that impact urban systems (red)
Urban systems include short-lived systems that can be renewed every 3-10 years (unplanned spaces) to long-lived systems that last beyond 100 years (natural resources). Within a single planning timeframe, different urban systems are at different stages of their lifecycles, which must be harmonised or realigned to manage climate stresses and shocks. However, mid-course corrections or modifications in urban systems are often not accounted for in planning timeframes.
Planning Timeframe A (black) includes the beginning or ends of lifecycles of several urban systems (both short and long-lived). The lifecycles present windows to integrate new insights, thus becoming a critical juncture in managing urban change.
Planning Timeframe B (grey) includes the beginning or ends of only a few short-lived urban systems, which offer fewer windows to integrate long-term change.
Disrupted Timeframe (red) are a result of exogenous drivers and climate-change-related disruptions. This timeframe must be leveraged to bring long-term systemic transformation [3]. However, empirical evidence has shown that disasters do not lead to policy change.

4.2 Results

Across both cases, participants acknowledge the need to formulate and implement long-term visions and align the dynamics of different urban systems to plan for resilience. They highlight the role of exogenous drivers in bringing about transformative change. For planning approaches, participants spoke both to the possible enablers of considering temporal dynamics such as scenarios, storylines, and high-level strategies as well as the barriers that prevent long-term planning in practice. In the following, we formulate three main findings reflecting the three lines of enquiry of temporal urban dynamics outlined above, reflecting upon the specific context of Mumbai Metropolitan Region (MMR) and Metropolitan Region Amsterdam (MRA). Table 4.1 synthesizes and summarizes commonalities and differences between the findings for the two cases. In addition, Table 4.3 and Table 4.4 present a clear overview of the frequency of themes and quotations from the interviews.

Finding 1 (Endogenous Lifecycles): Short-lived urban rhythms and tactical urbanism dominate in the face of lock-ins - rendering long-term planning futile.

Endogenous lifecycles illustrate the speed & duration of change in different urban systems, including their renewal and decay.

MMR: While participants emphasized the importance of interventions in long-lived urban systems, concrete climate strategies predominantly focus on bottom-up approaches in short-lived systems, such as plot-level adaptation and rooftop rainwater harvesting. Long-term thinking is sporadic, mainly observed in systems like transport, which provide the spatial structure for urban expansion. Planning discussions focus on *"solving urgent problems rather than central ideas"* [P22] or *"alternatives for future development"* [P23]. [P36] clarified that *"India's planning is stuck in a 10-year time step"* forced by financial and political processes that align to this temporal frame. Mega-infrastructure projects are viewed as catalysts for urban transformation. However, planning beyond 20 years is considered counterproductive *"given the speed of technology and climate change"*[P36].

P29 cites the *"shortsightedness of planners* as obstacles to resilience thinking. As MMR experiences rapid growth and invests in long-lived systems, it needs to adopt a risk-informed approach to planning. However, P21 confirms that *"MMR hasn't been able to actively integrate risk or climate projections in long-range planning decisions or visions."*. Delays in the acceptance and implementation of plans render the original assumptions and projections outdated, leading to asynchronicity with the lifecycles of urban systems [P35] .

MRA: has developed programs to consolidate tactical local-level responses for climate adaptation, exemplified by initiatives like Amsterdam Rainproof [217]. The initiative aims to capture and channel excess rainwater into planned and unplanned spaces, buildings, and neighbourhoods - largely short-lived systems.

Having said that, we observe that MRA still acknowledged endogenous lifecycles better than MMR, as it must conserve and renew older infrastructure systems while meeting resilience and sustainability goals. P7 explicitly stated that *"planning and policies must account for multiple and nested temporal frames within a single planning timeframe."*. However, the underlying masterplan or urbanization concept that ties systems together is static. P1 explained that there is *"an overarching resistance to change"* and, P3 confirmed this by stating that *"We need to try to not make very big investments, where they are locked-in."*

Synthesis: While participants in both cases acknowledge the importance of long-term thinking in theory, the high densities and existing lock-ins in MMR and previous locked-in investments in MRA limit the scope for spatial readjustment necessary for transformative change. Hence, climate-related strategies tend to be tactical, targeting fast-changing urban systems and immediate returns, with limited examples of long-term investments. This results in a prevailing belief that long-term planning is futile and counterproductive in meeting resilience goals.

Further, MMR and MRA develop formal urban plans with fixed timeframes of 20-30 years, aligning with the definition of 'short-term' provided by the IPCC. Participants in both cases endorse the need for flexibility in plans, suggesting modifications every 1-5 years [P7,P27,P31] or every 10-20 years [P14] . However, multiscalar temporal planning is neither explicitly discussed nor fully understood. Instead of embracing and planning for complexity, P1 & P34 recommended that *"interconnected (urban) rhythms must be cut loose from each other"*. However, in a complex environment, this is not feasible.

Finding 2 (Exogenous Drivers): Disasters fail to inform transformative urban change

Exogenous drivers include climate change disruptions, disasters and shocks that may accelerate or impede the speed of urban change.

MMR: MMR experiences recurrent flooding disruptions, including the 1-in-100-year mega-flood (2005). While the event led to a surge of reactive interventions such as weather stations and floodwater pumping facilities [267], it did not lead to risk-informed urban policies. P25 endorsed that *"In consultations on climate and disasters, they* [the city] *will always discuss traffic, parking, and waste management issues*." Despite recurrent flooding, land continues to be reclaimed for development in low-lying areas [P39]. P33 stated the urgent need for courageous trade-offs and to accept trial-and-error planning mechanisms to use disasters as an opportunity for building region-wide resilience. Current strategies are deemed insufficient to effectively manage extreme events [P21,P35,P36,P38]

MRA: In the Netherlands, the 1953 flooding disaster catalysed a shift in flood management from relying on historical metrics to focusing on future probability [268]. The Western Europe flood (2021) also renewed interest in resilience planning, especially for outlier events [269]. However, risk management in the Netherlands is driven by a 'protection' approach, where *"people trust the national government and high dikes to protect them"*. [P5].

Synthesis: Systems shocks and disruptions are low points of resilience that break, shift or reset temporal dynamics, revealing windows for transformations. In line with that, MRA & MMR participants expressly acknowledge the role of disasters as catalysts for change. However, planning practice treats disasters as *'episodic events'* [P30] and does not use them to bring in long-term, systemic change. Integration of disruptions or disasters as temporal windows in urban planning, especially under climate change, remains abstract and is not implemented systematically [P2].

A. Endogenous Dynamics (Speed, Duration & Rhythms)

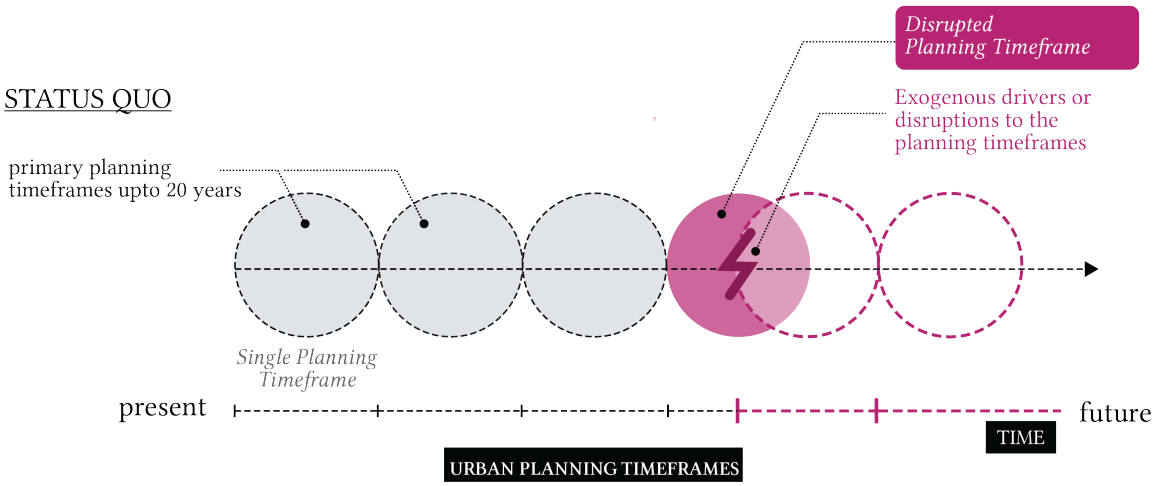

Figure 4.2: Illustrating the current status quo of urban planning. Planning is myopic to the long-term implications of urban change. It follows a fixed, linear sequence of around 20-year periods (grey circles). It may have smaller incremental time steps within to update plans due to exogenous drivers such as politics, industrial lobbies or technology.
Under disruptions (in red), the planning timeframe is reset, and cities fall back on re-establishing the status quo. Due to the restrictive nature of planning, recovery processes extend into future timeframes, impeding long-term resilience goals.
Hence, cities are stuck with tactical, small-scale technical planning where they continue to promote incremental alleged 'quick wins' in urban systems with short lifecycles. Harmonization of nested temporal frames is discarded as it is too complex.

Finding 3 (Planning approaches): Overtly structured planning in MRA and prescriptive planning in MMR restricts temporal flexibility.

Urban systems are influenced by temporal dependencies and tools utilised by conventional planning institutions such as regional governments and municipalities, which are often resistant to change.

MMR: MMR's planning approach is broadly characterised as *"conservative, prescriptive & mechanical"*, where decisions rely on past metrics and market forces and are largely inflexible to temporal changes [P29, P30, P35, P36, P38]. Physical planning is done at the level of land parcels using mathematical restrictions [P21, P37], leaving little flexibility to integrate additional climate goals. MMR does not have an official repository of land-use changes, nor do participants discuss tools or approaches to utilise temporal dynamics. A critical factor hampering well-coordinated, flexible responses is the lack of a vision or 'attractor', which is essential to attaining alternative development trajectories [15]. In addition, proper

implementation of original plans in MMR is weak, further exacerbating the gap between planning timeframes and the lifecycles of urban systems [P29,P37]. Hence, project implementation routinely deviates from the original plan [P29,P33] , resulting in ineffective channelling of positive path dependencies required to meet long-term goals .

MRA: Although the Netherlands is exploring the dynamics of individual systems using the 'urban layers approach' [81], its planning approach is characterised as '*too structured*' by participants. The plan's inertia to change [P1] extends to planning policies and climate adaptation strategies that use fixed scenarios despite the uncertainties acknowledged [P7,P9] . MRA's urban planners discuss flexibility by keeping several options open and avoiding negative path dependencies, even if the system is inflexible [P3,P4]. To some extent, participants discuss concrete planning approaches identified in literature, notably urban landscape dynamics [270], as MRA benefits from a national record of historical land-use changes. Participants propose the development of abstract visions [P1], storylines [P8], and scenarios for changing dynamics. While scenarios are developed nationally, they are not yet downscaled to the metropolitan region scale where plan implementation happens [P3,P13].

Synthesis: Reflecting the need to consolidate lifecycles of old and new infrastructures in a complex environment, MRA participants discussed the dynamics of urban renewal and transformation as a path to meet resilience goals [P5]. Similarly, MMR emphasised renewal and maintenance as the sole temporal windows that offered flexibility in a hyper-dense region. However, such approaches are time-consuming and focused on one fixed point in time. Given the relatively short time available in the aftermath of disruptions, visions and storylines would need to be (re-)developed continuously to ensure they are available and ready for use when (climate) disaster strikes.

A critical outfall of not accounting for temporal dynamics is that plans and policies become outdated earlier than expected. For instance, Amsterdam's Structure Vision (2012) for 2040 became outdated within a few years as the city grew faster than expected [P3, P4] . Similarly, MMR's Regional Plan 2014-2034 was sanctioned only in 2021 [P37].

The barriers to incorporating temporal thinking

Participants across MRA and MMR acknowledge the necessity of reconciling multi-temporal goals in planning. However, interviews in both regions indicated no systematic consideration of temporal aspects in urban planning. Processes are based on a fixed point in time and consider urban systems to be in temporal equilibrium.

Figure 4.2 presents the status quo of urban planning processes (representative of both cases), which follow a fixed sequence of 20-year periods (which may have shorter time steps within to update plans). Hence, cities are stuck with small-scale tactical planning where they continue to promote incremental interventions in urban systems with short lifecycles. Harmonization of nested lifecycles is discarded as too complex as there are no clear mechanisms, processes or incentives to enable long-term planning. Hence, policies are often outdated, and the relevance of thinking across temporal scales is not valued.

Under disruptions, the planning timeframe is reset, cf. Figure 4.2. Cities fall back on re-establishing the status quo soon after disruptions due to the shortsighted and restrictive nature of planning. Processes of recovery and re-calibration of development goals extend into future timeframes, impeding long-term resilience goals. Finally, both cases demonstrate an aversion to non-confirmative planning processes, with a fear of failure and strong inertia to change. They promote the perception that long-term planning is futile and further discourage planners from pushing longer-term temporal boundaries, essential to manage climate disruptions. P17 warns that *"the climate crisis has bypassed us as even an issue that needs to be considered politically"*.

4.3 Three lines of enquiry: Endogenous lifecycles, Exogenous drivers of change and Planning approaches

The starting point of this research is to develop the empirical and theoretical foundation to conceptualise major temporal dynamics for "connecting and moving" cities planning for urban resilience. It argues that planning must be rooted in understanding temporal dynamics for transitioning to urban resilience under climate disruptions and supporting progress towards the SDGs. Our main finding is that even though the need for understanding and utilising different timescapes of urban planning is recognized, there is a noticeable absence of planning theories and approaches to put this concept into action. As a result, current planning overlooks the complexities of preparing for a long-term future impacted by climate disruptions.

We synthesise existing literature along three lines of enquiry - endogenous lifecycles, exogenous drivers of change and planning approaches towards climate change. We complement this with empirical interviews in two climate ambition case studies to explore real-world planning approaches and their temporal dynamics.

We find that practitioners' perspectives [P5,P10,P29] are largely consistent with literature that emphasises embedding resilience in urban systems with long lifecycles [10, 271, 272]. This is, however, in sharp contrast to *Finding 1*, where climate-related interventions focus on 'quick wins' in systems with short lifecycles . Tactical urbanism measures are adopted when institutional gaps or resource scarcity hinder sustained, long-term responses to risks [57].

Both cases acknowledge disruptions from disasters and climate that shift urban rhythms drastically and open up intervention windows. While literature endorses the role of disruptions as opportunities for planners to implement transformative adaptation measures and enable mid-course corrections in systems to extend or revise their lifecycles, our interviews indicate that planning remains fixed and unresponsive. Despite disruptions, the focus is primarily on building back the status quo ante. The overarching vision or 'attractor' required to implement transformative resilience goals is missing and cannot be developed in the few weeks or months available to plan for the recovery from disruptions.

Utilising temporal dynamics requires explicit consideration of short-, medium- and long-term interventions, aligning, realigning and negotiating them into formal planning timeframes. A critical challenge is the

integration of uncertainties. The lack of flexibility in planning approaches leads to lock-ins resulting from undesirable investments. Overall, only 3-4 participants, notably in the MRA, explicitly discuss flexibility in planning when drafting new development plans and urbanization strategies [P1,P2,P6,P22] . Overall, the findings reflect the stark contrast between the perception and practicalities of temporal dynamics. They highlight the methodological gaps in why current urban planning cannot utilise temporal flexibility. Enhanced understanding of temporal dynamics will require existing planning theory to acknowledge the limitations of practice, increasing the emphasis on adapting planning policies over time as well as better monitoring systems to deal with anticipated and unanticipated changes.

To leverage temporal dynamics in urban planning, we design vignettes of temporally flexible urban planning processes that consider endogenous lifecycles and exogenous drivers in Figure 4.3. We contrast them with the status quo of urban planning (Figure 4.2) to highlight how planning timeframes could be adjusted to leverage disruptions to enable forward-looking decisions. The options are prototypical vignettes whose advantages, drawbacks and implementation requirements are discussed below.

Both options feature a primary (grey) and secondary (green) timeframe (Figure 4.3). The primary timeframe* serves as the primary window for decision-making and serves as the key temporal unit for exploring flexibility and variations. The influence of exogenous factors and disruptions is depicted in red. Option 1 (Nested Timeframes) introduces two timeframes: 20 years (primary) and 100 years (secondary). Typically, a two-tier planning process involves a national strategy and a regional strategy (like in MRA). The secondary timeframe (green) allows for monitoring slower-changing systems like water or transport. It offers flexibility under disruptions to adapt to changes and facilitate abrupt transformations by guiding adjustments in primary timeframes. This enables the derivation of explicit requirements and goals for *each* primary planning timeframe, which can be translated into planning visions for short-lived systems. Option 1 may work well in regions like MRA with well-established spatial planning and the capacity to create multiple strategies, given that the urban fabric is also not changing dramatically. MRA already integrates long-term sectoral visions into its national adaptation strategy. However, in rapidly evolving regions like MMR, heavily investing in new urban systems, a fixed long-term vision may hinder adaptation to the dynamics of emerging urban systems.

Option 2 (Flexible timeframes), similar to Option 1, presents a short-term primary planning timeframe (grey) guided by a long-term secondary timeframe (green). Both timeframes are flexible and can adapt to changing planning variables. Option 2 goes beyond Option 1 as the secondary timeframe can acknowledge dynamics of short- and long-lived urban systems and guide incremental decisions within primary timeframes. Decisions could range from major projects to consolidating measures in local rainwater harvesting interventions, developing amphibious neighbourhoods or re-hauling the water or energy systems.

Both timeframes can adapt during disruptions, aligning with shifting short-term goals and long-term vision, promoting harmonisation. It offers flexibility to add extra planning layers (shorter or longer than the primary timeframes) after significant disruptions for rapid recovery without compromising long-term resilience. This approach demands a highly

* Primary timeframe: typically 5-30 years for major urban regions, e.g., MRA and MMR

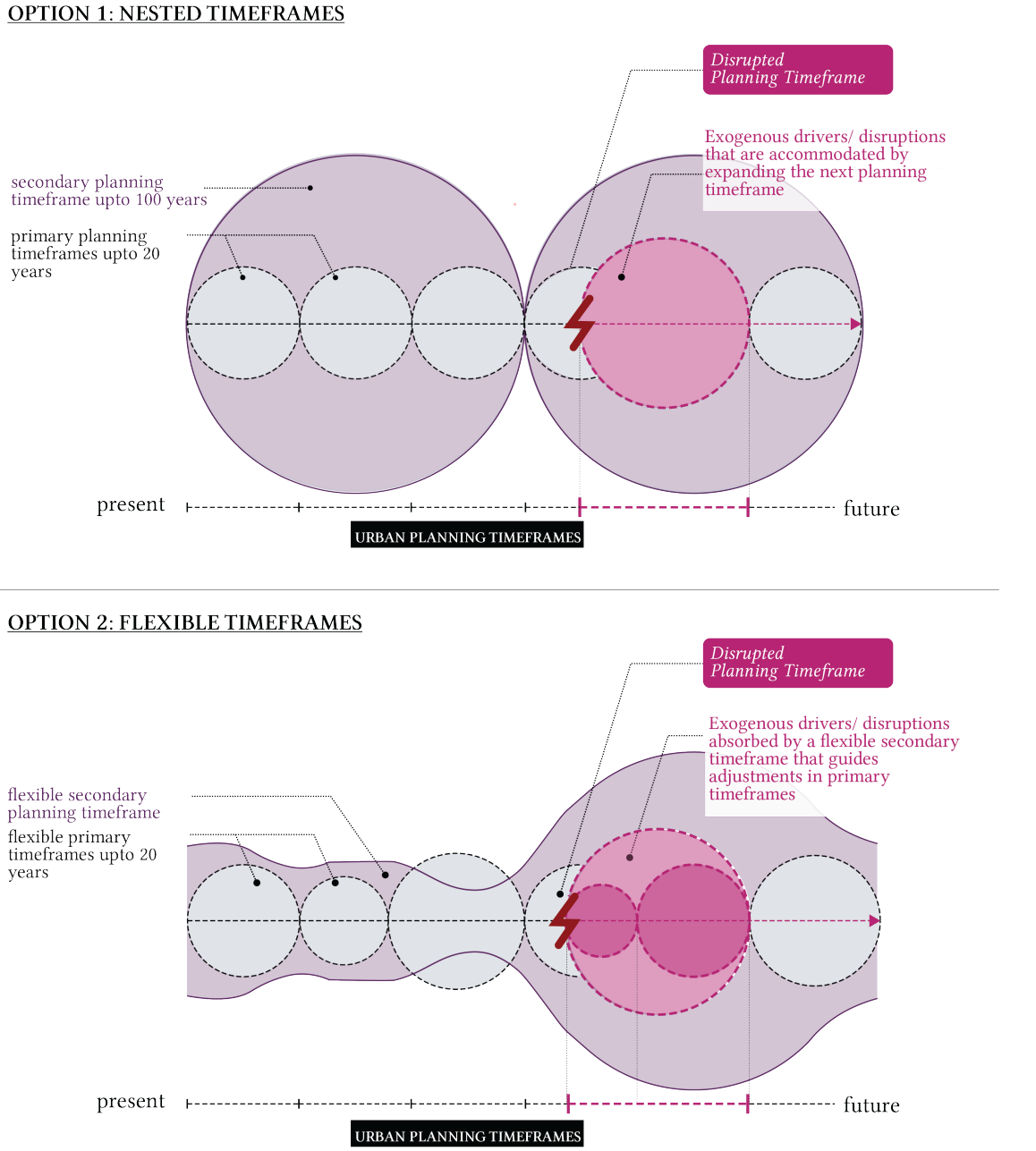

Figure 4.3: Exploring prototypical vignettes of temporally flexible urban planning processes. We demonstrate how current planning timeframes (in grey circles) could be adjusted to leverage disruptions (in red), harmonize lifecycles of urban systems and enable forward-looking decisions for urban resilience.
(a) In **Option 1 (nested timeframes)**, we propose two nested plans for the *same* spatial scale. Under disruptions, the secondary timeframe (in green) offers the room to absorb changes or enable transformations by guiding adjustments in primary timeframes (in grey). It allows monitoring changes in systems with longer lifecycles, such as water or transport networks.
(b) In **Option 2 (Flexible timeframes)**, both timeframes are flexible and can evolve due to changing planning variables. The secondary timeframe (in green) allows consideration of the impacts of major endogenous lifecycles of long-lived urban systems and guides incremental decisions within each primary timeframe. Under possible disruptions (in red), both timeframes can adjust and re-align with changing objectives.

responsive planning and governance system to monitor, understand and capture the right variables to bounce forward after a disruption. Clear markers and monitoring are crucial to initiate new responses; without them, the plan becomes vulnerable to political powerplay and urgent development agendas and may fall back to the status quo.

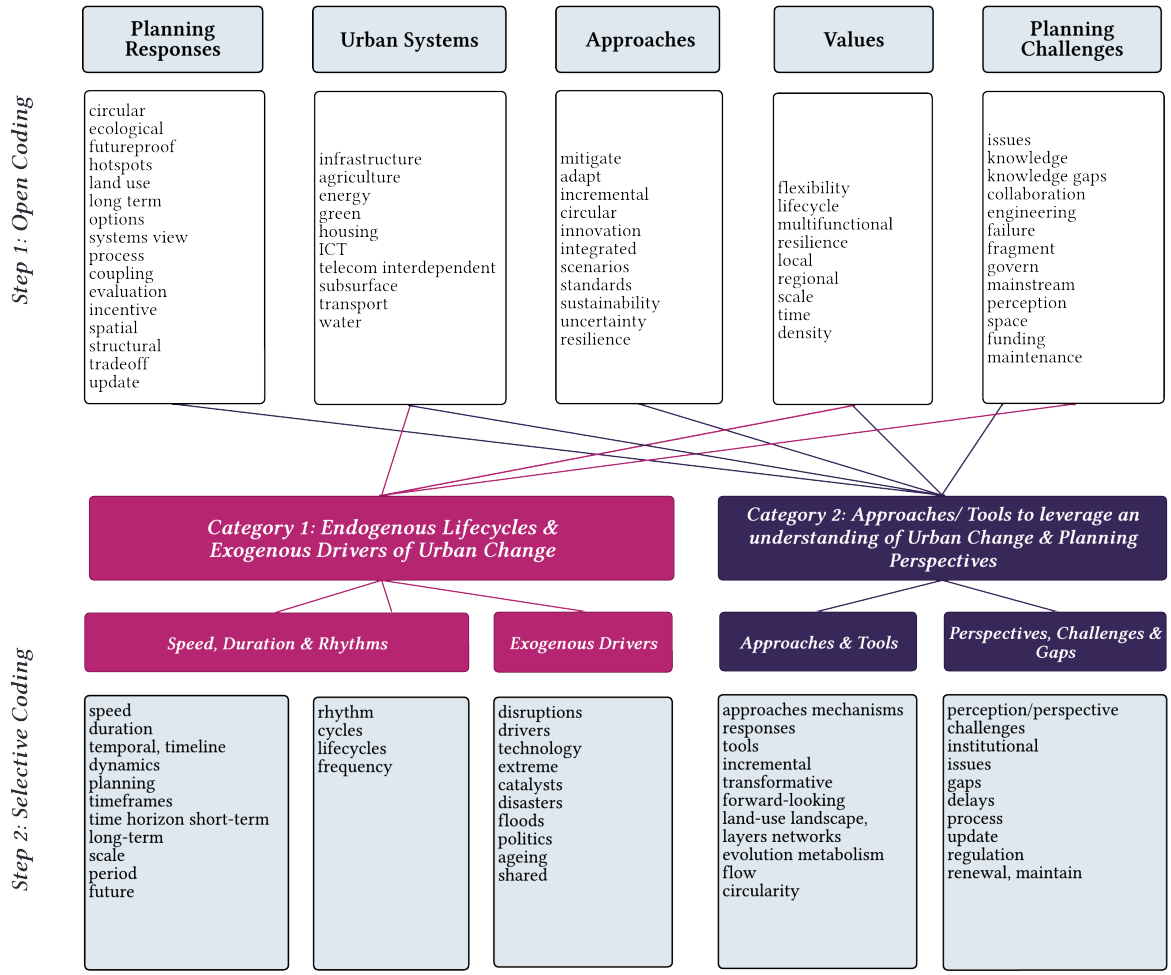

Figure 4.4: Two-step qualitative coding scheme used for the analysis of interviews for MRA and MMR. Findings are organized under two main coding categories:
Category-1: Endogenous Lifecycles/ Rhythms & Exogenous Drivers of Urban Change (in pink)
Category-2: Planning Approaches: Tools to leverage an understanding of Urban Change & Planning Perspectives on Urban Change (in blue)

This option could potentially become effective when regions review their development objectives every few years due to accelerating climate change, paving the path for newer insights. It enables a two-way knowledge exchange between the primary plan and the long-term vision. A downside of offering high flexibility for planning a region like MMR with significant capacity gaps is that it might not effectively regulate interventions between the two timeframes.

This paper investigates the synthesis of major temporal dynamics (endogenous and exogenous) of urban change for resilience. It uses the synthesis to propose two options for temporally flexible urban planning processes to manage climate disruptions. While understanding and implementing temporally flexible planning processes is already challenging for planners, doing so under climate disruptions compounds the problem. Leveraging disruptions to achieve urban resilience requires moving away from decision-making solely at the end of the planning timeframe or an urban systems' lifecycle towards making changes mid-cycle or in moving time intervals where insights can be continuously integrated and harmonised. Several participants recommend updating plans every few

years, which allows the opportunity to implement new insights, provided there are policies for it [P5,P7,P14,P27,P31,P36].

Currently, in the absence of such temporal considerations, P3 expressed aversion to making big investments, whereas participants in both cases recommend formalising renewal and maintenance of infrastructures as temporal windows for updating insights [P5,P6,P14,P32] , which is a key area for further research.

Introducing mid-cycle changes in urban systems also requires a reliable knowledge base on their condition, accessible to planners. Lack of data or outdated data are cited a major roadblock to planning in the MMR [P35]. The Netherlands however has a publicly available repository of building construction and age. A similar system may be scaled up for other urban systems. This also allows for finding couplings between urban systems to capitalise on resilience opportunities.

This study expands on primary research on temporality in less-studied and rapidly changing urban contexts of the Global South. MMR exhibits different perspectives and resistance levels for achieving urban resilience. As an emerging region, it benefits from relatively fewer structural lock-ins to adopt newer temporal planning processes [273]. However, theoretical findings indicate resistance to respond to changes due to rigid and unresponsive planning regimes and negative path dependencies embedded due to past investments [24, 238]. Our interview findings suggest no strategies or thinking in that direction, making it essential for future research.

This study recognizes the distinctiveness of various planning contexts and emphasizes that these case studies do not represent the only city 'types' in the Global North and South. The theoretical foundations developed in this can be expanded by researching other cases. Nonetheless, the significant urbanization characteristics displayed by our case studies offer the necessary diversity for this research.

The planning vignettes (Figure 4.3) are initial steps to reorganize planning processes for leveraging temporal dynamics. They must be adapted for specific regions. Planners have access to tools like scenario thinking, visioning, model-based decision-making, climate projections, and improved data availability. Understanding temporal dynamics in the Global South also requires examining emerging, non-standard growth patterns, such as informal settlements [P32,35,36]. Ultimately, this study urges a methodological shift in urban planning and policy-making processes to account for multi-level temporal dynamics.

Table 4.2: Combined Participants grid for MRA (P1 to P20) and MMR (P21 to P39) classified based on their role in the urban planning process and their domains of expertise. 'X' indicates that we did not receive responses from the right participants from that domain (Table borrowed from [274], a preceding study by the authors of this study focusing on resilience in urban planning for climate uncertainty).

	Role in the urban planning process			
Domain	Strategic/ Policy Advisors/ Bureaucrats	Academic Researchers	Sustainability/ Climate/ Environment/ Engineers	Urban Planners
Urban Planning, Geography	P1, P2, P26, P30, P33, P38	P11, P20, P34, P35, P36	P3, P15, P18, P27	P4, P5, P17, P19, P21, P22, P37, P39
Climate and disaster risks, environmental planning	P6, P7, P9, *P24, P28*	P10	P12, P31	P8, P13, P23, P25
Infrastructure	P14, P16, P29	X	P23	X

4.4 Methods

This section discusses the research approach, case study selection, data collection, and analysis. In this study, we make the first attempt to develop the theoretical foundation for major temporal dynamics "connecting and moving" cities that can be used in planning for urban resilience.. The objective is to understand, through empirical insights from contrasting case studies in the Global North and Global South, how urban planning deals with temporal dynamics.

Case Studies
We use multi-case analysis to assess contextual variability in the case studies and combine it with the conceptual lines of enquiry derived from the literature. Amsterdam and Mumbai, located in the Global North and Global South, respectively, were selected due to the contextual and cultural variation they offer to examine planning processes, perspectives and institutional characteristics of decision-making. Both regions have solid financial and cultural functions and are undergoing urban regeneration, ranging from massive infrastructure renewal and maintenance to investments in new infrastructure and adaptive reuse. Their dual ambitions to meet development goals while tackling climate disruptions frame the opportunity to derive diverse insights.

Case Study 1: Metropolitan Region of Amsterdam (MRA), Netherlands: The MRA is an advanced urban economy with robust formal planning structures, well-coordinated investments, consensus-driven political processes, and [111]. It is an agglomeration of 32 municipalities housing 2.48 million people spread over 2580 sqkm. Its urbanization strategy includes climate ambitions for 2050 and identifies vital urban systems that must become resilient under climate change. Future growth involves consolidating and streamlining temporal dynamics of renewing ageing infrastructure, building a large volume of housing, and transitioning to a fossil-fuel-free economy [275]. 70% of MRA is vulnerable to one or more risks, such as extreme heat, rainfall, prolonged droughts, and sea-level rise.

Case Study 2: Mumbai Metropolitan Region (MMR), India: The MMR is a developing economy where planning is a mix of formal and informal processes. It is an agglomeration of 9 major municipal corporations housing 26 million people spread over 6355 sqkm, making it amongst the most populous metropolitan areas in the world [276]. Its regional planning strategy includes high-level actions for climate change, but they are not integrated with infrastructure and land-use aspects. MMR's future growth involves capitalising on temporal dynamics to invest mindfully in a large volume of long-lived new infrastructure, including metros, industrial corridors, airports, high-speed rail, and coastal roads. MMR was originally built on reclaimed land, and large portions along the coast lie below the high tide level. Hence, planning must respond to chronic disruptions from flooding and heat waves coupled with inadequate infrastructure.

Data Collection and Interview Design
We conducted 39 semi-structured interviews with senior practitioners who work on four critical domains in urban planning: (a) Urban Planners; (b) Strategic/ Policy Advisors/ Bureaucrats; (c) Academic Researchers; and (d) Specialists in Sustainability/ Engineering. The interviews were

conducted over one year (2020-21) online using Zoom/Teams calls due to travel restrictions during the Covid-19 pandemic. Each interview was approximately 60 minutes long.

To select interview participants, we used a combination of snowball sampling, personal referrals, and social media (LinkedIn) to shortlist 200 participants, of which 20 were selected for MRA [participants P1-P20] and 19 for MMR [participants P21-P39].

The interview questions were structured into three main sections (derived from the three lines of enquiry from the literature) to derive insights into Endogenous dynamics, Exogenous drivers, and Planning approaches. Using findings from the literature review, the questions investigated the characteristics and associated gaps for each line of inquiry through participants' accounts of how they understand and work with temporality, such as planning duration/ timeframes, urban infrastructure lifecycles, the role of disruptions and their integration into planning processes. Section C.3 presents an indicative semi-structured interview protocol with full documents disclosed under

DOI:10.4121/6952ac97-2753-4f4b-b9bc-8e65968d81e6[277]. We conducted a systematic qualitative data analysis of interviews to interpret the text and derive insights along the three lines of inquiry to extend theoretical insights. We developed a corpus of interviews by transcribing the voice recordings and memos written during the interviewing process. Each case was analyzed separately using two-step uniform qualitative coding.

In *Step-1*, we used open coding to extract broad findings on experiences in urban planning responses and climate change, urban systems, broad approaches, planning values and challenges. In *Step-2*, we used *selective coding* to extract findings under two main coding categories to investigate the lines of enquiry and gaps derived from the literature (Figure 4.4).

Category-1: Endogenous Lifecycles (pink) & Exogenous Drivers of Urban Change (violet): Characterising urban change (speed, duration, & rhythms, planning timeframes); external drivers (extreme events, disruptive technologies and political shifts).

Category-2: Approaches/ Tools to leverage an understanding of Urban Change & Planning Perspectives on Urban Change (blue): Specific approaches and tools to assess temporal dynamics of the urban landscape, networks, and flows; participants' perspectives and challenges in long-term thinking (institutional issues, delays).

Open coding was conducted by four student researchers. The heterogeneous participants used different terminologies to describe similar concepts of planning and temporality. Hence, to keep the coding consistent, the researchers were provided with an exhaustive list of 77 codes encompassing various aspects of the interview responses, which were double-checked by the authors with the support of one student assistant. Next, selective coding was conducted by the authors to investigate the themes relevant to this study. Detailed documents on the interview process, including the detailed interview protocol, consent forms, list of questions and codebooks, are available at DOI:10.4121/6952ac97-2753-4f4b-b9bc-8e65968d81e6 [277].

Table 4.3 and Table 4.4 enlists the coding categories, terms included under each category, and example quotations. We quantified the codes,

Table 4.3: Overview of discussions under Coding Category 1: Endogenous Lifecycles/ Rhythms & Exogenous Drivers of Urban Change. It highlights concepts discussed by participants in both cases including frequency of codes and example quotes. [Amsterdam participants (MRA): P1 to P20; Mumbai participants (MMR): P21 to P39)]

S.no.	Coding sub-category and Terms	Mentions	Participants	Example Quotes
1	SPEED & DURATION speed, duration, temporal, dynamics, planning, timeframes, time horizon, short-term, long-term, scale, period, future	112	P3, P6, P7, P29, P30, P34, P36, P38	P7: "Planning and policies must account for multiple and nested temporal frames within a single planning timeline." P30: "When you do a city as large as Mumbai, obviously, you cannot make short-term plans." P38: "The speed of the temporal and statutory cycles is a mismatch."
2	RHYTHMS *rhythm, cycles, lifecycles, frequency*	9	P1, P7, P9, P14, P30, P36	P1: "MRA acknowledges different elements with different frequencies and rhythms. Cut these rhythms loose from each other." P7: "Planning and policies must account for multiple and nested temporal frames within a single planning timeline." P14: "Is it future-proof?" Is it able to absorb changes? Can it be easily replaced in 10-20 years? you should make that in such a way that it can be easily replaced in 10-20 years." P36: "India's planning is stuck into a 10-year time step because the census is a ten-year time step."
3	EXOGENOUS DRIVERS OF URBAN CHANGE drivers, technology, extreme, disruptions, catalysts, disasters, floods, politics, ageing, shared	94	P1, P11, P13, P25, P27, P29, P30, P34, P36	P1: "Only when there is a big event like an earthquake or flood or a bombarding, then we change the layout of the city." P11: "Political roadblocks in planning approaches and horizons might be preventing effective climate adaptation." P29: "MMR acknowledges the role of system-shocks and disasters in driving urban transformation." P36: "For a rapidly urbanizing region, a vision for 20 years is too long given the speed of technology and climate change."

Table 4.4: Overview of discussions under Coding Category 2: Approaches/ Tools to leverage an understanding of Urban Change & Planning Perspectives on Urban Change. It highlights concepts discussed by participants in both cases including frequency of codes and example quotes. [Amsterdam participants (MRA): P1 to P20; Mumbai participants (MMR): P21 to P39)]

S.no.	Coding sub-category and Terms	Mentions	Participants	Example Quotes
1	APPROACHES & TOOLS approaches, mechanisms, responses, tools incremental, transformative, forward-looking, land-use, landscape, layers, networks, evolution, metabolism, flow, circularity (pertaining to urban metabolism studies)	95	P1, P2, P3, P5, P6, P7, P8, P10, P24, P29, P30, P33, P34, P35, P36, P38	P2: "Make an abstract vision for the future. Then it works out in different programs that can change so you can be flexible." P8: "There are techniques to link (flood) return periods to planning storylines, but the future will evolve differently, but at least think of some catastrophic storylines." P33: "The more you are in reactive response mode, the lesser time and resources to devote for strategic thinking." P34: "We need a multilevel framework for assessing (long-term) trade-offs for coastal roads, overhauling the drainage systems." P35: "Temporality of the informal landscape cannot be assessed using existing approaches as they cannot be fully regulated." P36:"Development could be controlled using transit networks which offer a spatial structure for future growth...with long lifecycles".
2	PERSPECTIVES, CHALLENGES & GAPS: perception, challenges, institutional, issues, gaps, delays, process, update, regulation, renewal, maintain	119	P2, P3, P5, P7, P8, P21, P29, P30, P33, P35, P37	P3: "Amsterdam's Structurevision (2012) became outdated soon after its release as the city grew faster than expected." P5: "Policies to implement climate norms will always be dated. How do you allow the policy design to respond and go beyond what is set in stone?" P29: "Projects with long gestation periods are hard to implement as planners can't even see beyond three years." P37: "This lag in planning and implementation timelines cascades to day-to-day decision-making which then stretches to several months."

dived into the associated quotations, and went back to the interviews to position them in the broader context of this research. We conduct a cross-case assessment to observe the similarities and differences between the cases.

Data Availability Statement

All interview data in this study were collected through a GDPR-compliant framework and with approval from the Human Research Ethics Committee (HREC) at the Delft University of Technology, the Netherlands. The publicly available datasets supporting the study's findings may be accessed at DOI:10.4121/6952ac97-2753-4f4b-b9bc-8e65968d81e6 [277]. Restrictions apply to the availability of the interview participants' personal data per the consent received by all participants. Datasets containing personally identifiable information are for verification and validation only; they may not be used for further research and are available upon request until March 2025, after which they will be deleted.

Code Availability Statement

Qualitative data coding and analysis of interviews was conducted using software *Atlas TI* (Version 9).

FutureScapes

A Design Thinking Approach to Blending Computational Models and Scenario Narratives for Urban Futures.

5

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Accelerating urbanization and the inherent uncertainty in urban planning are increasing the demand for approaches that meaningfully integrate qualitative insights with quantitative analysis. While scenarios are widely used to explore multiple urban futures, existing methods that combine narrative storylines with computational models face persistent challenges: narrative assumptions are often oversimplified during translation; model structures frequently lack transparency regarding their underlying assumptions; and integrative processes tend to prioritize consensus, often sidelining the specialized insights of practitioners essential for urbanization strategies. Design Thinking (DT) offers a promising framework to address these limitations through its iterative, non-linear structure that bridges creative and analytical reasoning.

Yet, a systematic, reproducible workflow that operationalizes DT for urban scenario development remains underdeveloped. This paper introduces FutureScapes (FS)*, a stepwise Design Thinking methodology for blending computational models and scenario narratives that embeds expert feedback into the modelling process. FS centers the spatial reasoning of expert stakeholders and introduces semi-quantitative boundary objects - in the form of scenario design maps - to break the traditionally linear sequence from story to simulation.*

This enables a reflexive process where model outputs actively reshape qualitative scenario assumptions to inform policy-relevant outcomes. The study contributes a generalizable methodology that enhances the contextual relevance, transparency, and strategic utility of computational scenario modelling for regional urban planning.

Keywords: *Scenario planning, Design Thinking, scenario development, planning support systems, blended tools, land use modelling, urban land use, urban spatial dynamics.*

5.1 Introduction

Rapid urbanization is making urban planning increasingly complex and uncertain. To navigate this uncertainty, planning practitioners use scenarios as analytical tools to explore alternative futures shaped by diverse *factors* (e.g., economic trends, climate change), *sectors* (e.g., housing, transportation), and *actors* (e.g., government agencies, private developers, local communities) [103, 207, 278–280]. Urban scenarios - whether qualitative (discursive) narratives or quantitative (computational) models - play a central role in long-term urban planning and policy-making. Together

they can enable the exploration of complex interdependencies to inform strategic decision-making under uncertainty.

The growing attention in academic literature to large-scale urban models as well as statistical models, cellular automata, agent-based simulations - alongside their increasing use in practice - highlights the need to improve modelling processes by harmonizing computational advances with practitioners' preferences to enhance the decision usefulness of modelled scenario outputs for planning and policymaking [281–283]. However, this demand remains unmet.

Qualitative narratives, often in the form of descriptive storylines, are widely used to explore urban futures, including under unprecedented conditions such as climate change [207, 284–286]. They enable high-level assessments of complex urban environments by considering multiple quantifiable and non-quantifiable variables, values, design preferences, and trade-offs. They are prone to cognitive biases and typically involve a limited number of scenarios, which may result in overconfidence or oversimplification of complex realities [279, 287, 288]. Further, they may lack the scalability and system-level detail required for informing metropolitan urbanisation strategies.

In contrast, computational models can quantify interactions between multiple socio-technical-environmental variables [101, 103, 280], generating hundreds or even thousands of scenarios to explore urban futures [101]. However, computational models come with their own algorithmic biases and hidden assumptions [289]. Choices regarding data, algorithms, and parameters shape what can and cannot be represented, which may not reflect the design preferences or spatial reasoning of urban practitioners. Despite longstanding calls for greater transparency [290], proprietary "black-box" models often obscure these assumptions, leading to generic outcomes or a false sense of certainty [291–295].

Despite advances in participatory scenario methods and modelling techniques, there is a lack of robust approaches that integrate the contextual knowledge of expert stakeholders into computational urban models [64, 295]. A persistent challenge remains in linking creative, exploratory narratives with the analytical rigor and scalability of computational models, without compromising either the model's fidelity or the scenario's relevance [296, 297].

Integrative Scenario Approaches

Established traditions have sought to couple computational models and narrative storylines through stakeholder engagement include GeoDesign [298–302], Story and Simulation (SaS) [297], Model-driven exploratory scenarios, Participatory Scenario Planning (PSP) [303], and sketch planning tools [304]. The above approaches are particularly effective in democratizing the planning process by involving a broad spectrum of stakeholders and prioritizing urgent needs of citizens and communities to foster inclusive dialogue [305].

A prominent strand is **Geodesign**, which provides workflows linking design propositions with geospatial or analytical models [298, 306]. While Geodesign has demonstrated the value of collaborative spatial deliberation [307, 308], its emphasis typically lies in *evaluation* and testing of the scenario in the model environment and not using that to reflect on the initial scenarios itself.

A second body of work concerns **Model-driven Scenarios**, which also includes Exploratory Scenario Planning (XSP) which utilize expert judgment for parameterisation of scenarios into models. Large-scale regional initiatives, such as the *Engaging the Future* project and modelling of the Baltimore–Washington region [309], utilize computational models to explore policy-sensitive futures. Influential frameworks by Avin and colleagues [294, 310] support the coupling of scenario formulation with model-based evaluation. These methods treat qualitative reasoning as a pre-defined input that is parameterized through expert judgment.

A third body of literature on **participatory modelling** provides frameworks for co-producing scenarios with stakeholders [311]. While these approaches prioritize collaborative sense-making, they frequently focus on consensus and trust-building and broad social learning as primary outcomes. Consequently, frameworks such as Public Participatory GIS (PPGIS) or community-based modelling can be ill-suited for the **technical and regulatory complexities** inherent in large-scale masterplanning [312]. In these contexts, the strategic rigour required to navigate institutional constraints and technical fluency in land-use and socio-economic dynamics often necessitates the **situated knowledge of expert practitioners** over broad-based community elicitation [296, 313, 314].

In the above approaches, the "story-to-simulation" pipeline is still a one-way translation and there is limited attention to how qualitative narratives can be reshaped when experts engage with the emergent outputs of land-use simulations. Hence, their influence in generating grounded, actionable scenarios that directly inform masterplanning or urbanisation policies become limited which can reduce their relevance for spatial planners tasked with managing complex feedbacks and interdependencies [286, 297, 315–317].

The Hypothesis

We hypothesize that Design Thinking (DT) - a systematic, iterative, and user-centred approach - can meaningfully contribute to the formulation of long-term urbanization strategies by enabling effective engagement with complex "wicked problems." DT has been widely adopted in business innovation and product design for its non-linear, exploratory structure that supports early experimentation, incorporation of diverse perspectives, and learning from failure. Its methodological flexibility is essential for addressing ill-structured, multidimensional challenges in the urban environment that lack clear, definitive solutions [42, 119, 318–321].

The FutureScapes Approach

To test the above hypothesis, this paper introduces *FutureScapes (FS)* - a design-thinking-led approach to scenario development that systematically blends the strengths of narrative storylines with the analytical rigour of computational models through iterations. Grounded in core principles of DT - such as prototyping, ideating, and iterative refinement. FutureScapes provides a structured yet flexible approach to enable experts to iteratively move back and forth between narratives and spatially grounded model outputs to support a responsive and policy-relevant modelling workflow to inform regional growth strategies.

FS aims to enable a transparent assessment of underlying assumptions, trade-offs, and expert preferences, thereby strengthening the alignment

between model outputs and real-world planning constraints, thus supporting more inclusive, adaptive, and accountable urban planning practices. FutureScapes is demonstrated through its application in the Metropolitan Region of Amsterdam (MRA), the Netherlands.

By positioning the expert practitioner at the center of the synthesis, the approach introduced scenario design maps as semi-quantitative **boundary objects** [322, 323]. The objects visualise the scenarios and serve as a mediating interface between the worlds of strategic narratives and of land-use modeling, facilitating a feedback loop to break the strict linear sequence from story to simulation. The feedback triggers what Schön (1983) terms **'reflection-in-action'** [319], where the map becomes a "spatial probe" that allows experts to refine quantitative parameters through their nuanced, tacit, and value-based preferences.

Unlike broad participatory tools such as PPGIS, which often struggle to reconcile citizen data with the technical and regulatory density of formal planning [312], this expert-centric approach leverages the **situated knowledge** of practitioners [313]. This allows for the integration of non-standard spatial logics—such as complex institutional or regulatory constraints—that conventional land-use models typically overlook, ensuring that the resulting scenarios are both computationally rigorous and institutionally plausible.

Acknowledging the technical density of regional strategic planning, FutureScapes deliberately establishes a methodological 'expert guardrail,' prioritizing the situated knowledge of senior practitioners to ensure policy relevance. This ensures that the resulting scenarios are technically robust to withstand the scrutiny of professional decision-making that typical participatory methods may lack. Hence, *FutureScapes* is intended as a novel complementary methodological contribution to the field of urban analytics and integrated scenario development.

5.2 Using Design Thinking to Combine Scenarios Narratives and Models

Urban planning is often characterized by institutional risk aversion and deep-rooted path dependencies, which significantly constrain practitioners' capacity to respond to uncertainty, and ongoing transformations [30, 32]. Planning approaches that embrace uncertainty or acknowledge failure - such as *Design Thinking* - find limited uptake in mainstream strategic planning, particularly in contexts demanding long-term foresight [41].

Blending qualitative narratives with computational models necessitates careful consideration of the respective strengths and limitations associated with each technique [297, 324, 325]. Qualitative narratives are valuable in urban planning for surfacing context-specific knowledge, stakeholder perspectives, and long-term uncertainties that are not easily quantifiable [93, 279, 326]. However, narratives often suffer from vague terminology (epistemic uncertainty) and conflicting stakeholder values (normative uncertainty), which complicate their translation into formal model inputs. Their inherently unstructured nature and lack of standardized formats also hinder comparability, reproducibility, and iterative refinement [104]. In contrast, computational models - while capable of generating a large number of internally consistent scenarios through rule-based simulations [293, 327, 328] - often contend with structural uncertainty (incomplete or inaccurate representations of the system) and aleatory uncertainty

(randomness or variability) when extrapolating from historical data [136, 207]. A model's reliance on historical training data limits its utility in exploring unprecedented futures, such as climate extremes or institutional transformations [283, 329].

Furthermore, narratives are commonly parameterized into models using direct estimation by practitioners, numerical ranges, or fuzzy set methods (e.g., defining variable ranges or interdependencies such as high/low increase or strong/weak impact). However, much of this nuance may be lost in translation. The opacity of computational models often hinder intuitive interpretation and stakeholder engagement, restricting feedback on scenario assumptions and parameters [288, 330–333].

5.2.1 Design Thinking in Urban Planning

Public institutions - particularly municipal governments - are increasingly exploring *Design Thinking (DT)* as a strategic tool in urban planning through innovation labs, policy design studios, and co-creation platforms aimed at reconfiguring the inetraction between planning expertise and community input [43]. This shift reflects a broader recognition that traditional planning approaches, which often rely on top-down models or linear forecasting, struggle to address the complexity and contested nature of contemporary urban challenges.

Following this trend, emerging research positions DT as a critical framework that can bridge the epistemological and operational gap between narratives and models [334–336]. DT is known to go beyond functioning as a mediating method and introduces a process aligned with the inherently iterative, negotiated, and future-oriented character of urban planning [44].

Specifically, DT offers three core capabilities essential for urban planning: (1) divergent–convergent thinking, which fosters exploration, experimentation, and creativity; (2) visual reasoning through sketching, mapping, or prototyping, enabling practitioners to spatially interpret abstract policy goals and narratives [278, 337, 338]; and (3) iterative refinement and feedback, which supports learning through adaptation.

The above capabilities align closely with the demands of urban planning practice, positioning DT as an important approach in the context of long-term planning, where linear, technocratic approaches often fall short and combining diverse data and knowledge streams consistently is essential [339–341].

The current implementation of DT in urban planning - particularly within long-range, strategic processes - can best be described as fragmented and underdeveloped [42–44].

First, DT's methodological openness can become a limitation. While its flexibility encourages experimentation, it often leads to inconsistent or improvised applications in planning contexts [342]. Without a clearly defined structure, DT may appear ad hoc in high-stakes environments, reducing its credibility in formal planning settings that require procedural transparency, reproducibility, and accountability.

Second, despite DT's growing popularity in participatory contexts, its adoption in technically demanding planning at regional or metropolitan scales remains limited. Activities such as spatial modelling, scenario testing, or infrastructure forecasting require structured data inputs, formal

logic, and robustness - areas where DT methods are often not integrated [343, 344]. As a result, DT tends to function at the periphery of strategic planning, generating engaging insights that are difficult to reconcile with technical workflows.

Third, DT's human-centred orientation - while critical for inclusive scenario-making - can inadvertently amplify dominant perspectives or short-term priorities. In complex planning environments, this may marginalize slower-moving, large-scale considerations of regional trade-offs, which require structured representation [288, 345].

Although existing DT frameworks such as the Double Diamond, IDEO model, or the Hasso Plattner model are frequently cited, few, if any, urban planning projects systematically operationalize them through all their steps. In practice, DT is reduced to isolated tools - workshops, canvases, stakeholder mapping - detached from a coherent methodology [43]. This limits its ability to contribute meaningfully to scenario development, particularly in contexts that require integrating different input types and addressing the constraints of both qualitative and quantitative scenario techniques (Table 5.1).

Long-term Urban Scenario Development as a Design Challenge

We argue that combining narratives and models is fundamentally a **design challenge**, going beyond purely methodological or analytical concerns. Integrative scenario development necessitates mediating competing values, navigating spatial trade-offs, and constructing scenarios as multifaceted artifacts - characteristics that mirror the 'wicked problems' defined in design theory [348]

Table 5.1 presents a Comparative analysis of the characteristics of qualitative scenario narratives and quantitative scenario modelling techniques. It then explains how Design Thinking can be operationalised to combine the two for urban scenario development.

We drew upon the building blocks of a scenario development process for public sector practitioners by [279], which outlines tensions between predictive versus explorative scenarios, data-driven versus deliberative methods, and expert versus stakeholder roles. We assesses approaches for linking exploratory scenarios to different planning contexts from [296], particularly around institutional relevance, integration, and communicative value in urban scenario work. The table discusses how DT contributes value in combining the two approaches, by: **1. Providing Decision Support** in formulating and assessing long-term urban scenarios by informing the selection of scenario inputs [R1], enhancing explainability and engagement [R2], working within constraints [R3] and generating actionable outputs [R7]; **2. Integrating Flexibility** in the scenario development process by explicitly accounting for uncertainties [R4], addressing multiple spatial scales [R5], and accommodating diverse data types [R6].

Specifically, DT's principles, as outlined in the Hasso Plattner / Stanford Design Thinking Model [349–351], address the following integration challenges: *Empathy* helps reveal underlying values to inform scenario-building in context; *Define/ Problem framing* treats scenario development as the design of decision-support tools, rather than predictive modelling exercises. It can enable identification and adaptation of constraints of both

Table 5.1: Comparative analysis of the characteristics of qualitative scenario narratives and quantitative scenario modelling techniques - indicating how Design Thinking (DT) can combine the two. We discuss the potential of Design Thinking to (1) Provide **Decision Support** in formulating and assessing long-term urban scenarios; (2) Integrate **Flexibility** in the scenario development process.

S.no.	Design Thinking Step	Aspect	Qualitative Narratives	Quantitative Model	Potential for Design Thinking (DT)
R1	Empathize	Selection of Inputs	Qualitative/ Subjective: Desk research, empirical methods, participatory processes.	Quantitative/ Measurable: Numerical assumptions, forecasts, trends, statistics	DT can help identify foundational variables and values through interviews, focus groups, document analysis, and ethnographic observations and combine them with model assumptions to ensure the simulations are grounded in local realities [279, 296, 334–336, 346].
R2	Empathize - Test	Explainability and Engagement	Enhanced problem perception, high-level analysis of complexity, assessing qualitative aspects (values, conflicts, and trade-offs), fosters ownership	Calibrated, data-driven, high spatial resolution, incorporates several datasets, account for complex interactions	DT can support engagement with underlying scenario assumptions, socio-spatial context and trade-offs, through discussions with experts - linking scenarios to lived realities [43, 117, 279, 347]. It can further support learning loops, iterative refinement through expert walkthroughs, backcasting exercises, and stress-tests where spatial consequences prompt a reflective iteration of the initial qualitative narrative logic.
R3	Define	Addressing Constraints	Consideration of few macro-variables, tendency to oversimplify complex narratives, validation, replicability	Data scarcity, modeller's bias and model's limitations, false certainty, relies on trend extrapolation, lack of ownership/transparency, resource intensive, difficulty in interpretation (black box).	DT can enable identification and adaptation of constraints of both qualitative and quantitative techniques, through collaborative scoping or problem framing to establishing boundaries via SWOT/PESTLE analysis. This could reduce overconfidence of modelled outputs and support critical reflection. [280, 346].
R4	Define - Test	Uncertainties Considered	Epistemic (lack of knowledge), linguistic (imprecise language), subjective (personal judgment), normative (values, beliefs)	Aleatory (inherent randomness), epistemic (variables unclear), structural (model structure), computational (methods, algorithms)	DT can potentially foreground and communicate uncertainty through prototyping, divergent thinking, using Impact-Uncertainty Matrices [136], reflexive spatial probing and reframing to define which qualitative drivers require computational quantification to help for long-term planning [280, 296, 346].
R5	Ideate	Multi-scalarity	Considers multiple spatial scales to develop and evaluate scenarios.	Works with predetermined spatial scale(s) for simulations. Some models may offer a second scale that must be clearly defined at the outset	DT can potentially support exploring the impacts of urban scenarios across spatial (and temporal) scales through encouraging divergent-convergent thinking, design exercises, mapping and co-design workshops to help link local decisions to regional or global dynamics [336, 338, 347].
R6	Ideate - Prototype	Diverse Data Types	High-level/historical trends, design choices, policy documents, experts' perspectives, pictures/visions, values/beliefs, analogues	Accurate numerical (demographic, socioeconomic), spatial (GIS, satellite), networks (infrastructure), behavioral (social media, consumer), statistical (census, survey), risk, health data.	DT can address the translation gap between policy language and model parameters. It can facilitate integration of diverse data types - empirical and subjective by using Story-and-Simulation (SAS) methods, Cross-Impact Balance (CIB) analysis, and boundary objects such as scenario design maps and scenario logic diagrams that translate high-level policy "storylines" into spatially explicit attraction/repulsion variables. [278, 279, 296, 337].
R7	Prototype	Generating actionable Outputs	Verbal, textual narratives, visual representations (photos, collages, maps)	Statistical models, large-scale urban models, cellular automata models, agent-based land use models, GIS tools	DT can support planning practitioners generate rapid prototypes through visual reasoning & mapping, parameter translation tables, interactive dashboards, sketch-planning tools, and modular simulation environments that can produce spatial outputs to enable practitioners to spatially interpret abstract policy goals.[278, 296, 337, 338].

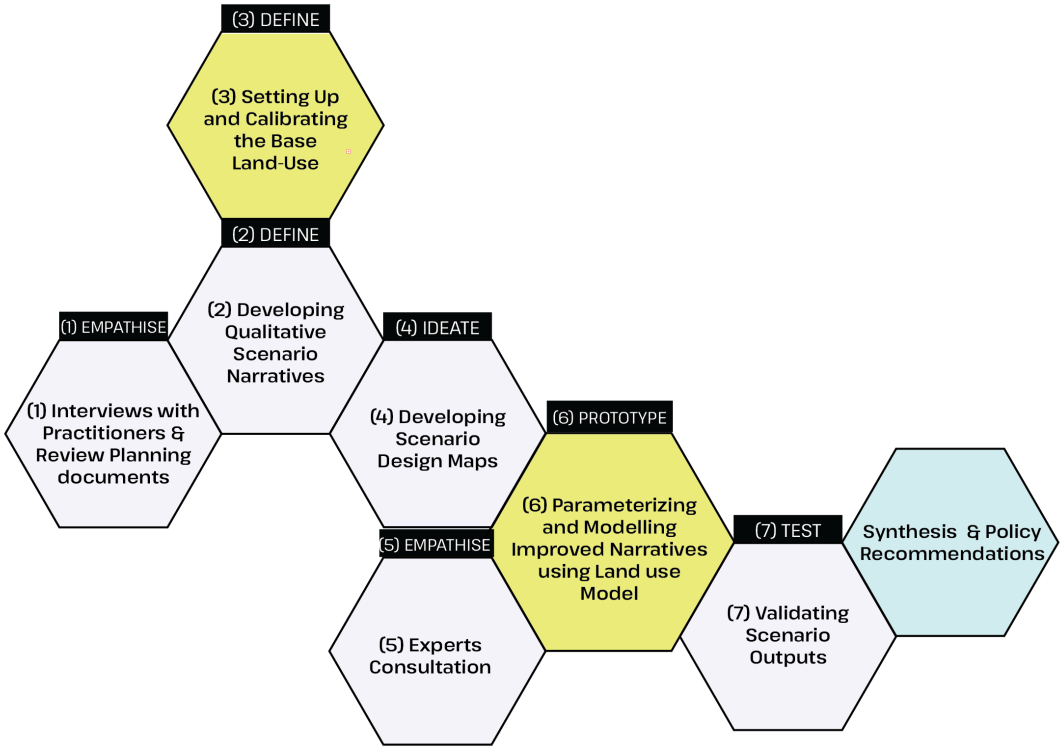

Figure 5.1: Flowchart of the FutureScapes approach, which uses design thinking to blend computational models and scenario narratives for designing urban futures.

qualitative and quantitative techniques, through collaborative scoping or problem framing [136] to establish the boundaries of the model; *Ideation* facilitates the generation of multiple (spatial) interpretations - via maps, sketches, workshops or narratives - to explore different solution spaces or to translate high-level policy narratives into computational variables; *Prototyping* enables rapid testing of narrative-to-model translations; *Iteration* allows refinement based on expert feedback, rather than aiming for immediate consensus.

Our methodological standpoint is to apply and test the comprehensive Design Thinking (DT) sequence as a procedural scaffold to facilitate the refining of qualitative narratives and computational model-based reasoning. By iteratively refining both components, the approach enhances the credibility of scenario assumptions and ensures the strategic relevance of model outputs for practitioners navigating complex, long-term urban uncertainty.

5.3 The FutureScapes Approach: Embedding Expert Feedback into Design Thinking for Model-Narrative Synthesis

FutureScapes is a seven-step scenario development approach that operationalizes Design Thinking (DT) as a procedural scaffold to blend qualitative narratives and computational land-use models. Grounded in the Hasso Plattner / Stanford Design Thinking framework—comprising the Empathize, Define, Ideate, Prototype, and Test phases [351, 352] -

the approach enhances the strategic relevance of computational land-use scenarios by systematically embedding the situated knowledge of expert stakeholders into the modelling process 5.1. This methodology shifts the modeling workflow from a linear translation exercise to an iterative, non-linear synthesis, where practitioners' spatial reasoning and institutional values improve computational parameters. By balancing narrative storytelling with analytical rigor, *FutureScapes* provides a robust framework to navigate long-term urban uncertainty and translate complex spatial dynamics into actionable policy recommendations.

Step 1: Empathize (Interviews with Practitioners & Context Mapping)

Understanding the socio-economic context of urbanization is essential for grounded scenario development. Through semi-structured interviews with practitioners responsible for both operational and strategic planning decisions and thematic document analysis, *Step 1* identifies the foundational spatial drivers, latent institutional constraints and spatial priorities that inform the subsequent development of scenario narratives. This ensures that the subsequent modeling environment is grounded in the professional priorities and strategic reasoning of the practitioners who navigate the city's regulatory landscape.

Step 2: Define (Scoping & Developing Qualitative Scenario Narratives)

Based on findings from *Step 1*, narratives are developed to reflect the strategic planning ambitions of the region. The narratives draw on extensive desk research into future urbanization, mobility, environmental trends, and demographic pressures. The scenarios developed in this study are best described as explorative planning scenarios, intended to examine how different policy directions and development visions might affect urban form [279, 353]. We steer away from the scenario axes approach, as the intent is not to explore the plausibility space, but to develop socio-economically relevant scenarios for expert feedback. Given the reliance on expert knowledge, the number of scenarios and the time horizon must strike a balance between adequately capturing the region's goals and minimizing cognitive burden [338, 354].

Step 3: Define (Setting Up and Calibrating the Base Land-Use Model)

To simulate land-use dynamics over time, we establish the modelling boundary and then select a stochastic computational model that allows for configurable land-use classifications (extending beyond land cover alone), accommodates functional interactions between land-use categories, integrates diverse drivers of change, and visualizes temporal/time-stepped simulation for understanding spatial trade-offs. Model selection also considers the need for granular output and rapid run-time, drawing on established precedents [283, 315, 337, 338]. For this study, the model is calibrated using context-specific data and validated through probability mapping to ensure robustness and fitness-for-purpose for scenario simulation [115].

Step 4: Ideate (Developing Scenario Design Maps)

The Ideate phase addresses the 'translation gap' between policy language and model parameters, operationalized through the steps detailed in Table 5.1. Eliciting spatial feedback is operationalized through sketching and mapping techniques to support collaborative framing and creative synthesis [355]. Scenario design maps serve as semi-quantitative mediating instruments to visualize spatial logic and sectoral priorities in each scenario narrative from *Step-2* [356]. The maps are created using a combination of hand-sketched and digital tools to represent key elements - growth nodes, mobility corridors, ecological assets - based on official planning documents and stakeholder inputs, presenting compelling urban visions. Broad distance and area calculations may be included to support representation at scale. Using a graphics editor, the maps are stylized to maintain consistency with computational model outputs, enabling experts to relate design concepts to simulation parameters and provide concrete spatial feedback (Fig. 5.2).

Step 5: Empathize (Experts' Consultation)

Expert consultation serves two purposes: (1) to evaluate the base model assumptions, and (2) to elicit structured expert stakeholder feedback on the scenario narratives. The design-thinking-driven exercise deviates from prescriptive consensus-building in favour of surfacing diverse viewpoints. The use of **scenario design maps** plays a central role, enabling experts to express development and design preferences, priorities, and trade-offs without being constrained by a rigid modelling environment [44, 357].

The expert group is selected for technical depth in domains critical to regional urbanization - urban planning, infrastructure, water management, climate adaptation, and regulatory frameworks - rather than for broad demographic representativeness. In the scope of this study, we propose conducting the consultation in two iterative rounds [334]. The first round captures broad reactions and general feedback on both the narrative scenarios and baseline model outputs. The second round involves a deeper, guided exploration of the scenarios, focusing on specific sectoral assumptions, parameters, and their implications.

Step 6: Prototype (Parameterizing and Modelling Improved Narratives)

Narrative assumptions refined in *Step-5* are translated into model-ready inputs through systematic parameterization. This involves extracting spatial "clues" from the narratives [358] and design maps - such as preferred or inevitable growth areas, zoning constraints, and demand estimates. These inputs are coded into model parameters such as interaction rules, exclusion zones, and attractor weights.

Step 7: Test (Validating Scenario Outputs)

Validation is carried out through two complementary steps. First, computational validation uses Monte Carlo simulations and landscape metrics - such as kernel density and patch indices - to test model stability and

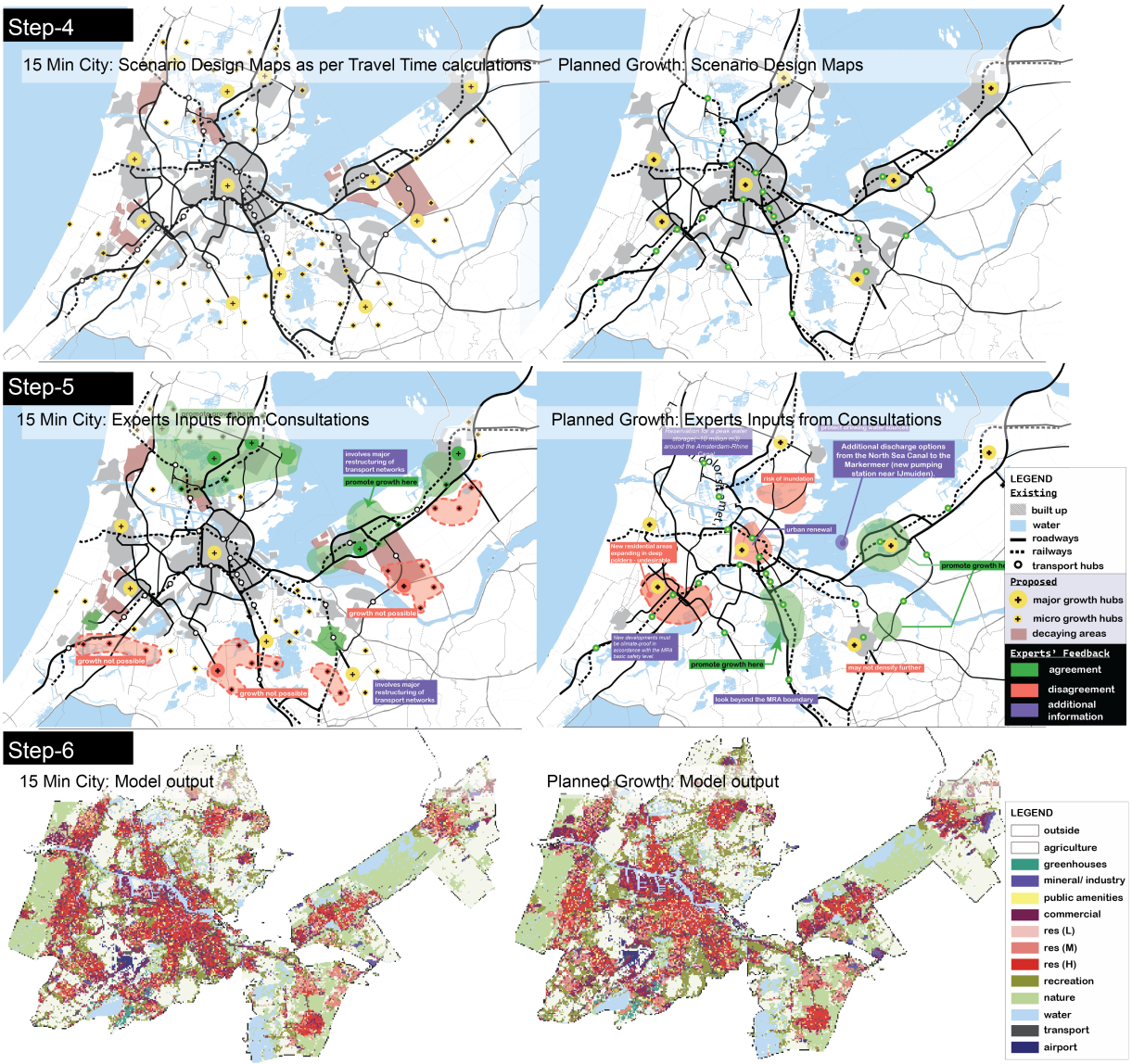

Figure 5.2: Illustrating Three stages of the FutureScapes approach: *Step-4* (Scenario Design Maps as boundary objects), *Step-5* (Expert stakeholder feedback loops), and *Step-6* (Parameterization of qualitative narratives into modeled spatial outputs).

spatial coherence. Monte Carlo simulations are run with variable random seeds to assess consistency and differentiation across scenarios. A representative map is selected per scenario for further analysis *(see Supplementary Material)*. Second, expert feedback is gathered on the model outputs in consultation rounds to assess whether the outputs reflect contextual priorities and narrative intent. By doing so, the validation step ensures that the scenarios are both technically robust and contextually grounded.

Table 5.2: Factors determining Scenario Narratives for the MRA (in addition to the Business as usual scenario (BAU)): Planned growth (PG) and 15-Minute City (15MC)

Factor	Planned Growth (PG)	15 Minute City (15MC)
Urbanization	Mixed-use, multi-core development	Highly decentralized, accessible micro-hubs with essential amenities within a walking/biking radius
Mobility	Multimodal hubs for public transport, car-oriented: direct traffic to ring roads, suburban living	Active mobility (walking/biking): expand non-motorized pedestrian/bicycle networks
Economy	Market-driven, internationally oriented growth hubs	Area-based local hubs to improve livability, promote e-working, support small and medium businesses
Environment	Landscape-inclusive urbanization: protect and enhance biodiversity and strengthen green-grey zones; strict restrictions to protect nature	Moderate to light restriction on urban expansion in protected areas, promoting decentralized growth and recreational structures

5.4 Implementation of FutureScapes to the Case of the Metropolitan Region of Amsterdam (MRA)

We apply the FutureScapes approach to model urbanization strategies for the Metropolitan Region of Amsterdam (MRA), Netherlands for the year 2050. MRA is a major socio-economic hub in Western Europe comprising 30 municipalities and the Amsterdam Transport Region. It houses 2.5 million residents, 300,000 enterprises, 1.5 million jobs and is highly vulnerable to climate change due to its extensive low-lying land and faces acute challenges such as housing shortages, mobility constraints, and socio-economic inequality.

Step 1: Empathize (Interviews with Practitioners)

Twenty semi-structured interviews were conducted with senior practitioners, including urban planners, policy advisors, climate adaptation leads, and sustainability specialists. These interviews, analyzed in prior studies by the authors [28, 274], provided a foundational understanding of spatial priorities, planning tensions, and long-term transformation pathways in the MRA.

Step 2: Define (Developing Qualitative Scenario Narratives)

Three scenario narratives were developed for the 2050 planning horizon, drawing from official planning documents [359–361], practitioner interviews [274], and regional goals related to mobility and health. The narratives also incorporate additional challenges such as space scarcity, housing crises, biodiversity loss, soil subsidence, infrastructure renewal, and the impacts of COVID-19 and climate change. The scenarios are:

Business as Usual (BAU): Continuation of current trends with minimal policy innovation. Restrictions around protected zones remain, but no new spatial strategies are introduced.

Planned Growth (PG): Reflects the official MRA strategy, promoting seven high-density, mixed-use hubs with enhanced intercity transport connectivity and biodiversity preservation.

15-Minute City (15MC): A decentralized model prioritizing self-sufficiency and proximity to services through the creation of numerous mixed-use micro-hubs accessible within 15 minutes by walking or cycling. The

scenario draws from a growing global interest in accessibility-based planning, compact urban form, and infrastructure aging - especially in the aftermath of the COVID-19 pandemic.

Step 3: Define (Setting Up and Calibrating the Base Land-Use Model)

We selected *Metronamica*, a stochastic, cellular automata-based, spatially explicit land-use model [362] (www.metronamica.nl). The model simulates yearly urban dynamics and allows interaction among up to 32 land-use categories (LUCs). The MRA model was calibrated using data from 1996-2006 and validated with 2006-2016 data. Calibration focused on aligning model simulations with observed patterns using Kappa performance metrics. The resulting fuzzy kappa score of 0.90 outperformed both random (0.87) and neutral (0.82) models [363], confirming robust model performance (see *Supplementary Material*).

Certain modelling decisions were shaped by practical constraints, such as the availability of compatible spatial data during the calibration period and conceptual maps available in MRA's policy documents (e.g., mobility maps from MRA's open data portal and geoservers), as well as the region's broader spatial goals.

Step 4: Ideate (Developing Scenario Design Maps)

Scenario design maps were developed in a semi-quantitative manner to present a consistent spatial representation of the narratives and to elicit expert feedback that could be parameterised (see Figure 5.3). For each scenario, we reviewed relevant literature to understand its spatial representation. For instance, in the 15MC scenario, we used GIS tools (TravelTime) to calculate travel distances and identify growth hubs (see Fig. 5.3 *Step 3*). These hubs informed preliminary design maps that depict the distribution of urban functions, transport networks, and development nodes.

We made a design decision to emphasize urban growth hubs and highlight areas of decay or redevelopment, as these are central to eliciting spatially explicit feedback from experts. The final maps for each scenario were drawn to approximate scale, representing the distances and sizes of urban parcels.

Step 5: Empathize (Experts' Consultation)

In Fall 2021, we convened nine expert stakeholders who steer decision-making for urban planning and policy in the MRAfor a 3-hour consultation session to review the scenarios. The group included two planners working on climate adaptation, two policy advisors specializing in scenarios, two land-use specialists, one urban designer, one landscape architect, and one urban water expert. Due to COVID-19 restrictions, the consultation was conducted online via Microsoft Teams and the Mural online collaboration board. Detailed consultation protocols, workflow, and participant profiles are available in the *Supplementary Material*.

We presented the data sources used for model calibration and performance metrics (e.g., Kappa indices, clumpiness, kernel density), along

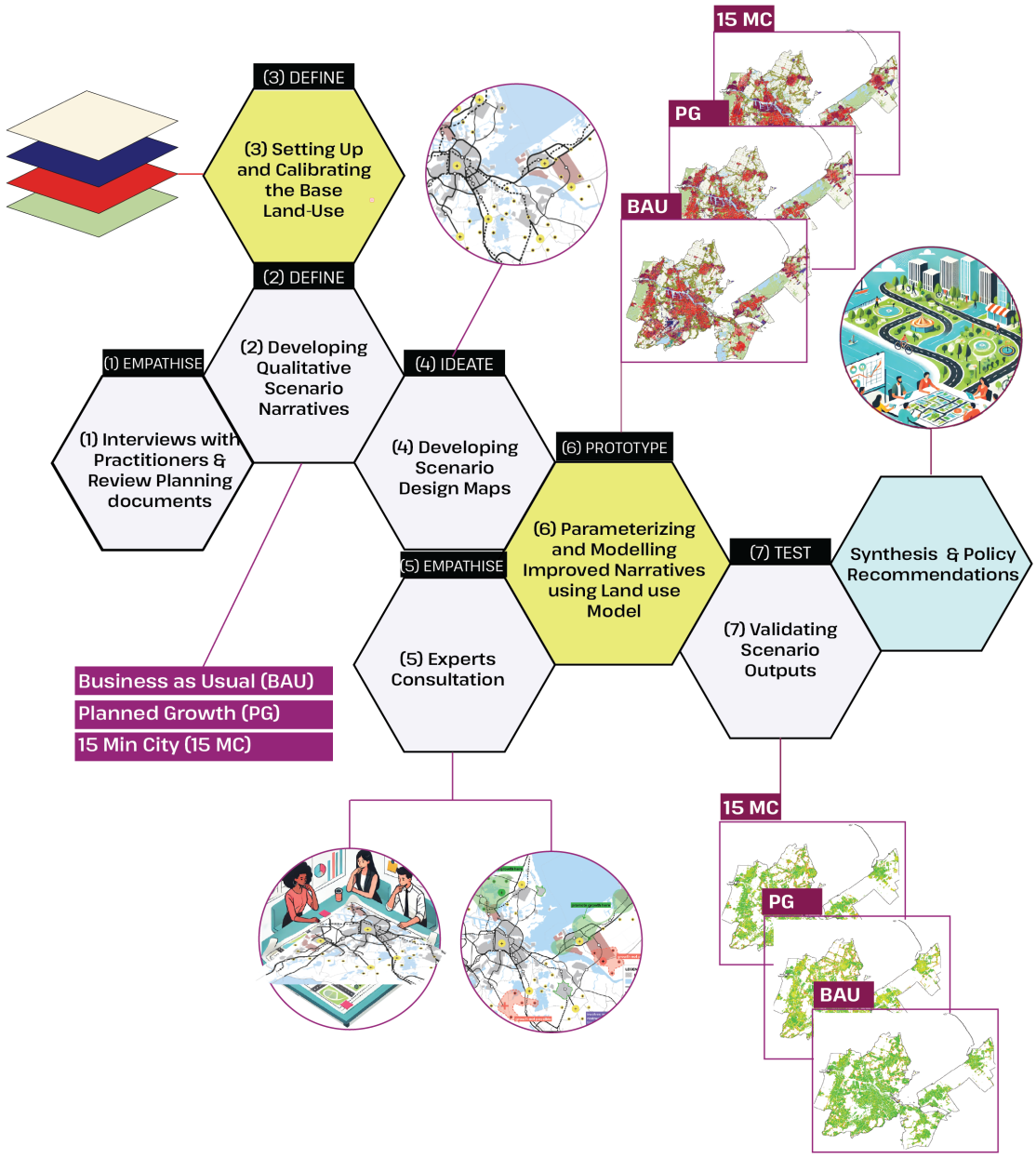

Figure 5.3: Illustrating the detailed application of the FutureScapes Scenario Development Approach on the case of the Metropolitan Region of Amsterdam (MRA) following the Workflow in Fig 5.1

with a comparison map showing actual versus simulated growth. Experts reviewed the model's performance and the BAU scenario simulation for 2015–2050, generally validating the model's depiction of urban growth. They recommended further sub-categorization of land uses, particularly for mixed-use areas and green spaces.

Feedback on narratives was structured around two interactive rounds, where experts worked in small groups to review all narratives and minimize groupthink [364].

Round 1 focused on spontaneous insights, such as agreement or disagreement with narrative assumptions and growth patterns. These discussions led to debates among urban designers, planners, and water management

Table 5.3: *Parameterising Scenario Narratives (Step-5), detailed table moved to Supplementary Material*

Scenario	Key developments	Scenario Parameters		
		Zoning Policies	Accessibility & Attractors	Interaction Rules derived from model calibration
Business as Usual (BAU)	Free growth under basic regulations	• Soft restrictions: Heritage buildings, New Dutch Waterline, World Heritage the Defense Line of Amsterdam, UNESCO, Places of scenic importance, archaeological monuments. • Hard restrictions: Protected nature areas (Natura2000, Nature Network Netherlands (NNN)) • Schiphol Airport: Restrictions for noise-sensitivity, density, height.	• Networks: Highways, Secondary roads, Railways, Navigable waterways • Nodes: Main Railway Stations, Secondary Railway Stations, Motorway Junctions, Bus Terminals	
Planned Growth (PG)	• Multi-core metropolitan structure (7 centres) • Highly urban mixed-use growth at transport hubs. • Preserve environmental assets, promote biodiversity	In addition to the BAU-Scenario: • 7 mixed-use, high-density urban zones of 1.5km radius (Residential, Commercial and Public Amenities) • Residential and commercial areas for 2050 • industrial noise zones • Landscape & recreation corridor, “Scheggen" • Active conversion of Residential (low density) to other LUCs. • Restrict growth in vulnerable locations (noisy areas, nature reserves.	• Nodes: 7 urban cores • Nodes: Multimodal hubs • Nodes: Other stations, Existing transport nodes (strong attractors)	• Attraction between Residential (high & medium density) and Commercial increased to encourage their proximity to each other at seven urban zones.
15 Minute City (15MC)	• Decentralized urban development model with micro mixed-use hubs. • Essential functions (public amenities, recreation, offices) accessible at 15-min biking radius.	In addition to the BAU-Scenario: • Micro-urban zones accessible within 15-min biking radius • Zoning restrictions relaxed for functional LUCs to expand into protected areas. • Facilitate conversion from Residential (low density) and Recreation to other LUCs.	• Nodes: Attractor Points to promote mixed-use hubs within a 15-min biking distance - using Travel time calculator (ArcGIS) and expert judgment. • Networks: Residential roads introduced to expand biking access. • Networks: Transport accessibility parameters **(distance decay function)** adjusted to modify their attraction. • Networks: Attraction of secondary roads and residential roads increased to promote public amenities and recreation.	• Attraction between Residential (medium density) and Commercial is increased at 100m to encourage mixed-use growth at hubs and meet space demands for 2050.

experts, with feedback ranging from agreement (*"This is already happening"*) to strong disagreement (*"This will never work because it requires major restructuring"*), along with more localized insights (*"Innovation is only possible in this neighbourhood"*).

Round 2 involved a structured evaluation of the scenario design maps using guided questions (Table 5.3). Experts marked key locations on the maps, identifying growth hubs (e.g., pilot projects, circular economy potential, protected areas, major projects, and connectivity hubs) and stressors (e.g., subsidence, decaying areas, heat islands, rising land prices, and pollution/noise). In total, 68 pieces of feedback were provided across the three narratives, identifying areas to promote or discourage growth, as well as unrealistic situations and high-risk locations.

While the BAU and PG scenarios were deemed realistic, concerns were raised that car-oriented suburban growth may counteract sustainability goals. The 15MC scenario, although praised for its potential to improve recreational access, reduce climate impacts, and alleviate the housing crisis, was met with skepticism due to its expansion into flood-prone and nature-conserved areas - potentially fragmenting green networks and requiring policy adjustments to accommodate higher-density development.

Experts recommended increasing the sub-categorization of land uses in the model to provide a more detailed representation of urban functions. However, this was not feasible due to the need to balance model complexity with data availability and computational reliability: (a) critical data for mixed-use classes was unavailable in a format compatible with the model, and (b) adding subcategories would have required extensive pre-processing and recalibration to reflect the dynamics of additional categories. Drawing on insights from similar case studies using Metronamica [365, 366], the model was limited to 13 land use categories (LUCs).

Step 6: Prototype (Parameterizing & Modelling Improved Scenario Narratives)

Based on expert consultations and official statistics, the narratives were quantified as thoroughly as possible. Each narrative was systematically analyzed to estimate its spatial impacts (e.g., growth, degrowth, city centres) using location-specific feedback from the scenario design maps. These impacts were first assessed semi-quantitatively (from very strong increase to very strong decrease), then translated into specific numerical values, growth curves, and input maps.

While the consultation provided substantial factual input, not all assumptions behind developments were clearly stated. Some were validated using official datasets, though others could not be fully verified. Despite the model's need for more detailed input, critical assumptions about work–live patterns, mobility, and shifts in nature or agricultural land were successfully parameterized.

Future space demands were derived from regional population projections and the Planning Capacity Monitor. Simulations were run from 2016 to 2050, assuming consistent demographic trends and space demands. Zoning layers, accessibility metrics, and interaction rules - such as attraction and repulsion between land uses - were adjusted to reflect the land-use logic for each narrative, with scenario-specific rules applied.

For example, in the PG scenario, mixed-use growth hubs were promoted by increasing attraction at key transport or motorway junctions. This was implemented by introducing attractor points and zoning radii to stimulate development in targeted areas. Table 5.3 outlines the detailed parameterization of narratives, while Fig. 5.4 displays the resulting computational scenario outputs. An ex-post evaluation of these outputs helped identify key parameters influencing each scenario, allowing adjustments to align with both narrative goals and expert feedback. Additional maps were also introduced to resolve inconsistencies.

- In the PG scenario, five additional zoning maps were created to promote mixed-use development in seven hubs, integrate land reservations aligned with regional landscape policy, and simulate zoning for residential, commercial, and industrial land by 2050.
- In the 15MC scenario, two additional zoning maps and an infrastructure network map (residential roads) were introduced to support mixed-use hubs within a 15-minute biking radius. Despite these adjustments, the modeled scenario diverged from the idealized narrative. Achieving 15-minute access would require major restructuring of the road network and loosening nature protection policies to allow greenfield expansion - neither of which was supported by the experts. However, zoning restrictions for nature areas were eased slightly in the model to permit limited expansion.
  Fig. 5.2 illustrates the development process for the 15MC scenario, based on Fig. 5.1. Of the 86 originally proposed mixed-use hubs (based on travel time calculations), 52 remained after incorporating expert feedback. The final computational scenario simulated growth at 46 hubs, constrained by spatial/network limitations and insufficient space demand.

Experts also emphasized the vulnerability of drinking water sources due to subsidence and rising sea levels, recommending protective zoning measures for freshwater reserves. Accordingly, zoning layers were updated to discourage built-up functions in these areas in the refined scenarios.

Step 7: Test (Validating Scenario Outputs)

Each scenario was tested using 100 independent Monte Carlo iterations, producing pixel-level probability surfaces for every land-use class. From these ensembles, we extracted standard deviation (SD) and entropy measures to serve as quantitative indicators of model stability and spatial ambiguity.

Results indicate that core urban areas had low variability (SD values between 0.008–0.03), reflecting a high degree of predictive confidence in areas with well-established development trajectories. In contrast, urban peripheries and mixed-use corridors exhibited high dispersion due to overlapping land-use categories and competing development logics, indicating plausible but complex growth patterns.

These outputs - particularly the spatial zones with high uncertainty - highlight areas for future deliberation, negotiation, or targeted policy intervention.

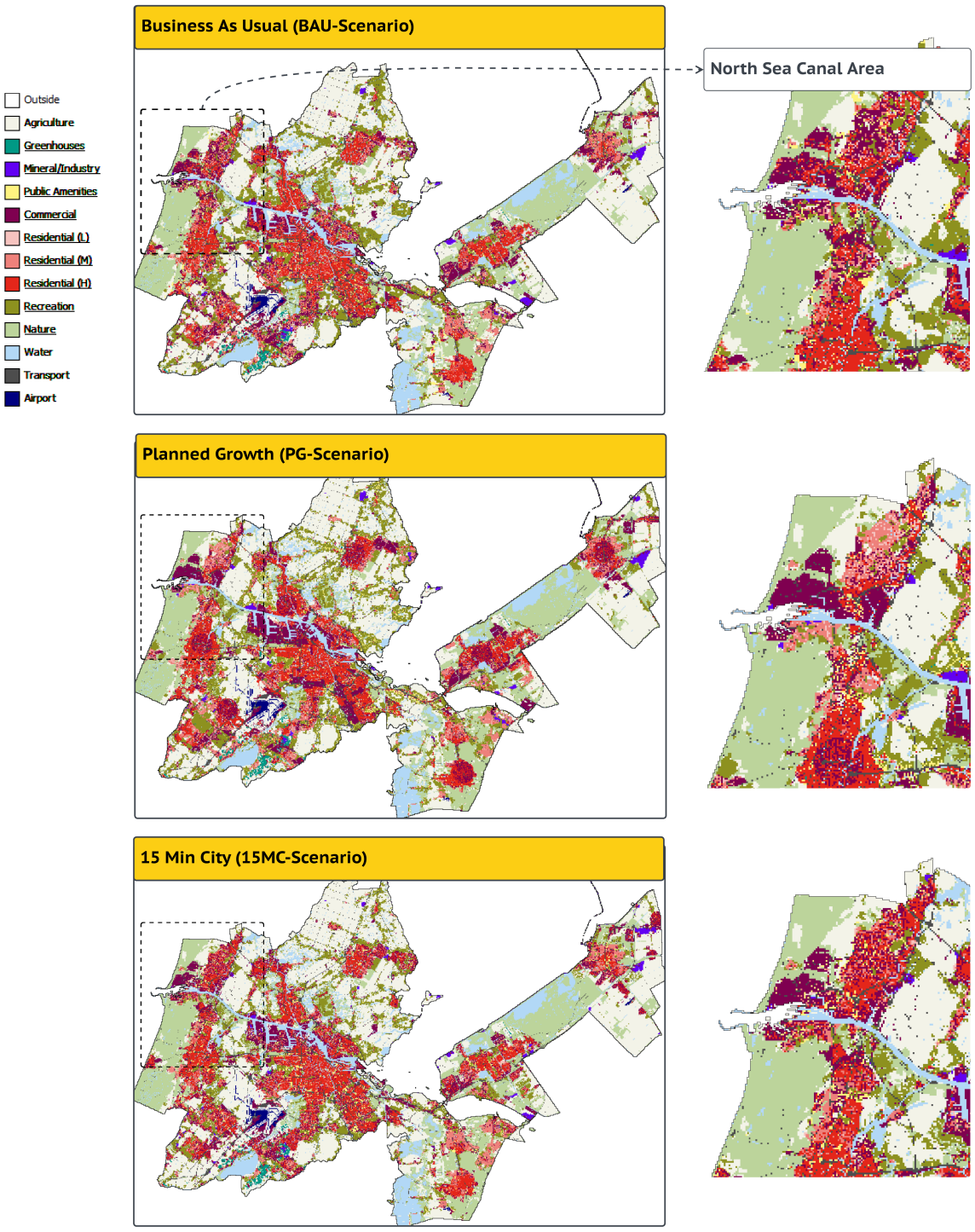

Figure 5.4: Computational scenario outputs illustrating different urban growth patterns for the Metropolitan Region of Amsterdam in 2050: *(a)* Business-as-Usual (BAU Scenario), *(b)* Planned Growth (PG Scenario), and *(c)* 15-Minute City (15MC Scenario). Each scenario includes a zoom-in on urban expansion patterns in the North Sea Canal Region to highlight variations in land-use allocation, supporting reflection on future policy directions.

Synthesis and Policy Recommendations

The policy recommendations presented in this study are derived by synthesizing the modelled scenario outputs with qualitative scenario narratives and practitioner inputs - and not solely from computational outputs. This blended approach is central to the *FutureScapes* approach. It reflects the understanding that computational models and narratives need not operate in a linear sequence - where one feeds into the other - but rather in an iterative manner, where they mutually shape and refine the scenario development process. This ensures that tacit knowledge of expert stakeholders and their value-based judgments are incorporated into model assumptions [297, 315, 324].

We assessed the three computational scenarios against the Metropolitan Region of Amsterdam's (MRA) strategic goals for health and sustainability [359]. Several mismatches emerged between modeled outputs and narrative expectations.

Notably, the 15-Minute City (15MC) scenario aimed to improve recreational access by decentralizing growth into walkable micro-hubs. Experts expressed concerns about the feasibility of significant infrastructure restructuring - particularly regarding the road network - and highlighted institutional path dependencies that may hinder the implementation of micro-hubs across the region. Furthermore, spatial realization of this scenario required trade-offs, such as easing development restrictions in ecologically sensitive nature reserves.

In contrast, the Business-as-Usual (BAU) scenario - despite lacking targeted interventions - showed the shortest average walking distance between residential and recreational functions (0.44 km), better aligning with the MRA's health objective of promoting active mobility. This finding underscores the importance of evidence-based urban decision-making. Widely promoted planning heuristics, such as the 15-minute city, often presume that proximity-based design inherently ensures accessibility. However, without empirical validation, such assumptions may result in trade-offs and misalignments between policy goals and implementation realities, potentially leading to inefficient or costly outcomes.

Similarly, the second regional objective - supporting sustainable development in the North Sea Canal zone - was realized differently across scenarios. All three scenarios simulated urban expansion to the northwest, northeast, and southwest (Fig. 5.4), but differed in their spatial allocation of recreational areas. The PG scenario promoted commercial intensification in this corridor, which experts noted could justify policy shifts to formally recognize its emerging strategic role. However, trade-offs between economic development and ecological preservation - particularly the spatial demands of energy transition infrastructure - remained unresolved and contentious, illustrating tensions that computational models alone cannot resolve.

Further, while all scenarios met the projected space demands for 2050, experts flagged problematic expansions into flood-prone and subsidence-affected areas - particularly in the southwest and central MRA. Although these risks were detectable through land-use overlays, they were not embedded in the model's constraint logic. Experts recommended precautionary planning measures to limit densification in such zones and advocated for the integration of adaptive strategies into zoning frameworks. These

judgments could only be surfaced through expert deliberation, reaffirming the critical role of expert insight in enhancing and contextualizing model outputs.

The insights from this study challenge the assumption that scenario ambitions necessarily translates into spatial efficiency. They emphasize the value of qualitative assessments in combination with model metrics to produce robust, policy-relevant insights.

Table 5.4: Assessing how the FutureScapes Approach Operationalises Design Thinking for scenario development for the Metropolitan Region of Amsterdam (MRA)

S.no.	Design Thinking Step	Aspect	Implementation of Design Thinking in the FutureScapes Approach
R1	Empathize	Selection of Inputs	FS Utilized thematic analysis of MRA's planning documents and semi-structured interviews with 20 senior practitioners to identify spatial drivers to ground the model in reality. Does not incorporate real-time data or citizen inputs.
R2	Empathize - Test	Explainability and Engagement	FS employed "Expert Consultations" where we used used semi-quantitative scenario maps as boundary objects to walk through the scenario and to spatially probe the logic from qualitative narrative to spatial outcome. This offered a high level of transparency to expert stakeholders and linked the scenarios to loved realities.
R3	Define	Addressing Constraints	FS used findings from interviews, narratives, and experts insights to refine the model assumptions. This fosters a critical reflection across both narrative and modelling components. Integrates "Hard" constraints (environmental protection zones, UNESCO sites) and "Soft" policy constraints into the Cellular Automata transition rules. Model outputs are socio-economically relevant and "plausible" within the existing regulatory framework of the Netherlands.
R4	Define - Test	Uncertainties Considered	FS addresses global uncertainty by generating distinct computational scenarios, while capturing local uncertainty through the stochastic land-use model. It evaluates uncertainty within each scenario using Monte Carlo simulations and landscape metrics to inform planners of spatial areas requiring attention. Thus, moves beyond predictive "accuracy" toward exploratory "robustness" in line with the Walker et al. (2003) [136] framework.
R5	Ideate	Multiscalarity	FS linked regional-level strategic narratives (top-down) with local-level cellular land-use dynamics (bottom-up) through experts consultation. Does not explicitly model the tension between regional policy intent and local spatial availability - though the regional implications is discussed during the expert consultations.
R6	Ideate - Prototype	Diverse Data Types	FS parameterises narratives "storylines" (e.g., 15 min City) into quantitative inputs, by setting attraction/repulsion coefficients and with subjective inputs (e.g., expert judgment, design preferences). Bridges the "translation gap" between policy language and computational parameters by using boundary objects in the form of scenario design maps during the expert consultations to produce relevant, grounded scenarios.
R7	Prototype	Generating actionable Outputs	Developed **scenario design maps** as "boundary objects" to encourage experts discussion on each scenario. Further, they were used to produce high-resolution (100m) spatially explicit land-use scenarios for 2050. Outputs correspond to planning zones used in regional policy drafting.

5.5 Evaluating the role of Design Thinking in Blending Computational Models and Scenario Narratives

This section evaluates how the FutureScapes methodology operationalizes Design Thinking (DT) as a procedural scaffold to bridge the creative strengths of qualitative narratives with the analytical rigour of computational models. We assess how DT specifically addresses the scenario development requirements outlined in Table 5.1, with the implementation results from the Amsterdam (MRA) case study summarized in Table 5.4.

The application of FutureScapes to the MRA region demonstrates its capacity to resolve persistent tensions in urban analytics. By mapping the implementation against key methodological aspects—including multiscalarity, explainability, and the management of uncertainty—we provide a template for transparent, expert-led scenario development. Our findings suggest that the integration of Design Thinking provides the necessary procedural rigour to navigate epistemic uncertainty [136].

The case study illustrates that FutureScapes effectively integrates diverse inputs, specifically the design preferences and situated knowledge of expert stakeholders. These inputs, elicited through document analysis and practitioner interviews, were translated into quantitative model parameters via scenario design maps (Table 5.4). Simulation using Metronamica enabled the production of spatially explicit scenarios at a fine resolution (100m), significantly enhancing both interpretability and strategic relevance [R7].

By framing narratives around regional priorities and utilizing expert consultations to address trade-offs and spatial dynamics—supported by design maps rendered to match expected model outputs—the approach improved the clarity and communicability of complex spatial decisions [R2]. Crucially, it validated relevance by grounding simulations in local knowledge, including informal rules, unmodelled risks, and context-sensitive constraints, thereby mitigating model overconfidence [R3]. Practitioners contributed critical tacit knowledge regarding community resistance, adaptive reuse potential, and redevelopment priorities. While limited by its current exclusion of non-expert inputs, FutureScapes offers a high-resolution, actionable pathway for regional practitioners to co-produce urban futures that are both narratively rich and computationally sound.

The findings support our core hypothesis: Design Thinking can bridge the epistemological divide between models and narratives in urban planning. The approach facilitated a bidirectional co-evolution between measurable trends and professional spatial reasoning [R6]. Unlike general participatory modelling, FutureScapes utilizes specific design interventions—such as parameter co-design and reflexive spatial probing—that leverage professional domain expertise to bridge the gap between narrative intent and computational execution.

The primary scientific contribution of FutureScapes lies in its capacity for reflexive reframing. While frameworks like GeoDesign incorporate evaluation loops to assess a design's impact, *Step-6* utilizes model-generated maps as probes to reflexively redesign the initial qualitative narratives. Consequently, the approach does not merely use the model to evaluate the scenario; it closes the loop between 'story' and 'simulation,' ensuring that qualitative futures are grounded in the emergent spatial logic of the quantitative model.

Regarding uncertainty [R4], practitioners highlighted the difficulty of estimating space demands amidst rapid socioeconomic shifts. They noted that the flexibility of scenario narratives, supported by Metronamica's rapid runtime, allowed for shifting assumptions while remaining policy-relevant. Monte Carlo simulations were utilized to assess internal model uncertainty, flagging spatial areas requiring further scrutiny. Finally, model assumptions were refined using location-specific expert insights and supplementary data, further mitigating the epistemic uncertainty inherent in long-term urbanisation strategies.

FutureScapes advances these traditions by integrating their complementary strengths into a unified, design-thinking-led workflow. Its primary contribution lies in operationalizing the synthesis of narratives and models reflexively inform one another through structured Design Thinking steps. Within this framework, scenario design maps function as boundary objects [322] that translate narrative logic into semi-quantitative spatial representations (scenario design maps), facilitating the elicitation of situated knowledge and precise model parameterisation.

In doing so, *FutureScapes* demonstrates that computational models can serve not only as evaluative benchmarks but as reflexive instruments for the collaborative exploration of long-term spatial strategies. This represents a methodological synthesis that moves beyond the linear "story-to-simulation" pipeline common in previous approaches. Furthermore, by following the framework of Walker et al. (2003) [136], *FutureScapes* systematically manages epistemic uncertainty through expert elicitation and addresses structural uncertainty through the reflexive feedback loops characteristic of the Design Thinking process.

5.5.1 Limitations & Future Work

Despite its methodological contributions, the FutureScapes approach presents several limitations that warrant further refinement.

First, practitioners involved in *Step-5* noted that the departure from the familiar **2x2 scenario axis framework** - a standard in scenario planning practice - was initially disorienting. While these matrices are increasingly critiqued for oversimplifying multidimensional uncertainties [367], they remain a primary institutional heuristic. FutureScapes deliberately moved beyond this by grounding scenarios in socio-economic realities of the MRA. For instance, the 15MC scenario reflects shifts toward non-motorized mobility and polycentric growth promoted post the COVID19 pandemic. By parameterizing these narratives into a model capable of capturing complex land-use interactions, the approach enabled a nuanced evaluation of competing spatial demands, though at the cost of the simplicity provided by traditional frameworks.

Second, the approach prioritized engagement with **expert stakeholders** over broader community participation. While this decision allowed for technical depth and alignment with institutional priorities, it potentially constrained the diversity of the scenario narratives. Broader engagement with citizens and community organizations could reveal alternative values and perspectives that expert-driven processes may overlook. Future iterations of FutureScapes should explore methods to integrate community-driven inputs to enhance inclusivity, and the broader societal relevance of planning outcomes.

Third, the study highlights tensions in **multiscalar thinking** ([R5] in Table 5.2). Scenarios like the 15MC require analysis across nested scales—from local adaptive reuse to regional mobility dynamics. Our findings demonstrate how model selection influences scenario representation: the hub-based growth in the PG scenario aligns well with the cellular automata (CA) logic of Metronamica, whereas the decentralized logic of the 15MC scenario might be better captured by agent-based models (ABM) that simulate behavioral processes [368, 369]. This study prioritized analytical consistency over scenario-specific model selection to ensure direct comparison, but this choice may have constrained the representation of certain narratives. Future research should investigate strategies for cross-model comparisons without compromising structural coherence.

Fourth, the model was calibrated on historical data (1996–2016), which does not inherently incorporate transformative regime shifts or future policy interventions. The assumption that behavioral patterns derived from past trends will persist introduces a common constraint in land-use forecasting. While expert consultations helped mitigate this reliance on stationarity, the use of historically calibrated models remains a limitation when addressing unprecedented urban futures [283, 329].

Finally, the study validated the scenarios through computational methods and did not include a planned third expert consultation to review final modelled outputs. Additional rounds of expert consultation could refine model assumptions, and stress-test scenario logic, to strengthen the legitimacy and usability of outputs for decision-making. These steps remain a priority for future research.

5.5.2 Concluding Remarks

The FutureScapes approach demonstrates the value of integrating qualitative narratives and expert insights into computational modeling to produce spatially grounded urban scenarios that reflect the scoio-economic realities of the region. Rather than treating models as isolated technical tools or narratives as abstract visions, FutureScapes synthesizes both through a design-thinking-led, iterative process. This enables expert stakeholders to evaluate and refine model assumptions, visualize alternatives, and refine outputs using specific contextual knowledge.

Existing scenario development traditions such as GeoDesign, exploratory scenario modelling, and participatory modelling demonstrate strong precedents for linking models with stakeholders (see Section 5.1). However, these approaches often remains methodologically fragmented when applied to metropolitan or regional urbanisation strategies. FutureScapes' unique contribution lies in its operationalisation of narrative creation, spatial ideation, parameter translation, and model testing as interconnected design activities. By doing so, it enables computational models to serve not only as evaluative tools but as active co-design instruments. This advances the field by offering a generalizable method for blending narratives and models that is transparent, replicable, and suited to the early strategic stages of long-term planning.

The introduction of the scenario design maps serves as a critical spatial probe, facilitating a deeper reflection on the generated scenarios. It enhances the spatial reasoning capabilities of planning practitioners, supporting deliberation on land-use trade-offs and development choices in a visual, place-based format.

FutureScapes' capacity to integrate diverse information sources—including empirical data, policy goals, expert judgment, and stakeholder values—is essential for addressing contemporary urban planning challenges defined by deep uncertainty, climate risk, and accelerating technological change. By providing a replicable framework for developing scenarios that are spatially and institutionally grounded, FutureScapes reflects real-world constraints, regional objectives, and the situated expertise of decision-makers. Ultimately, this enhances the relevance, usability, and strategic value of scenario planning for uncertain urban futures.

5.6 Acknowledgements

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5.7 Supplementary Material

Supplementary materials are accessible at: 4TU Data Repository and GitHub: MRA Model

Discussions and Conclusion 6

Despite the growing number of urban resilience and climate adaptation frameworks - such as the City Resilience Framework [147], C40's Climate Action Guide for Urban Planners, and various "resilient city" planning approaches [10, 12] - current practice still lacks concrete mechanisms to spatially embed resilience under conditions of climate uncertainty. Most strategies remain siloed within individual sectors and rarely account for the interconnected spatial and temporal dynamics of urban systems, limiting their ability to adapt as conditions evolve.

This thesis argues for a planning culture that moves beyond reactive, project-driven responses towards one that systematically aligns with change, manages sudden disruptions, sequences planning actions, and supports forward-looking urbanisation strategies under stress and shock. While long-lived urban systems such as transport, water, and energy networks cannot themselves be made "flexible", their planning can incorporate flexibility by aligning maintenance and upgrade cycles with iterative plan reviews. In doing so, cities can shift from linear, build-and-forget timelines toward more adaptive planning frameworks. Developing a fundamental understanding of the temporal dynamics of urban systems, and of how planning timeframes can better synchronise with overlapping lifecycles, is therefore essential. Advancing this temporal perspective is one of the key contributions of this thesis (*chapter-4*).

Overall, the dissertation contributes to climate urbanism by examining how urban planning can embed resilience and adaptation into long-term urban development. Drawing on two contrasting metropolitan regions - Amsterdam in the Netherlands and Mumbai in India - the research advances theories of urban resilience and long-term planning under uncertainty, and proposes an integrated methodology for designing future metropolitan urban growth trajectories. Organised across four interlinked studies (*Chapters 2–5*), it explores how resilience principles, temporal dynamics, and design-thinking approaches can together reorient urban planning to better address climate uncertainty.

6.1 Answering the Research Questions

The main research question guiding this thesis is: *How can urban planning be re-envisioned using resilience, temporality, and design-based methods to enable planning under climate uncertainty?*

Findings for RQ1 (chapter-2: PSS)

How can urban planning approaches and Planning Support Systems (PSS) be advanced to enable long-term climate resilience?

chapter-2 (PSS) establishes the foundations of the dissertation by presenting a large-scale, text-mining-based review of academic and grey literature at the intersection of urban planning, resilience, and adaptation.

The analysis confirms that existing Planning Support Systems (PSS) tend to be reductionist: they address discrete sectoral issues rather than the complex interactions that characterise urban resilience challenges. Long-term planning, however, demands explicit attention to spatial and temporal dynamics. PSS could support this by allowing planners to explore different time horizons and infrastructural lifecycles, and to align short-term actions with long-term climate goals. Yet terms such as *spatio-temporal* appear only rarely in the resilience literature, despite some studies implicitly addressing dynamic space–time processes.

Concepts prominent in policy discourse - such as circular economy, nature-based solutions, or multi-hazard scenarios - also appear less frequently in academic work, signalling a disconnect between research and practice. With respect to resilience principles, *robustness* and *efficiency* dominate, while *flexibility* and *redundancy* are under-represented. This asymmetry foreshadows empirical findings in later chapters: Amsterdam's urban planning culture emphasises robustness at the expense of adaptability (*chapter-3*), while rigid long-term investments can create "locked-in" vulnerabilities (*chapter-4*).

chapter-2 concludes that transformative long-term urban planning requires understanding and managing the tensions among resilience principles. In practice, these principles can conflict spatially: for instance, enhancing efficiency through dense development may reduce redundancy or ecological diversity. Planners need better evidence on how interventions in one system ripple across others. PSS can help illuminate such trade-offs, but only if underpinned by solid conceptual foundations. *chapter-2* therefore provides a baseline that motivates the theoretical and empirical investigations in *Chapters 3–4*.

Findings for RQ2 (chapter-3: RISE-UP)

How can resilience principles be systematically integrated into urban planning to address climate uncertainty across different contexts?

chapter-3 (RISE-UP) develops a conceptual framework to integrate resilience principles into long-term, adaptive urban planning under climate uncertainty. It employs an exploratory, theory-building approach, using two contrasting case studies - the Metropolitan Region of Amsterdam (MRA) and the Mumbai Metropolitan Region (MMR) - to examine how planners in different contexts interpret resilience principles and long-term planning.

In both regions, climate-related planning responses are mostly incremental, targeting interventions in open spaces or buildings, while longer-lived systems such as energy grids, transport networks, and water infrastructure remain governed by rigid, siloed regimes. Planners in both cities acknowledged the need to update masterplans regularly, yet climate is rarely treated as an explicit factor guiding those updates.

Institutional, economic, and cultural contexts strongly mediate how flexibility versus robustness are prioritised. Amsterdam's highly coordinated, rule-bound planning system ensures stability and technical robustness but tends to discourage experimentation, illustrating robustness without adaptability. In highly developed contexts, an assumed adaptive capacity can breed complacency, allowing latent vulnerabilities to persist [225]. Recent climate extremes in the Global North have revealed "locked-in" risks from past investments and design assumptions.

Conversely, Mumbai's open-ended and improvisational planning approach exhibits *flexibility without institutionalisation* through informal adaptations and reactive measures. This yields a high tolerance to risk but also recurrent infrastructure damage and diminished public trust. MRA planners view MMR's openness as a source of adaptive potential, whereas MMR participants critique it as a symptom of fragility and lack of robust standards. These cross-cultural insights demonstrate that a highly developed planning context does not automatically equate to greater resilience.

Building on this comparative analysis, *chapter-3* presents four propositions for enhancing long-term, adaptive urban planning under climate uncertainty:

1. Flexibility in planning processes is essential to continuously integrate changing variables and evolving conditions into long-term planning.
2. Resolving spatial trade-offs among resilience principles - such as the tension between robustness and flexibility - is necessary for long-term strategies to remain effective across scales.
3. Targeting renewal, redevelopment, and maintenance cycles provides critical entry points for aligning existing urban systems with emerging risks.
4. Embedding multiple urbanisation strategies within formal planning frameworks enables proactive adaptation as scenarios evolve.

chapter-3 concludes by emphasising the need to negotiate trade-offs and to strengthen evidence on system lifecycles and cross-sector interdependencies, so that planning interventions complement rather than confound one another (for example, pairing green infrastructure with engineered drainage to manage flood risk). These insights directly motivate the temporal focus developed in *chapter-4*.

Findings for RQ3 (chapter-4: TIMEWISE)

How can the temporal dynamics of urban systems be conceptualised and leveraged for flexible planning processes to enhance long-term resilience?

chapter-4 (TIMEWISE) focuses on temporality as one of the least addressed dimensions of urban resilience. It shows that although planners increasingly acknowledge that urban change unfolds through overlapping cycles (e.g. building renewal, infrastructural upgrades, demographic shifts), there is a striking absence of planning theories or tools that operationalise this understanding. A core challenge for long-term resilience is how to work within conventionally rigid planning structures anchored in heavy, long-lived infrastructure, while maintaining enough flexibility to adapt to future uncertainties.

Empirically, both Amsterdam and Mumbai exhibit institutional resistance to unconventional or experimental timing in planning. Whether due to fear of failure, political short-termism, or procedural inertia, there is a tendency to avoid deviating from standard planning timelines. This reinforces a self-fulfilling perception that extending beyond the typical 5–10 year planning horizon is futile, especially emphasised in the MMR, and discourages efforts to engage in longer-term strategies.

In MRA, participants critiqued the statutory masterplan as "a tightly wound blueprint that offers no flexibility", suggesting that plans should

incorporate iterative review cycles (one interviewee advocated for "one-third structure, two-thirds freedom") to enable adjustment as new information or technologies emerge. In MMR, overly prescriptive master planning, combined with a volatile, market-driven environment, makes flexibility both politically and economically risky.

Drawing on these findings, *chapter-4* conceptualises misalignments between planning and investment cycles as *arrhythmias* - temporal disjunctions where internal planning tempos are out of sync with environmental change. It argues that enhancing urban resilience depends on realigning these tempos and embedding deliberate feedback loops into planning. Treating maintenance and infrastructure renewal as strategic opportunities, rather than routine operational tasks, can create regular checkpoints to reassess and adjust city plans in light of evolving climate data or societal needs. *chapter-4* proposes flexible planning approaches that make time an organising principle in urban planning. By synchronising plan updates and critical investment decisions with the lifecycles of urban systems (and with global climate assessment cycles), cities can escape rigid long-term commitments and keep options open. In positioning time at the centre of resilience thinking, *chapter-4* builds a bridge from the conceptual insights of *Chapters 2–3* to the methodological innovation of *chapter-5*.

Findings for RQ4 (chapter-5: FutureScapes)

How can design thinking be operationalised to combine qualitative narratives and quantitative models, with expert insights, for decision-oriented future urbanisation scenarios?

chapter-5 (FutureScapes) addresses the practical challenge of bridging the qualitative, narrative-driven side of planning with the quantitative, model-driven side. It builds on the proposition from *chapter-3* that to mainstream climate considerations into long-term planning, cities must develop multiple adaptive urbanisation pathways rather than rely on a single prediction. It also extends *chapter-4* by redefining scenario planning as an iterative, design-led process rather than a one-off exercise.

The methodology uses a design thinking approach to tightly integrate qualitative scenario narratives with stochastic land-use modelling. Instead of treating narrative scenarios and computational models as separate, sequential components, FutureScapes combines them in an iterative loop. Planners articulate narrative "storylines" for future urban development based on local knowledge, values, and policy goals. These narratives then inform model parameters and assumptions, which produce spatially explicit, quantitative scenarios. Creative spatial representations of these scenarios are presented back to planners, whose insights prompt refinements to the narratives and model in tandem. This continuous dialogue ensures that tacit knowledge (experience, preferences, and normative goals) directly shapes model outputs, addressing a key critique from *chapter-2*: many planning tools lack contextual awareness and therefore remain underutilised in practice.

By systematically accounting for qualitative, normative dimensions - such as community visions, design preferences, and policy targets - FutureScapes produces scenarios that are both technically rigorous and grounded in local reality. Multiple plausible futures are generated and tested, rather than aiming for one ostensibly "optimal" forecast. The design-thinking ethos is evident in the way the method encourages continuous prototyping of scenarios and learning through iteration.

The methodology was piloted in the Metropolitan Region of Amsterdam using three scenarios, each evaluated for health and sustainability objectives. Results revealed counter-intuitive trade-offs between goals such as densification, accessibility, and biodiversity. For instance, a scenario inspired by the 15-minute city produced unintended outcomes: increased travel distances for some residents and encroachment on green spaces. Notably, the "Business-as-Usual" scenario yielded the shortest average walking distance between residential and recreational functions (0.44 km), aligning more closely with active mobility goals than the more transformative alternatives [370]. These findings highlight the need for evidence-based scrutiny, as even progressive planning concepts can introduce new vulnerabilities if not tested across spatial and temporal dimensions.

By blending design and modelling expertise with expert inputs, *chapter-5* closes the arc of the dissertation by operationalising theoretical insights from *Chapters 2–4* into a workflow that metropolitan planners can use to design long-term urbanisation strategies that are adaptive, credible, and attuned to planners' values.

Taken together, the four studies chart a progression from critique to innovation: diagnosing the limitations of existing planning approaches and systems (*chapter-2*), advancing theoretical integration between resilience and uncertainty (*chapter-3*), embedding temporality as an analytical dimension of resilience (*chapter-4*), and operationalising this synthesis through a design-thinking methodology (*Chapter-5*).

6.2 Implications for Science

This dissertation advances scholarship on climate urbanism, urban resilience, and long-term urban planning methodologies through four core contributions. First, it synthesises resilience theories and planning-for-uncertainty approaches into a unified conceptual framework, then applies and refines this through cross-case analysis. Second, it offers comparative insights into how institutional and cultural contexts mediate resilience implementation and approaches to uncertainty. Third, it introduces temporality as a critical and often overlooked dimension of planning for resilience, conceptualising arrhythmias and proposing time-aligned planning approaches. Fourth, it proposes a methodological framework - FutureScapes - that blends design thinking with land-use modelling to generate adaptive, spatially explicit planning scenarios. Together, these contributions support the reorientation of urban planning under climate uncertainty.

A. From Fragmentation Towards Integration

A recurring theme is the need to move from fragmented planning approaches towards more integrated ones. *Chapter-2 (PSS)* shows that current planning tools are often sectoral and piecemeal, rarely capturing interdependencies across urban systems. *Chapter-3 (RISE-UP)* links resilience principles (robustness, adaptivity, etc.) with planning approaches under climate uncertainty, showing that even in advanced contexts like Amsterdam, integration is partial: strong coordination exists, but comes with rigidity, while in Mumbai, improvisational adaptation occurs without formal cross-sector integration. *Chapter-4 (TIMEWISE)* highlights a different kind of fragmentation: temporal fragmentation, where short

policy and budgeting cycles are misaligned with infrastructure lifetimes and slow-onset climatic changes, leading to "arrhythmias" in resilience strategies. Finally, *Chapter-5 (FutureScapes)* demonstrates how integration across knowledge types and time horizons is possible by blending narrative scenarios with quantitative models in an iterative process. Across these chapters, the thesis reframes integration not just as connecting datasets or infrastructure, but as synchronising timescales, sectors, and epistemologies in a coherent decision-making process.

B. From "Bouncing Back" to Transformation

Early notions of urban resilience often emphasised stability and bouncing back (rapid recovery to the status quo). This work aligns with a shift toward transformative adaptation - changes that adjust a city's development path rather than merely recovering from disturbances. *Chapter-2* suggests that many planning tools still focus on short-term fixes. *Chapter-3* confirms that both case study regions often equate resilience with maintaining existing functions (or making incremental improvements) rather than pursuing more ambitious long-term changes. *Chapter-4* proposes that true resilience requires reconfiguring how we plan through time, for example by harmonising planning horizons with infrastructure renewal cycles to create windows for change rather than waiting for disasters to force it. *Chapter-5* operationalises this by enabling planners to assess scenarios before committing to them. The analysis of the 15-minute city concept in Amsterdam illustrates that even innovative, sustainability-oriented ideas can create new lock-ins if adopted uncritically. Moving beyond "bouncing back" therefore requires instituting long-term evidence and learning before strategies are fixed. Cities need the capacity to learn before failing - testing and iterating on strategies in advance, and adjusting course after implementation as new information emerges. Transformation is not a one-time project but an ongoing process of critical reflection, adaptation, and course correction.

C. Foregrounding Temporality in Urban Planning

This thesis demonstrates the value of embracing uncertainty within the design of plans. Historically, urban planners have often tried to avoid or control uncertainty by relying on fixed masterplans or "predict-and-provide" approaches. In contrast, this work advocates design-led exploration of multiple futures under uncertainty. *chapter-3* synthesises resilience thinking with planning-for-uncertainty, showing that cities can act despite incomplete information by using flexible, no-regret strategies. *Chapter-4* makes clear that uncertainty is inherently temporal and that aligning planning timeframes with infrastructure lifecycles can create opportunities to adjust within conventional planning work. *Chapter-5* demonstrates one way to design with uncertainty: generating multiple plausible futures and exploring a range of outcomes, so that planners engage with uncertainty proactively rather than ignoring it. This perspective encourages moving away from false certainties (for example, choosing a single "most likely" scenario) and instead considering a spectrum of possibilities. The methodological integration achieved in FutureScapes not only yields richer scenarios; it also fosters a mindset of adaptive planning. Planners become more aware of potential surprises, trade-offs, and tipping points, which in turn reduces overconfidence and tunnel vision.

D. Integrating Different Knowledge Types

Each part of this dissertation brings together multiple forms of knowledge: quantitative data and modelling, qualitative insights, expert judgment, and spatial reasoning. This pluralistic approach underscores the value of methodological versatility in addressing the complexity of climate-related urban challenges.

The FutureScapes methodology in *Chapter-5* uses design thinking to blend the analytical precision of simulation models with the contextual depth of narrative scenarios, producing outputs that are both scientifically robust and grounded in local realities. This helps counter the abstraction inherent in models by embedding planners' values and situated knowledge into scenario planning. The integration of design thinking with rigorous analysis remains relatively novel in computational urban modelling; this thesis demonstrates its potential.

Crucially, the findings affirm that no single knowledge system is sufficient on its own: to plan effectively for climate resilience under climate uncertainty, we must interweave system analytics, imaginative foresight, and stakeholder perspectives. This points toward a more co-evolutionary relationship between planning theory and practice, where theoretical ideas are refined through real-world experimentation and practical constraints drive the evolution of conceptual tools.

6.3 Societal Relevance and Guidelines for Urban Planners

This dissertation addresses a central challenge of our time: the growing misalignment between intensifying climate extremes and urban planning processes that remain poorly equipped to respond under development pressures. Recent climate-related disasters - record-breaking flash floods, unprecedented heatwaves, and protracted urban droughts - highlight that many cities remain ill-prepared for a future of more frequent and intense extremes. At the same time, advances in climate science and urban models increasingly enable practitioners to anticipate threats. This creates both an obligation and an opportunity for urban planning to act proactively.

Across the two metropolitan case studies - Amsterdam (MRA) and Mumbai (MMR) - urban planning for climate risk emerges as shaped by institutional path dependencies, capacity constraints, and spatial lock-ins. Building on the findings, the dissertation proposes **three foundational principles** for long-term planning under climate uncertainty: *flexibility*, *temporality*, and *spatial reasoning*.

The comparative analysis shows that neither regulatory sophistication nor institutional maturity automatically produces flexibility or resilience. MRA illustrates how a highly regulated "fail-safe" planning culture can suppress variability and become risk-averse, while MMR's recurrent disruptions have fostered situational adaptivity through self-organisation and informal resilience practices [221], which remain weakly supported by policy and existing development trajectories. Societal progress therefore depends on embedding flexibility through review loops, scenario testing, option pathways, and iterative master-planning cycles that allow cities to plan before climate risks force disruptive change. While there is considerable inertia in achieving flexibility, the flipside is that without

an overarching vision, flexibility can devolve into volatility and reinforce negative loops.

1. Flexibility in Urban Planning

Flexibility in urban planning must become an explicit objective of the process rather than a coincidental by-product. As demonstrated in *Chapters 3-4*, neither regulatory sophistication nor institutional maturity guarantee flexibility or adaptive capacity. The Amsterdam Metropolitan Region exemplifies a highly structured planning regime that values robustness and predictability, yet this "fail-safe" orientation often limits space for experimentation and constrains planners' ability to adjust to emerging risks. Conversely, the Mumbai Metropolitan Region, operating under looser institutional constraints, exhibits greater situational adaptability, but in the absence of formal mechanisms, the system remains fragile, inconsistent, and heavily reliant on informal or civic initiatives.

> *"If a system is too structured... once the world changes, it is too structured to change." (Interview excerpt)*

The comparison underscores that flexibility is not the automatic outcome of institutional advancement but a quality that must be purposefully built into planning. This includes establishing feedback loops, adaptive master-planning cycles, and scenario-testing processes that enable iterative course correction before risks escalate into crises. As argued in *Chapter-4*, aligning planning decisions with infrastructure renewal windows offers practical entry points for embedding adaptive capacity into long-term strategies.

The absence of planning flexibility carries significant socio-economic risks. In MMR, a lack of anticipatory mechanisms has led to recurring infrastructure failures, a precarious real estate bubble, and increased exposure of vulnerable populations, especially in informal settlements. In MRA, deferred adaptation in ageing infrastructure increases long-term maintenance costs and the risk of locked-in vulnerabilities, despite the region's financial and technical capacities. Rigid planning thus not only heightens risk exposure but can entrench inequality and undermine resilience dividends for future generations.

While cultivating flexibility is a procedural challenge and may not always be possible in rigid urban systems, designing planning mechanisms that enable it to the extent possible must become a socio-political imperative. Flexibility must also be balanced with a clearly articulated long-term vision to ensure it does not reinforce negative development cycles.

2. Temporality in Urban Planning

Time must become a foundational organising principle in urban planning - a lens through which climate risk, infrastructure investment, and short- and long-term policy cycles are harmonised.

Chapter-4 illustrates that cities operate with deep temporal misalignments: infrastructure lifecycles span decades, planning instruments are locked into fixed intervals, and climate disruptions unfold unpredictably. This limits the capacity to respond meaningfully to slow-onset climate risks or to seize critical intervention windows after fast-onset disasters. As [29] and [36] argue, the lack of long-term foresight has tangible societal

costs in the form of maladaptation and missed opportunities. When infrastructure investments are based on short-term assumptions, they can embed long-term inequalities (e.g. limited access to green space, urban heat islands) that become increasingly difficult to reverse.

Cities must therefore evolve from static plans to *living codes*: planning instruments that are time-stamped, require mandatory multi-year review cycles, and back-cast from recent climate events or revised thresholds. Some progressive planning guidelines, such as those by ICLEI and Louisiana's Coastal Master Plan, already recommend mid-cycle reviews between three and six years to incorporate the latest climate science and changing local conditions.

While full alignment of budget cycles with infrastructure renewal cycles may be unrealistic, particularly in capitalist systems driven by immediate returns, this thesis argues that aligning planning logic - rather than entire budget structures - with urban lifecycles is both feasible and necessary. Each major urban system programme (e.g. sewers, roads) could include a code-update protocol that synchronises fiscal, infrastructural, and regulatory cycles and provides option pathways to meet climate goals. Such mechanisms require less budget overhaul than a shift in governance culture: from rigid adherence to long-term projections to agile planning that evolves with temporal signals and emerging risks.

The FutureScapes methodology demonstrates how scenario planning, backed by design thinking and urban modelling, can help cities design multiple long-term urbanisation strategies. To institutionalise foresight, cities could establish decade-based review cycles tied to IPCC assessments or UN-Habitat frameworks. Crucially, they must first define what "long-term" means in their spatial and governance context and embed appropriate temporal granularity in planning decisions.

> *"Markets want one number, but planners work within plausible ranges." (Interview excerpt)*

3. Spatial Thinking to Plan for Uncertainty

Climate uncertainty must be rendered visible in space, because it is through space that risks are concentrated, experienced, and potentially mitigated. Many current policy frameworks articulate resilience goals but remain detached from spatial decision-making, leading to what [371] terms *optimism bias in plans*.

chapter-3 illustrates this blind spot: resilience principles like robustness, redundancy, and adaptability are often adopted conceptually but remain weakly grounded in spatial structure. It also proposes that transformative long-term planning requires reconciling trade-offs between principles with opposing spatial and temporal effects, which are challenging to perceive without spatial analysis. Systems thinking is essential when translating principles into spatial strategies.

Chapter-5 shows, with the help of a computational model, that even progressive concepts such as the "15-minute city" or compact city can involve trade-offs [372]. They must be scrutinised across multiple variables - connectivity, land-use diversity, ecological structure - and their interactions over time. This is especially important because climate strategies and their spatial implications are rarely visible in regional master plans or urbanisation strategies.

Spatial mismatches between resilience goals and planning practices can amplify inequalities, for instance when flood buffers protect high-income areas while exposing informal settlements, or when compact city policies increase land values and displace vulnerable populations. Trade-offs such as structure versus diversity, or efficiency versus redundancy, must therefore be recognised as political and social questions, not just technical design choices.

> *"There is an optimal balance between structure and diversity in an ecosystem. Cut these rhythms loose... make plans that are a bit abstract so programmes can change." (Interview excerpt)*

Conclusion. By foregrounding *flexibility*, *temporality* and *spatial reasoning*, this thesis contributes both a scientific foundation and a societal compass for re-imagining how cities learn, adapt, and evolve amidst the turbulence of climate change. Ultimately, it reframes urban planning as a temporal undertaking: one that integrates systems thinking, adaptive planning, and design-based experimentation into learning systems capable of navigating an uncertain climate future.

6.4 Future Research and Limitations

While this research breaks new ground in conceptualising and operationalising long-term resilience planning, it also has limitations that open avenues for further inquiry. The comparative case design - one Global North and one Global South metropolitan region - provided rich, contextual insights and allowed for theory-building through contrast. However, two cases alone cannot capture the full diversity of metropolitan experiences worldwide. The propositions and frameworks generated (for example, the resilience planning propositions and the temporality concept of arrhythmia) invite testing and refinement in other cities. Future research should examine a broader set of metropolitan regions, including mid-sized cities and those in different cultural or climatic contexts, to assess how generalisable these findings are and to discover new patterns beyond the scope of this dissertation. Comparative and longitudinal analyses across cities at different stages of institutional maturity and climate exposure could yield a more representative understanding of planning under uncertainty and support more transferable frameworks and methods.

A major practical challenge encountered was data availability, especially in the Mumbai Metropolitan Region. The research faced significant constraints due to inconsistent or coarse data on infrastructure, land use, and socio-economic variables in MMR. This limitation not only affected the precision of models and analyses for Mumbai, but also reflects a wider structural issue: many cities in the Global South operate with fragmented, outdated, or inaccessible planning datasets. Such data scarcity is not merely a technical gap but a manifestation of broader institutional and resource inequalities that shape how planning knowledge is produced, validated, and applied. Recognising and addressing this data and knowledge divide between well-resourced urban contexts and those where foundational planning data remain sparse is essential for advancing equitable and globally relevant approaches to climate resilience.

Addressing this may require methods that can work with limited data, such as leveraging remote sensing, crowd-sourced information, or AI-driven techniques to generate proxies for infrastructure and risk data.

There is promising progress in satellite-based mapping of informal settlements and machine-learning models that predict future growth, which could empower planners in data-scarce cities. Investing in open data platforms and inter-agency data sharing would also help reduce these inequities. Despite extensive efforts (including local partnerships and research fellowships), some analyses in this thesis could not reach the level of detail achieved in Amsterdam simply due to structural data gaps. Future projects should continue to innovate ways to conduct rigorous resilience assessments even where traditional data are lacking.

Regarding the methodological advancements in scenario planning (*Chapter-5*), an inherent trade-off exists between complexity and usability. The FutureScapes approach, while integrative, still relies on modelling choices that simplify reality (as any model must). There is scope to enhance the scalability of this method by incorporating multiple modelling paradigms.

A key methodological insight emerging from this dissertation is that conventional scenario-based approaches are fundamentally limited in their ability to represent deep uncertainty. As shown in the ESREL study by [373], CA-based models like Metronamica typically rely on expert-defined scenarios constrained by fixed suitability values and rigid "Story-and-Simulation" narratives. This restricts the exploration of the full space of plausible futures, especially when climate variables interact nonlinearly with land-use drivers. The difficulty of deriving representative maps from thousands of simulations, due to low intra- and inter-cluster similarity, further illustrates how sensitive spatial outcomes are to small changes in uncertain parameters.

These challenges highlight a broader methodological lesson: for climate-resilient urban planning, scenario modelling must evolve beyond deterministic pathways toward more flexible exploratory approaches. Coupling CA models with exploratory modelling enables sampling across wide uncertainty ranges, revealing alternative spatial configurations that conventional scenarios miss, but it also exposes computational and analytical burdens: large simulation loads, unstable clustering outputs, and difficulties in translating uncertainty into actionable planning insights. These findings reinforce the argument that long-term planning under uncertainty requires tools and methodologies capable of accommodating variability, ambiguity, and nonlinearity.

Emerging technologies offer an important frontier for advancing long-term, resilience-oriented urban planning. The rise of AI, digital twins, and big data analytics has the potential to transform Planning Support Systems by enabling richer simulations, real-time feedback loops, and rapid exploration of thousands of uncertainty-informed scenarios. These capabilities address several limitations identified in this thesis, particularly the restrictions of conventional scenario modelling and the difficulty of representing deep uncertainty within existing frameworks. However, as argued throughout, PSS must be embedded in inclusive, human-centric design processes that foreground qualitative judgement, local knowledge, and value-driven deliberation. The challenge ahead is therefore not only to expand computational capacity, but to integrate advanced tools into participatory, transparent planning practices.

Finally, although this dissertation focused primarily on planning processes and methodologies, the ethical and justice dimensions of resilience are an essential companion to future work. Whose futures are being envisioned? Who benefits from resilience investments, and who might be excluded? Climate adaptation efforts can inadvertently exacerbate social inequalities

if not carefully managed. Subsequent research should engage more deeply with questions of climate justice and equity in urban resilience. This might involve case studies of community-driven resilience initiatives, analyses of how vulnerable groups can be better included in planning (especially in the "majority" Global South), or frameworks for evaluating the distributional impacts of long-term plans to create more inclusive urban environments.

In sum, the way forward for urban planning in the climate era is not about predicting a single certain future but about cultivating the capacity to adapt as uncertain futures evolve. This dissertation has taken initial steps toward that vision by integrating resilience thinking, temporal analysis, and design methodology. The limitations noted here provide valuable lessons to refine these ideas. As cities around the world grapple with unprecedented change, the approaches developed - iterating, synchronising time horizons, and blending knowledge systems - lay the groundwork from which planners, researchers, and communities can continue to innovate. By planning for multiple evolving possibilities rather than a static end-state, cities can better adapt, transform, and thrive in the face of whatever the future brings.

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Appendix

Allianz Award 2024: Winning Essay

A

Winning Essay for the Allianz Climate Risk Award, for scientists at the start of their career whose work sheds light on the nexus between climate change and extreme weather events.

Riding Out the Storm: Proactive Urban Planning for Catastrophic Flood Resilience

In recent years, Western Europe has been drowning in catastrophic floods that far exceed the predictions of official hazard maps. In 2021, several rivers burst their banks, dams and dikes were pushed to the brink, and entire regions faced unprecedented levels of flooding, highlighting the need for more effective risk management strategies and resilient urban planning frameworks to protect vulnerable communities [1,2,3].

A.0.1 Minimizing Risks but Still on Shaky Ground

Engineered flood defenses—such as dikes, dams, and seawalls—are often seen as silver bullets for managing flood risks [4]. The Delta Programme in the Netherlands, considered a gold standard in water management, aims to reinforce over 1,500 kilometers of dikes and 426 structures to establish a ”baseline” level of protection [5]. However, recent disasters have exposed the Achilles' heel of even the best defenses, underscoring the need for a more comprehensive approach that includes both planning and insurance solutions for extreme weather. Damage to engineered structures can worsen risks from heavy rainfall and storm surges. Regions protected by dikes rely heavily on pumping capacity to manage floods, but a 5-meter sea level rise would require 60 times the pumping power of the largest facility in the Netherlands. Moreover, these defenses can create a false sense of security—a levee effect [6]—encouraging risky development in vulnerable areas. As climate conditions change, traditional methods like raising dikes are increasingly out of their depth, necessitating innovative approaches [7].

Further, as these once-rare catastrophic events become more frequent, they stretch the insurance industry to its limits. For instance, efforts to expand flood insurance in the Netherlands often hit a wall due to the high premiums required to cover such risks. Insurers tend to resort to short-term fixes and impose regulations to mitigate market fallout from catastrophic events. This mindset is also seen in urban planning, where low-probability, high-impact risks are often overshadowed by more immediate development priorities [8, 9].

A.0.2 Planning for the Worst

To build long-term resilience, urban planners and insurers must collaborate to think outside the box and promote preventive and adaptive measures, such as relocating from flood-prone areas and providing risk-adjusted insurance. This study explores how scenario-based planning can guide resilient urban growth in the face of catastrophic flooding, advocating for innovative strategies that go beyond traditional risk management methods.

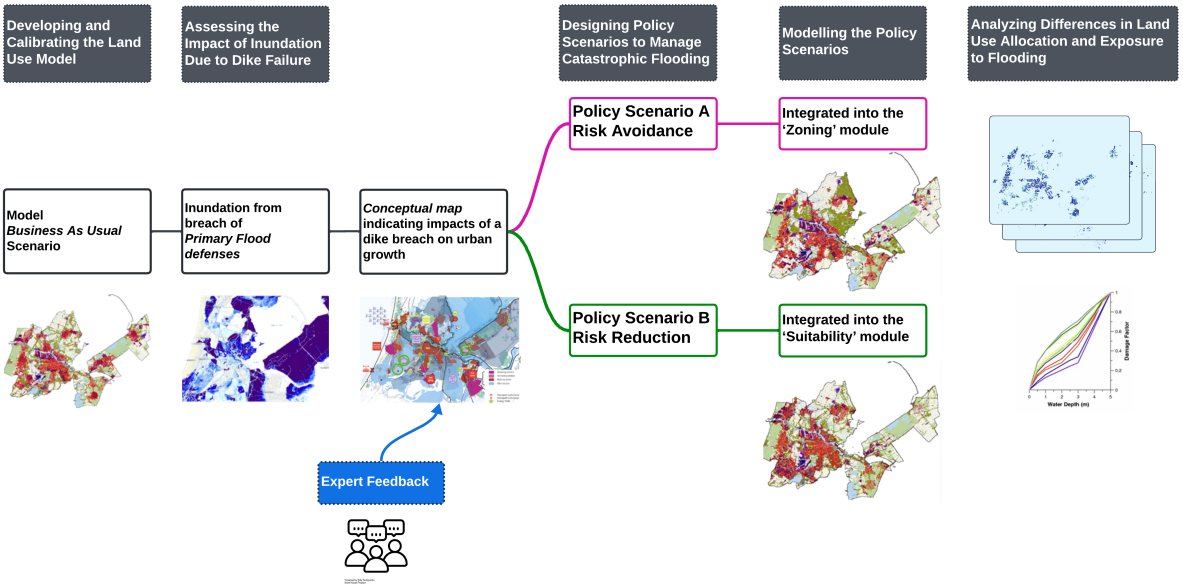

Figure A.1: Research Methodology highlighting the development of the land use model, the integration of the flood risk map, and the design and modeling of policy scenarios to manage catastrophic flooding from the failure of flood defenses. The methodology includes steps for scenario development, spatial modeling, and policy analysis to explore the impacts of different flood management strategies.

Managing extreme risks requires a multi-pronged approach: (1) risk-informed urban planning, (2) targeted upgrades of flood defenses, and (3) comprehensive insurance policies. These elements must work hand in glove to mitigate immediate threats while reducing long-term vulnerabilities. Planning with worst-case scenarios in mind is crucial, especially when major shifts—like relocating settlements, reinforcing dikes, and integrating flood management with broader goals—are necessary. These strategic decisions often require decades due to the long game of infrastructure development and the complexity of decision-making processes [8].

This research aims to chart a new course by assessing the spatial impacts of catastrophic flooding on urban regions, focusing on: (a) how different risk management strategies can guide urban growth to mitigate long-term risks, and (b) adapting policies to reduce future risk exposure.

We employ a mixed-methods approach, blending computational land-use models, expert insights, and desk research to evaluate two contrasting policy responses: Risk Avoidance and Risk Minimization. We focus on the Metropolitan Region of Amsterdam (Netherlands), a key economic hub in Western Europe, heavily investing in critical infrastructure yet highly vulnerable to sea-level rise and water management challenges. The region relies almost entirely on the IJmuiden pumping complex on the North Sea coast, which is already stretched beyond capacity, posing a significant flood risk (see Fig A.1).

- Scenario A (Risk Avoidance): "Better Safe Than Sorry": This scenario enforces strict regulations to prevent development in flood-prone areas and relies on robust structural engineering interventions to mitigate risks.
- Scenario B (Risk Minimization): "Walking the Tightrope": This approach balances flood risk with urban growth needs, incorporating adaptive measures like flexible zoning and green infrastructure to soak up floodwaters.

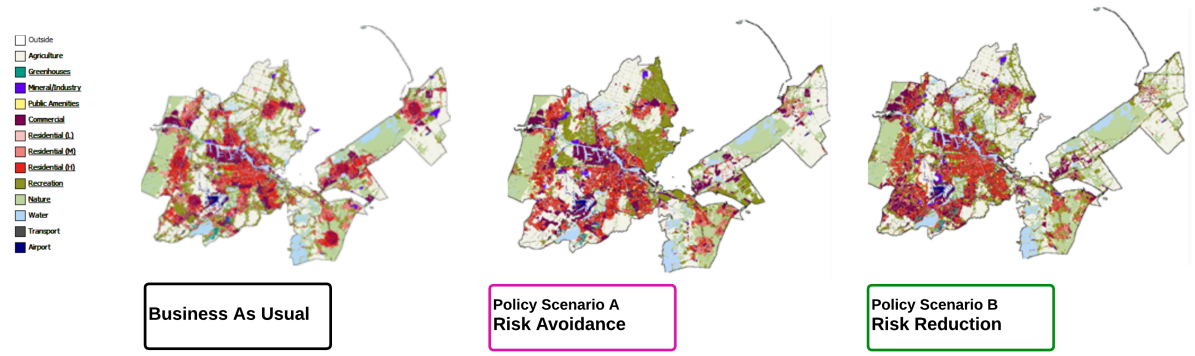

Figure A.2: Comparison of Urban Growth Patterns under different policy scenarios for managing catastrophic flooding from flood defense failures. The figure illustrates urban expansion under Scenario A (Risk Avoidance), where development is steered away from high-risk flood-prone areas; Scenario B (Risk Reduction), which balances flood risk with urban growth needs, incorporating adaptive measures within flood-prone areas; and the Business as Usual (BAU) scenario, representing growth without specific flood management interventions.

A.0.3 Navigating the Trade-Offs

Under each scenario, we analyze urban structure, land-use allocation, and risk exposure using the Global Flood Depth Damage Function. Comparing these with a Business As Usual scenario reveals the give-and-take between risk avoidance and risk minimization scenarios. Restrictive measures may conflict with development goals, while flexible strategies could enhance resilience but require careful management of cumulative risks (see Fig A.2).

Our goal is to paint a picture of long-term solutions for a future where climate-change-induced extreme flooding is a given. With that in mind, this study adopts a precautionary principle, assuming extreme inundation due to defense failure, to encourage a shift from reactive to proactive policy making. The scenario maps are designed to spark discussions among strategists and insurers about integrating these findings into master plans updated every 5 to 20 years.

A.0.4 Implications for the Insurance Industry

The research underscores the need for insurers and urban planners to join forces in building resilience. Developing shared visualization tools, like extreme scenario maps, can help both sectors better understand the impacts of catastrophic flood risks, consider both short- and long-term challenges, and adopt strategies that both regulate premiums and incentivize resilience-building efforts [10, 11]. This collaborative approach can provide a guideline for navigating an increasingly uncertain climate future, ensuring sustainable urban development and more secure, prepared communities.

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Paper: Incorporating Climate Risk into Urban Land-Use Models

B

Published as:

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Cities are complex socio-technical systems under tremendous stress due to climate change. To incorporate resilience into urban plans and move towards evidence-based long-term decision-making, it is essential to unravel complex land-use dynamics and the effect of climate uncertainties on cities. This study develops an integrated framework combining flood probability maps and land-use change modeling through exploratory modeling. The approach integrates flood uncertainties into the Metronamica Cellular Automata model and uses clustering to analyze resulting spatial outcomes. Applied to the Metropolitan Region of Amsterdam, the framework provides spatially explicit alternatives for climate-resilient development and supports resilience-informed decision-making.

Introduction

The recent impacts of climate-induced disasters have proven the need to shift away from conventional urban planning and introduce resilient and long-term, evidence-based decisions relying on data analytics to account for interactions and ripple effects within complex urban systems. Urban decision impacts extend far into the future, and while short-term responses are typically made in the aftermath of disasters, these must be complemented by adaptive decision-making to account for long-term uncertainties [263].

To achieve this ambition, it is essential to understand the complex dynamics of land-use change in cities. Urban land-use change models enable decision-makers to analyze the relationships between the driving forces of urban growth and to explore alternative futures by simulating hundreds of possible scenarios.

Cellular Automata (CA)-based models have become popular for spatially explicit exploration of urban growth, as they can integrate multiple drivers and processes relevant to land-use dynamics [632]. Built with in-depth expert knowledge and extensive quantitative and qualitative data, CA models can capture the non-linearity and self-organization of urban systems, producing realistic representations of how complex urban systems evolve and how spatial patterns change over time [114].

While CA models hold promise, their main limitation is that they can typically incorporate only a small number of scenarios using the conventional *Story and Simulation (SaS)* approach. This limits the comprehensive consideration of possible climate futures [358]. Consequently, climate-related uncertainties—particularly those related to extreme events—have

limited representation in CA-based frameworks. Structural approaches to systematically integrate climate uncertainties into CA land-use models remain scarce [207].

This research addresses this gap by developing an integrated framework that combines CA and exploratory modeling to investigate the impacts of climate uncertainties on long-term land-use changes. Specifically, we integrate flood probability maps into land-use suitability assessments and connect the CA framework with exploratory modeling to analyze multiple climate uncertainty scenarios systematically.

We selected **Metronamica**, a well-established CA-based modeling platform, to simulate land-use changes across a broad range of urban functions [362]. Metronamica allows dynamic simulation of spatial competition between land-use categories, such as residential, commercial, and industrial zones, under a set of suitability and policy constraints.

To capture the long-term uncertainties associated with climate risks—particularly flooding—we link Metronamica with the **Exploratory Modeling and Analysis (EMA) Workbench** [647]. This integration enables the translation of multiple flooding probability scenarios into hundreds of spatially explicit outcomes, thus expanding the model's ability to assess uncertainty systematically.

The following sections describe the data, methodological framework, and case study used to demonstrate this integrated approach for the Metropolitan Region of Amsterdam (MRA). The MRA serves as a representative urban region facing the dual challenges of climate exposure and rapid urban expansion, making it an ideal testbed for assessing how deep climate uncertainties may affect spatial planning and resilience-oriented policy decisions.

Methods and Materials

Land-Use Change Modeling

Cellular Automata (CA)-based land-use change models have gained popularity due to their ability to integrate multiple factors contributing to urban growth in spatially explicit ways [641, 642]. In this study, we used the **Metronamica** CA modeling framework developed by RIKS, which provides an integrated approach to model dynamic interactions among demographic, economic, and spatial factors [631]. Unlike single-sector models, Metronamica allows consideration of multiple interacting urban processes such as population growth, infrastructure expansion, and zoning policies.

Metronamica's land-use allocation component models how different land-use classes (LUCs) compete for spatial dominance within the model boundary. The following key factors influence the allocation process:

- **Local accessibility:** including roads, railways, and stations.
- **Physical suitability:** elevation, slope, and soil characteristics.
- **Zoning regulations:** such as protected areas, airports, and nature reserves.
- **Attraction/repulsion between LUCs:** spatial interactions defining proximity preferences.

Spatially Explicit Exploratory Modeling

Exploratory Modeling (EM) is a decision-support approach for analyzing outcomes under conditions of deep uncertainty [647]. Unlike traditional scenario-based planning, EM generates and analyzes hundreds or thousands of simulations without requiring predefined scenarios, thereby reducing bias from modelers and planners.

Conventionally, the **Exploratory Modeling and Analysis (EMA) Workbench** is used for non-spatial decision problems. In this research, we extend EMA to operate in a **spatially explicit** manner by coupling it with Metronamica. This combination allows sampling and combination of uncertain climate variables—specifically, flood probabilities—and generating multiple land-use outcomes.

The EMA Workbench was used to define ranges of uncertain parameters, sample combinations of flood probabilities, and automate simulation runs in Metronamica. Each simulation produces a land-use map representing spatial allocation under a unique combination of uncertain flood conditions. These maps are then analyzed and clustered to reveal dominant spatial patterns and variability.

Integrating Flood Probability

We use suitability values to determine the appropriateness of a LUC to occupy a specific position under a specific probability of flooding. A standard Metronamica simulation requires a fixed suitability value for each simulation. However, we argue that the impacts of flood probability categories and damages cannot be accurately translated into a single set of suitability values. Instead, we assign a range of values for each LUC to model the impact of climate uncertainties.

We use the EMA workbench to define the upper and lower bounds of the flood suitability ranges that influence the land-use allocation module in Metronamica. EMA samples values between the lower and upper bounds of the uncertain parameters. Metronamica uses these samples to generate outcome maps that indicate how land-use changes under different flooding probabilities. Fig. B.1 demonstrates the overall workflow of the integrated modeling framework between Metronamica and EMA workbench *.

Case Study: Metropolitan Region of Amsterdam

The study area modelled is the Metropolitan Region of Amsterdam (MRA) in the Netherlands. The MRA is an agglomeration of 32 municipalities and houses 2.5 million people, 14% of the country's total population. MRA's economic attractiveness has led to high inward migration, housing shortage, and pressure on existing infrastructure systems. The region faces accelerated climate threats from rainfall and sea-level rise, making it an ideal case to study the impacts of climate change on long-term urban planning.

* The full codebook may be accessed at https://github.com/feifeiyuzhuzhu/Master_thesis.

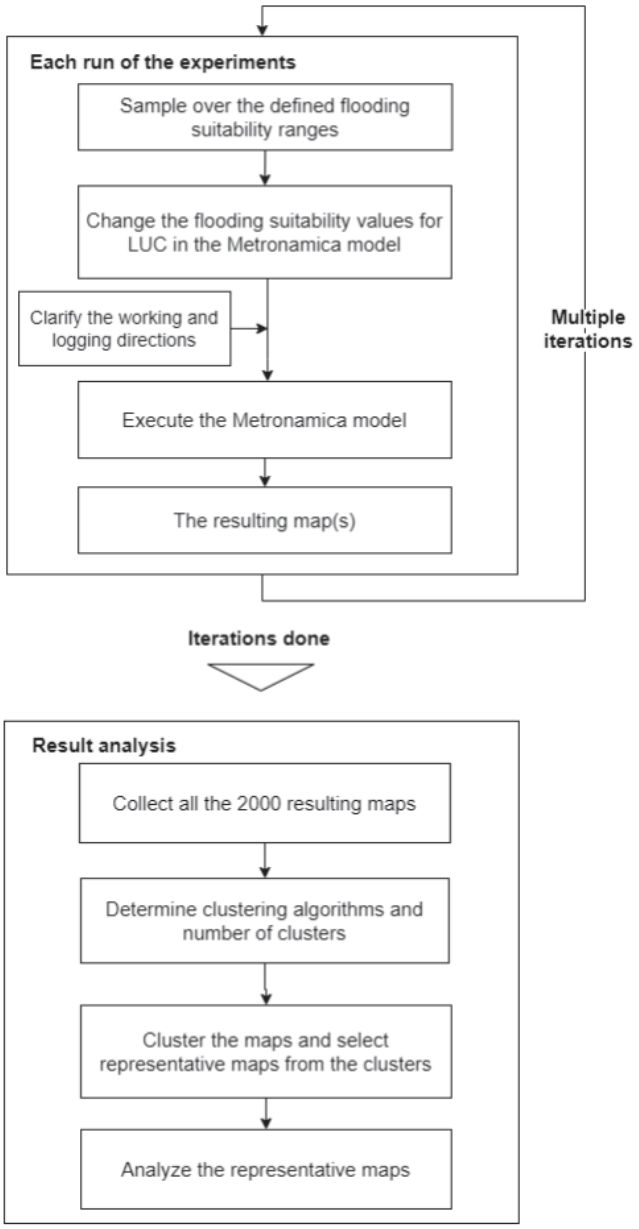

Figure B.1: Overall workflow of the integrated modeling framework connecting Metronamica and the EMA Workbench.

Data Sources and Model Calibration

Data were obtained from open-access databases:

- **Dutch Central Bureau of Statistics (CBS):** demographic and land-use data.
- **Publieke Dienstverlening Op de Kaart (PDOK):** geographic base layers.
- **Netherlands Environmental Assessment Agency (PBL):** land-use projections.
- **OpenStreetMap (OSM):** transport infrastructure.

All spatial layers were prepared as raster datasets at a **100 × 100 m resolution** to capture sufficient detail for urban analysis. The base Metronamica model was calibrated using historical land-use maps (1996–2015) to define

attraction–repulsion rules among LUCs (e.g., *Commercial* tends to cluster near *Public Amenities*).

Flood Probability Data

Flood data were obtained from the *KlimaatEffectAtlas Netherlands* (2050 projections). We use the probability of flooding exceeding 50 cm in depth — a threshold at which significant damages occur [498]. Flood probabilities range from once in 30 years to once in 30,000 years (return periods).

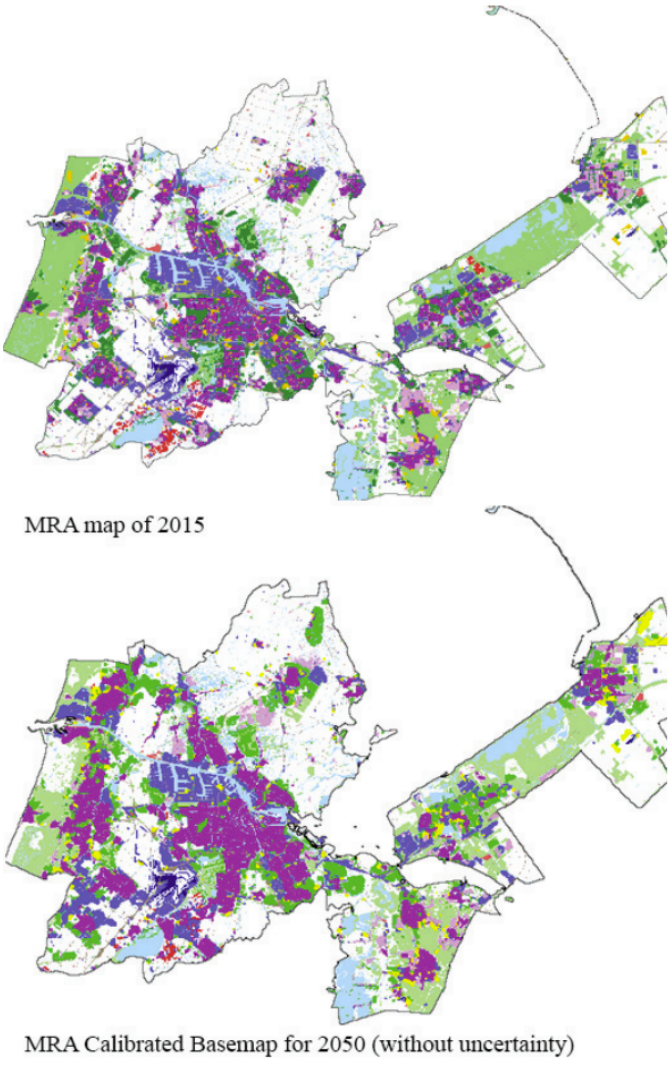

Figure B.2: Baseline (2015) and simulated land use (2050) for the Metropolitan Region of Amsterdam.

Setting up the Baseline Scenario

Suitability Values

The baseline scenario defines suitability values for each LUC based on flood probability and expected damage levels. Suitability values range from 0 (unsuitable) to 1 (highly suitable). Table B.1 summarizes these

for five flood probability categories: Extremely Small (ESP), Very Small (VSP), Small (SP), Medium (MP), and High (HP).

Table B.1: Suitability values for the baseline scenario under increasing flood probabilities.

Land-Use Class	ESP	VSP	SP	MP	HP
Nature	1.0	1.0	1.0	1.0	1.0
Agriculture	1.0	1.0	0.9	0.9	0.8
Recreation	1.0	0.9	0.9	0.8	0.7
Industry	1.0	0.9	0.9	0.8	0.7
Greenhouses	1.0	0.9	0.8	0.7	0.6
Residential (L)/Public	1.0	0.8	0.6	0.4	0.2
Commercial/Residential (M)	1.0	0.8	0.5	0.3	0.1
Residential (H)	1.0	0.7	0.4	0.2	0.0

Uncertainty Ranges

Flood probabilities were grouped into three categories—low, medium, and high—to balance computational efficiency and variability in outcomes. EMA sampled these ranges to represent uncertainty across scenarios.

Table B.2: Uncertainty ranges for suitability of each land-use class under different flood probability categories.

Land-Use Class	**Low Probability**	**Medium Probability**	**High Probability**
Nature	1	1	1
Agriculture	(0.9, 1.0)	(0.8, 0.9)	0.8
Recreation/Industry	(0.9, 1.0)	(0.7, 0.9)	0.7
Greenhouses	(0.8, 1.0)	(0.6, 0.8)	0.6
Residential (L)/Public	(0.6, 1.0)	(0.2, 0.6)	0.2
Commercial/Residential (M)	(0.5, 1.0)	(0.1, 0.5)	0.1
Residential (H)	(0.4, 1.0)	(0.0, 0.4)	0.0

Clustering Algorithms

A total of **2,000 simulations** were conducted, producing 2,000 land-use maps. To interpret these results, multiple clustering techniques were tested, including:

1. Agglomerative clustering (complete linkage, 3 clusters)
2. Agglomerative clustering (average linkage, 3 clusters)
3. Agglomerative + Multidimensional Scaling (MDS = 4, 4 clusters)
4. Agglomerative + MDS = 9, 4 clusters

The clustering was evaluated using the **Kappa Index**, which measures similarity between maps [637]. Ultimately, 14 clusters were identified, with 34 representative maps selected based on highest, lowest, and median similarity scores.

Selection of Representative Maps

Representative maps were chosen to summarize the land-use change patterns in each cluster:

- **Highest/lowest variation maps:** determined by total pairwise Kappa scores (18 maps).
- **Random selections:** replacing duplicates across clusters (8 maps).
- **Outliers:** included to capture unique patterns excluded in clustering (8 maps).

A total of **34 maps** were analyzed for subsequent comparison with the baseline 2050 map.

Results

In all simulation experiments, the total allocation of land-use classes (LUCs) satisfied the projected spatial demands. In other words, incorporating flood exposure and uncertainty did not affect the total volume of urban growth but rather its spatial distribution.

To assess the influence of flood uncertainty, we compared each of the 34 representative maps generated from the exploratory simulations with the baseline 2050 map (without uncertainty ranges). The comparisons were made visually and quantitatively, through cell-by-cell differences in land-use allocation.

Land-Use Changes from 2015 to 2050

The representative maps illustrate significant changes in land-use composition between 2015 and 2050 under flood probabilities exceeding 50 cm. Figure B.3 shows examples of representative maps selected from different clustering algorithms.

Overall, we observe that **Residential areas become more compact and connected**, with a marked increase in high-density zones in flood-safe regions. Low- and medium-density residential classes are frequently converted to high-density types to accommodate population growth.

In the baseline scenario (see Figure B.2), a large share of *Residential (H)* appears in a zone (Location 1) characterized by a high probability of flooding. When flood uncertainty is incorporated, the same area shows a significant reduction in *Residential (H)* allocation. Instead, land is reassigned to a mix of *Residential (M)* and *Recreation*, both of which exhibit higher suitability under moderate flood probabilities.

This reallocation indicates that incorporating flood risk changes the spatial attractiveness hierarchy of land-use classes. *Residential (H)* suitability (0.4–0.7) under high flood probabilities drops markedly, steering growth toward safer, more absorptive functions such as *Recreation* and *Nature*.

Location 2: Low Flood Probability Zone

In the northeast MRA (Location 2), the baseline scenario projects a rise in *Residential (M)* areas. As this zone has low flood risk, the integration of flood uncertainty shifts growth further toward *Residential (H)*. Additional *Nature* and *Public Amenities* appear adjacent to residential zones—likely to support rising population densities and because these categories maintain high suitability values under low-probability flooding.

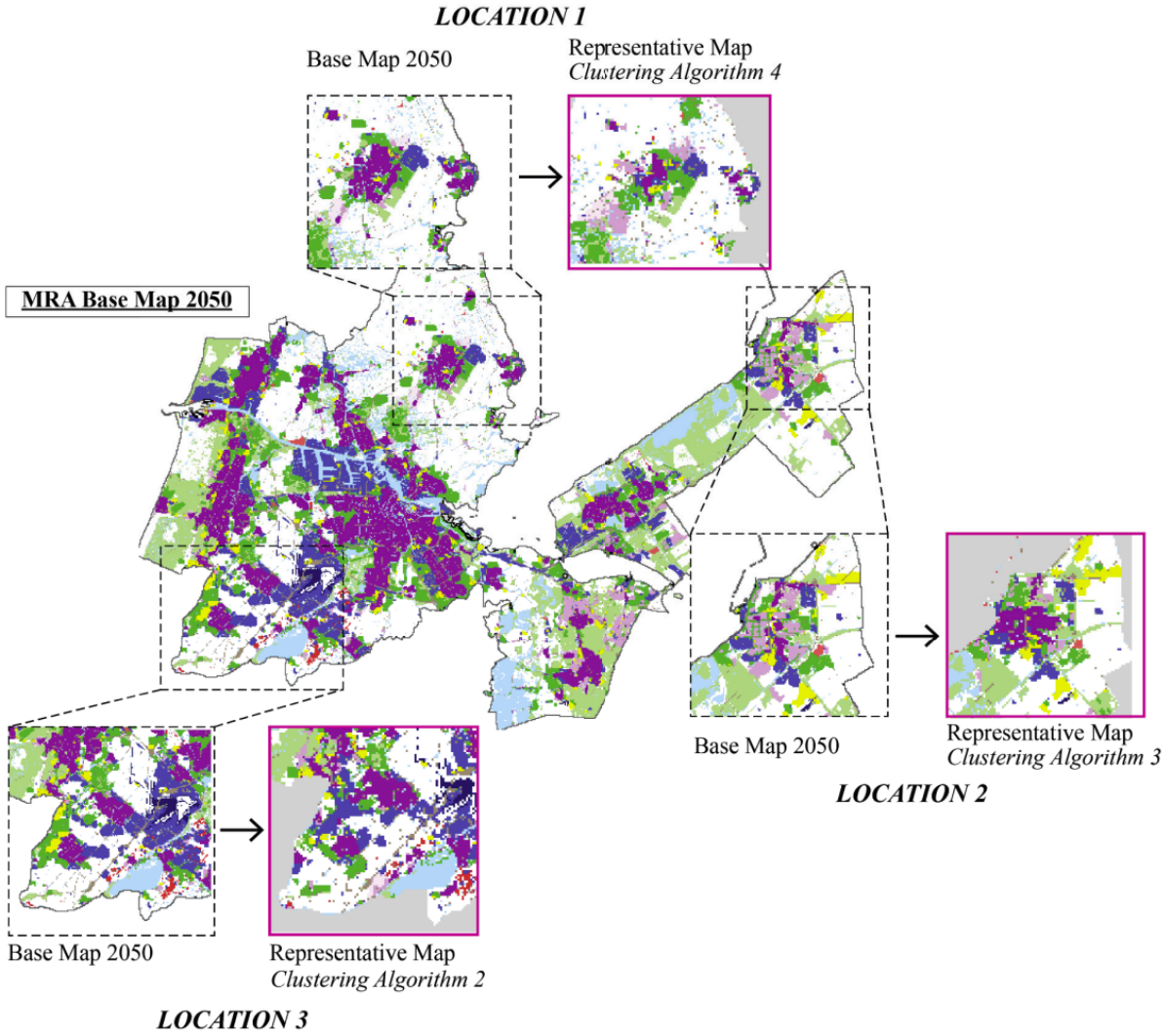

Figure B.3: Comparison of baseline (2050) versus representative land-use maps under flood uncertainty, generated from different clustering algorithms. Key classes: Residential (H) (purple), Residential (M) (dark pink), Residential (L) (light pink), Agriculture (white), Nature (green), Commercial (blue), Public Amenities (yellow), Recreation (light green).

Location 3: Medium Flood Probability Zone

In the southwest MRA (Location 3), baseline simulations indicate substantial expansion of *Commercial* areas near Schiphol Airport. This area, however, is classified as a medium flood-risk zone. When flood uncertainty is modeled, the *Commercial* distribution becomes more dispersed and shifts westward, away from high-risk zones.

This redistribution suggests that while total commercial demand remains constant, spatial allocation adapts to minimize flood exposure. *Mineral and Industry* areas shrink as demand declines between 2015 and 2050, reflecting broader economic transitions.

Effects of Flood Uncertainty on Land-Use Patterns

Across the 34 representative maps, three consistent patterns emerge:

1. **Resilient densification:** High-density residential zones concentrate in low-risk areas, whereas vulnerable flood-prone areas transition to recreational or open-space uses.
2. **Spatial redistribution of economic functions:** Commercial and industrial zones are reallocated to medium-risk zones near transport corridors that remain economically viable yet less exposed.
3. **Expansion of green buffers:** Nature and recreational land uses expand along high-risk peripheries, providing ecological buffer zones and enhancing flood absorption capacity.

These findings illustrate that incorporating flood uncertainty into the CA model leads to spatial adaptation rather than reduction in total growth potential. It enables planners to visualize trade-offs between urban development and resilience objectives.

Cluster Analysis Insights

Clustering analysis revealed that different flood-suitability combinations produce spatially distinct but thematically consistent outcomes. Figure B.3 summarizes typical spatial configurations identified across clusters.

- **Cluster 1:** Compact growth in existing urban centers with peripheral green buffers.
- **Cluster 2:** Polycentric pattern with multiple medium-density nodes distributed across municipalities.
- **Cluster 3:** Expansion along transport corridors with strong zoning effects near the airport.

Among the algorithms, the agglomerative clustering with *complete linkage* provided the most balanced distribution of maps across clusters and the highest intra-cluster similarity (Kappa ≥ 0.85). Maps from this cluster were therefore used as reference cases for further comparison.

Representative Map Selection and Interpretation

From the total 2,000 runs, 34 maps were selected using three criteria:

1. Highest and lowest variation in each cluster (18 maps).
2. Randomly selected substitutes for duplicate clusters (8 maps).
3. Outliers representing extreme configurations (8 maps).

Together, these maps capture the plausible range of spatial outcomes under future flood uncertainty scenarios. The differences between representative and baseline maps underscore the necessity of incorporating probabilistic climate data into land-use planning tools.

Key Takeaways

- Flood risk integration changes the *spatial suitability hierarchy*, steering high-value functions to safer elevations.
- Uncertainty sampling via EMA reveals spatial extremes that deterministic models overlook.
- The integrated Metronamica–EMA workflow enhances transparency and reproducibility in scenario evaluation.

Overall, the results demonstrate that accounting for deep flood uncertainty supports climate-resilient urban planning by identifying spatial configurations that maintain functionality while minimizing exposure.

Discussion and Conclusions

Climate change presents a profound challenge for cities, and enhancing resilience against climate-induced shocks has become a strategic priority for decision-makers worldwide. Because urban form evolves slowly, today's spatial decisions largely determine a city's vulnerability or resilience for decades to come. Yet, many existing resilience strategies remain conceptual and lack spatially explicit analysis.

This study introduced an integrated framework that combines **Cellular Automata (CA)**–based land-use modeling (Metronamica) with **Exploratory Modeling and Analysis (EMA)** to evaluate the long-term effects of flood uncertainty on urban land-use change. The approach enables systematic sampling of uncertain climate variables and their translation into spatially explicit outcomes.

Applied to the Metropolitan Region of Amsterdam (MRA), the framework produced a large ensemble of simulated land-use maps, clustered to identify representative spatial configurations. Results reveal that, although total urban growth remains constant, spatial distribution patterns shift significantly once flood uncertainty is considered. High-density residential and commercial zones migrate toward safer locations, while vulnerable areas are re-allocated to recreational and green uses that can better absorb flood impacts.

Methodological Contribution

The main methodological innovation lies in the explicit coupling of CA and exploratory modeling:

- It bridges quantitative land-use simulation with uncertainty analysis, expanding beyond the limited "Story-and-Simulation" approach.
- It allows decision-makers to visualize a wide range of plausible futures rather than a few deterministic ones.
- It offers a transparent and replicable workflow (see Figure B.1) for linking physical flood data with spatial planning models.

Policy and Planning Implications

Integrating flood uncertainty into spatial planning supports:

1. **Evidence-based decision-making:** providing spatial evidence of risk-exposure trade-offs.
2. **Resilient land-use allocation:** enabling planners to prioritize safe zones for high-value urban functions.
3. **Adaptive policy design:** allowing planners to iterate and test strategies under multiple futures.

By linking flood probability data with urban growth models, the framework helps translate climate projections into actionable urban design and zoning strategies. The outputs—representative maps and spatial clusters—can serve as communication tools between scientists, policymakers, and local governments to co-create resilient development pathways.

Concluding Remarks

The integrated Metronamica–EMA framework demonstrates a feasible path to embed climate uncertainty into urban simulation workflows. It extends conventional planning models by producing **spatially explicit, uncertainty-aware insights** that can guide resilient urban development. Furthermore, the approach can be replicated for other metropolitan regions, enabling comparative studies of climate-resilient growth trajectories.

Future Work

Although the current framework captures flood-related uncertainties through physical suitability parameters, other dimensions of uncertainty remain unexplored.

Model Extensions

- **Zoning and neighborhood dynamics:** Future work will incorporate uncertainty in zoning policies and neighborhood interaction coefficients within the CA framework.
- **Socio-economic indicators:** Integrating socio-economic variables such as income, employment, and mobility patterns could improve predictive capacity.
- **Longer time horizons:** Extending simulations beyond 2050 would reveal additional insights into the compounding effects of climate change and urban densification.

Stakeholder Engagement

Collaboration with MRA planners and decision-makers will help tailor the model to planning objectives and refine scenario selection. Co-designing representative futures can ensure that model outcomes inform real-world investment and adaptation strategies.

Data and Model Refinement

Data quality is a limiting factor for future projections. Improved flood-probability data beyond 2050 could be derived through spatio-temporal hydrological modeling and collaboration with climate experts. Integrating more complex land-use transitions (e.g., redevelopment cycles) may further enhance realism.

Outlook

By embedding uncertainty analysis within spatial planning models, cities can transition from reactive to proactive climate adaptation. The proposed framework lays the groundwork for scalable, resilience-oriented planning tools that support robust, long-term urban development under deep uncertainty.

Appendices for each Chapter C

C.1 PSS: Planning support systems for long-term climate resilience, a critical review

Corpus of Non-academic (Practice) Documents analyzed as part of this study

Global Frameworks

- **2020** – *Adaptation Principles: A Guide for Designing Strategies for Climate Change Adaptation and Resilience.* Author: World Bank Group.
- **2020** – *Integrating Climate Adaptation Toolkit.* Author: C40 Cities.
- **2019** – *Resilient Cities, Thriving Cities.* Author: ICLEI.
- **2018** – *CityStrength Diagnostic.* Author: World Bank Group.
- **2018** – *Guidebook for Urban Resilience.* Author: ASEAN.
- **2018** – *100 Resilient Cities Handbook.* Author: Rockefeller Foundation.
- **2018** – *The EU Strategy on Adaptation to Climate Change.* Author: European Commission.
- **2018** – *From Planning to Action: Mainstreaming Climate Change Adaptation into Development.* Author: World Resources Institute.
- **2018** – *CityRAP Tool – City Resilience: Action Planning Tool.* Author: UN Habitat.
- **2017** – *How to Make Cities More Resilient.* Author: UNDRR.
- **2017** – *Climate Action Planning Framework.* Author: C40 Cities.
- **2017** – *Building a Climate Resilient City.* Author: IISD.
- **2016** – *World Bank Group Climate Change Action Plan.* Author: World Bank Group.
- **2016** – *Urban Responses to Climate Change: Framework for Decisionmaking and Supporting Indicators.* Author: RAND Corporation.
- **2016** – *Climate Resilient and Disaster Safe Development.* Author: NIUA.
- **2015** – *Guiding Principles for City Climate Action Planning.* Author: ICLEI.
- **2015** – *Integrating Climate Change into City Development Strategies.* Author: Cities Alliance.
- **2014** – *Urban Climate Change Resilience.* Author: Asian Development Bank.
- **2014** – *Planning for Climate Change: A Strategic, Values-Based Approach for Urban Planners.* Author: UN Habitat.
- **2014** – *Building Urban Climate Change Resilience: A Toolkit for Local Governments.* Author: ICLEI ACCCRN.
- **2013** – *City Resilience Index.* Author: Arup.
- **2013** – *Building Resilience: Integrating Climate and Disaster Risk into Development.* Author: World Bank Group.
- **2013** – *Building Urban Resilience: Principles, Tools, and Practice.* Author: World Bank Group.
- **2013** – *A Framework of Urban Resilience Planning – UNDP-IIHS Working Paper on Integrated Planning for Development.* Author: UNDP-IIHS.
- **2012** – *Guidelines for National Adaptation Plans.* Author: UNFCCC.
- **2011** – *Guide to Climate Change Adaptation in Cities.* Author: World Bank Group.
- **2011** – *Catalyzing Urban Climate Resilience.* Author: ACCCRN.
- **2010** – *Climate Resilient and Sustainable Urban Development.* Author: DFID, IEP.
- **2009** – *Climate Resilient Cities: A Primer on Reducing Vulnerabilities to Disasters.* Author: World Bank Group.
- **2007** – *Adapting to Climate Change in Urban Areas.* Author: IIED.
- **2007** – *Climate Change Adaptation by Design: A Guide for Sustainable Communities.* Author: TCPS London.

City / Country-Specific Reports

- **2020** – *Action Plan for the Amsterdam Climate Proof.* Author: City of Amsterdam.
- **2020** – *Guiding Framework for India's Long-Term Strategy: Adaptation.* Author: TERI, India.
- **2020** – *Mainstreaming Urban Resilience: Lessons from Indian Cities.* Author: TERI, NIUA.
- **2020** – *Climate Resiliency Design Guidelines.* Author: New York City Mayor's Office.
- **2020** – *Chicago Climate Action Plan.* Author: Chicago Climate Task Force.
- **2020** – *Climate Action | Planning for Climate Adaptation.* Author: SWECO.
- **2020** – *Southern California Climate Adaptation Planning Guide.* Author: Government of Southern California.
- **2019** – *Chennai Resilience Strategy.* Author: GIZ Climate Smart Cities.
- **2019** – *Durban Climate Action Plan.* Author: GIZ Climate Smart Cities.
- **2019** – *Pune Resilience Strategy.* Author: GIZ Climate Smart Cities.
- **2019** – *Climate Ready Boston.* Author: City of Boston.
- **2018** – *Bangladesh Delta Plan.* Author: Bangladesh Planning Commission.
- **2018** – *Planning and Investing for a Resilient California.* Author: Governor's Office, California.
- **2018** – *Building Urban Resilience with Nature – A Practitioner's Guide to Action.* Author: 100RC, Earth Economics.
- **2018** – *Climate Change Adaptation Strategy: Vancouver.* Author: City of Vancouver.
- **2017** – *Rotterdam Resilience Strategy.* Author: City of Rotterdam.
- **2017** – *Coastal Hazards and Climate Change.* Author: Ministry for Environment, New Zealand.
- **2017** – *Enhancing Urban Resilience: Accra.* Author: World Bank Group.
- **2017** – *Making Fiji Climate Resilient.* Author: GFDRR, ACP–EU Natural Disaster Risk Reduction Program.
- **2017** – *Developing City Resilience Strategies: Lessons from the ICLEI–ACCCRN Process.* Author: ICLEI–ACCCRN.
- **2017** – *Pittsburgh Climate Action Plan.* Author: City of Pittsburgh.
- **2016** – *Brazil National Adaptation Plan to Climate Change.* Author: Ministry of Environment, Brazil.
- **2016** – *Singapore's Climate Action Plan.* Author: National Climate Change Secretariat, Singapore.
- **2016** – *Adapting with Ambition.* Author: Ministry of Infrastructure and Water, Netherlands.
- **2016** – *Kenya National Adaptation Plan.* Author: Ministry of Environment, Kenya.
- **2015** – *National Climate Resilience and Adaptation Strategy.* Author: Australian Government.
- **2015** – *Portland Climate Action Plan.* Author: City of Portland.
- **2015** – *King County Strategic Climate Action Plan.* Author: King County.
- **2015** – *Coastal Urban Climate Resilience Planning in Quy Nhon, Vietnam.* Author: IIED, Rockefeller, ACCCRN.
- **2014** – *Fundamental Plan for National Resilience.* Author: Government of Japan.
- **2014** – *National Action Plan for Climate Change Adaptation, Indonesia.* Author: National Development Planning Agency (BAPPENAS), Indonesia.
- **2013** – *Climate Proofing Guwahati, Assam.* Author: TERI.
- **2012** – *Climate Change in Asia and the Pacific: How Can Countries Adapt?.* Author: Asian Development Bank.
- **2012** – *A Workbook on Planning for Urban Resilience in the Face of Disasters: Adapting Experiences from Vietnam's Cities to Other Cities.* Author: World Bank Group.
- **2012** – *Baltimore Climate Action Plan.* Author: City of Baltimore.
- **2011** – *Building the Netherlands Climate Proof: Urban Areas.* Author: Deltares, UNESCO-IHE.
- **2011** – *Managing Risks and Increasing Resilience: The Mayor's Climate Change Adaptation Strategy.* Author: Mayor's Office London.
- **2011** – *Catalyzing Urban Climate Resilience: Applying Resilience Concepts to Planning Practice in the ACCCRN Program.* Author: Institute for Social and Environmental Transition.
- **2009** – *Understanding and Responding to Climate Change in Developing Asia.* Author: ADB Knowledge Institute.
- **2007** – *Preparing for Climate Change: Guidebook for Local, Regional, and State Governments.* Author: ICLEI.
- **2004** – *Adaptation Policy Frameworks for Climate Change: Developing Strategies, Policies and Measures.* Author: UNDP.

Sector-Specific Reports

- **2019** – *Urban Water Resilience Approach.* Author: Rockefeller Foundation.
- **2019** – *Climate Change and Critical Infrastructure – Storms.* Author: EU Science Hub.
- **2018** – *EC-RRG Resilience Guidelines for Providers of Critical National Telecommunications Infrastructure.* Author: Cabinet Office, UK.
- **2017** – *Vulnerability Assessment and Adaptation Framework.* Author: Federal Highway Administration, USA.
- **2017** – *Building a Climate-Resilient City: Electricity and ICT Infrastructure.* Author: Prairie Climate Center.
- **2016** – *Delta Programme 2019.* Author: Ministry of Infrastructure and Water, Netherlands.
- **2016** – *Toward Climate-Resilient Hydropower in South Asia.* Author: World Bank Group.
- **2015** – *Building Climate Change Resilience for Electricity Infrastructure.* Author: Power Grid Corporation of India.
- **2013** – *Increasing Climate Change Resilience of Urban Water Infrastructure.* Author: Asian Development Bank.
- **2011** – *Adapting to Climate Change: Strengthening the Climate Resilience of Water Sector Infrastructure in Khulna, Bangladesh.* Author: ADB Knowledge Institute.
- **2011** – *Keeping the Country Running.* Author: Cabinet Office, UK.

Special Projects

- **2015** – *Rebuild by Design.* Author: Rockefeller Foundation and partners.
- **2015** – *Towards an EU Research and Innovation Policy Agenda for Nature-Based Solutions.* Author: European Commission.
- **2012** – *Thames Estuary 2100.* Author: UK Environment Agency.

C.1.1 Pre-processsing data for LiTCoF Analysis

1. **Removal of words:** We first removed words that were overused but irrelevant such as *results, copyright, important, provided* in addition to conjunctions, adverbs, mathematical symbols, and numbers. We then removed relevant but overused words that did not bring much value to the analysis but ended up skewing results like *city, urban and data.*
2. **Merging words**: Words that shared the same meaning like *sustainable- sustainability, flooding-flood risk, flexibility-flexible* were merged. Plural and singular versions of the same word were merged.
3. **Grouping words:** This was the most important iteration to arrive at richer insights. Based on the preliminary rounds of analysis, we grouped together terms belonging to a single infrastructure sector or system to capture their combined frequencies. This was done in cases where terms on sub-sectors were too dispersed to provide relevant results. A few examples are given below:.
    - Energy: power, electricity, fossil fuel, industry.
    - Flood-control: dams, dikes, levees, seawalls, flood protection.
    - Transport: roads, railway, rail, port, airports, logistics.
    - Water: waterways, stormwater, wastewater, groundwater, etc.

C.2 Chapter 3: RISE-UP: Resilience in urban planning for climate uncertainty

Process of identifying academic literature on urban resilience planning frameworks *

1. **Literature Search:** Boolean search using Scopus. Search String (urban OR city) AND climat* AND (resilience OR adaptation) AND framework (n=1460).
2. **Screening of Titles.** Discuss the implementation of resilience in urban planning (n= 51).
3. **Screening of Abstracts.** Looking deeper into papers that discuss urban resilience planning frameworks.
4. Papers that specify Urban Resilience Principles that guide Planning Responses (n=20).

List of selected academic papers on Urban Resilience Planning frameworks and the Resilience Principles they discuss.

Table C.1: Table indicating the evolution of resilience principles discussed in academic frameworks on urban resilience.

S.no	Year	Document Ref.	Urban Resilience Principles mentioned in relation to urban planning						
			Adaptivity	Buffer	Connectivity	Diversity	Efficiency	Flexibility	Innovation
1	2003	[38]	Y			Y	Y		
2	2011	[438]	Y			Y		Y	
3	2011	[200]				Y			
4	2012	[201]	Y	Y	Y	Y			
5	2012	[198]				Y		Y	
6	2012	[218]	Y			Y			
7	2013	[203]	Y					Y	
8	2013	[439]	Y			Y		Y	
9	2013	[440]						Y	
10	2013	[12]	Y	Y		Y			
11	2014	[441]	Y		Y	Y	Y	Y	
12	2014	[196]	Y			Y			
13	2016	[442]				Y		Y	
14	2016	[14]	Y			Y	Y	Y	
15	2016	[9]	Y	Y	Y	Y		Y	
16	2016	[10]	Y	Y	Y	Y		Y	
17	2018	[524]			Y	Y	Y	Y	Y
18	2018	[11]	Y	Y	Y	Y		Y	
19	2019	[50]	Y		Y	Y	Y		Y
20	2020	[197]	Y	Y	Y	Y		Y	

* Papers accessed on: 30 Nov 2021

Table C.2: Table indicating the evolution of resilience principles discussed in academic frameworks on urban resilience.

S.no	Year	Document Ref.	Urban Resilience Principles mentioned in relation to urban planning					
			Modular	Multi-scalar	Multifunc.	Redun-dancy	Robust	Self org
1	2003	[38]				Y	Y	Y
2	2011	[438]						
3	2011	[200]		Y		Y	Y	Y
4	2012	[201]	Y	Y		Y		Y
5	2012	[198]	Y			Y	Y	
6	2012	[218]				Y		Y
7	2013	[203]					Y	
8	2013	[439]					Y	
9	2013	[440]				Y		
10	2013	[12]				Y		
11	2014	[441]				Y	Y	
12	2014	[196]				Y		Y
13	2016	[442]						
14	2016	[14]				Y	Y	
15	2016	[9]	Y			Y		
16	2016	[10]	Y					
17	2018	[524]	Y	Y	Y	Y		
18	2018	[11]	Y			Y	Y	
19	2019	[50]				Y	Y	
20	2020	[197]			Y		Y	

List of Planning Documents assessed for each case study †

1. **Case Study 1: Metropolitan Region of Amsterdam (MRA)**
   a) Strategie Klimaatadaptatie Amsterdam (Feb 2020) / https://bit.ly/3AId2sO
   b) Structuurvisie Amsterdam 2040 (Feb 2011) / https://bit.ly/3obNkbb
   c) MRA Urbanization Concept, Metropolitan Region of Amsterdam (Nov 2011) / https://bit.ly/33XsKVk
   d) Metropoolregio Amsterdam Klimaatbestendig/ (Action Plan) (2020) / https://bit.ly/3o9vq9d

2. **Case Study 2: Mumbai Metropolitan Region (MMR)**
   a) Regional Plan for the Mumbai Metropolitan Region (Apr 2021) & https://bit.ly/34dZpWh
   b) Development Plan for Greater Mumbai 2014-34 (2014) / https://bit.ly/3G9cpcZ
   c) Maharashtra State Adaptation Action Plan on Climate Change (2014) / https://bit.ly/3Gh6h2q
   d) Disaster Risk Management Master Plan Mumbai (2009) / https://bit.ly/3IMthYF

Summary of Semi-structured Interview Protocol 1

Each semi-structured interview was approximately 60 minutes long and conducted online using Zoom/Teams video calls due to Covid-19-related travel restrictions.

† Date of Access: 15 January 2022

1. **Introduction [5']**
    a) Introductions and overview of the research.
    b) Major climate-related projects and the participants' role in them.

2. **Climate-related planning responses and Sectoral focus** (selection from the following questions based on the participant's background) [15'].
    a) Perception and integration of climate in urban planning over the years.
    b) Regions in focus for planning and renewal projects.
    c) Knowledge sources and scenarios used.
    d) How to spur urban reforms that are climate resilient?
    e) At what spatial scale can these be translated as projects?

3. **Long-term thinking (beyond the current planning timelines [5]**
    a) Time horizons for planning.
    b) Adopting an uncertainty perspective in a complex context.

4. **Planning Variables and Values [10']**
    a) Key drivers of growth.
    b) Institutional preferences and biases.
    c) Reflections from leading and implementing key projects.

5. **Knowledge gaps and institutional challenges [10']**
    a) Issues with the current master planning process.
    b) Big knowledge gaps in long-term planning decisions for land use and infrastructure.
    c) Regulatory and policy challenges.
    d) Requirements and constraints for planners.

6. **Looking ahead [10']**
    a) Future vision and issues not addressed.
    b) Successful and unsuccessful examples.

7. **Wrapping up [5']**
    a) Room for additional questions and comments.
    b) Anything off the record? (not included in the analysis).
    c) Other experts to connect with.

C.3 Chapter 4: TIMEWISE: Temporal Dynamics for Urban Resilience

Summary of Semi-structured Interview Protocol 2

Each semi-structured interview was approximately 60 minutes long and conducted online using Zoom/Teams video calls due to Covid-19-related travel restrictions.

Overview

1. Experience working in urban planning and climate change space.
2. Fundamental issues with the current urbanization processes.

Endogenous Lifecycles

1. Perspectives on long-term thinking.
2. Planning timeframes, speed and duration of change and decision-making.
3. Updating and renewing plans and windows to integrate new information.
4. Spatial and temporal aspects of climate risks.

Exogenous Drivers

1. External drivers of urban change such as politics, finance, technology, and climate.
2. Approaches to managing disruptions and disasters.

Planning Approaches

1. Climate change-related projects and approaches in urban planning.
2. Approaches and tools used.
3. Long-term projects, sectoral focus, greenfield/ brownfield, public/private, and other development models.
4. Major knowledge gaps and institutional challenges.

Full protocol may be accessed at the 4TU.ResearchData Repository.

C.4 Setting Up the Computational Land Use Model for the Metropolitan Region of Amsterdam

Corresponding data and land use model files are available at: https://github.com/supadupa09/MRA-Model.git

This supplementary note describes the land use model used for scenario modelling of the Metropolitan Region of Amsterdam. The note discusses model setup, how it works, data sources & processing, model calibration and validation and model performance metrics. The authors would like to acknowledge the work of Aarthi Sundaram (former Masters's student at TU Delft), who was the research assistant in developing the model.

Land use model

We develop the land use model using Metronamica, which utilizes a constrained Cellular Automata (CA) approach [632]. CA models have become a widely adopted method for studying complex urban systems due to their effectiveness in capturing disaggregate and dynamic processes. They provide a flexible and neutral framework for simulating land use changes and urban growth. Since urban growth occurs over time and space, these models are essential for understanding the mechanisms of urban expansion and the unique spatial patterns that emerge [114]. CA models are particularly valued for their predictive capabilities and utility in policy development, enabling the analysis of dynamic urban growth and the evaluation of potential policy impacts.

A CA land use model divides a geographic area into a grid of cells, with each cell representing a small spatial unit assigned a specific land use type (e.g., residential, commercial). The model simulates changes in land use over time by applying predefined rules that govern how each cell's state changes. These rules consider the cell's current state, the states of neighboring cells, and external influences such as socio-economic drivers and environmental constraints. By iteratively applying these rules, the model forecasts the evolution of land use patterns, providing planners with a tool to analyze and visualize potential urban growth and land use changes over time.

Metronamica

Metronamica [362] (www.metronamica.nl) is a versatile, spatially explicit land use modeling framework developed by the Research Institute for Knowledge Systems BV, designed for urban and regional planning applications. Serving as a Spatial Decision Support System (SDSS), Metronamica integrates multiple drivers and processes crucial for understanding and evaluating land use dynamics [362]. It is developed within the Geonamica software environment as a standalone application featuring a user-friendly graphical interface. The Metronamica user interface caters to two types of users: policy analysts and scientists or modellers. Policy analysts use the system within their policy processes to conduct scenario and impact assessments. In contrast, scientists and modellers can update the underlying data, adjust parameters, and modify the model equations if necessary. The system incorporates the Map Comparison Kit for analyzing model outcomes, and both tools support data formats compatible with standard GIS packages such as ArcGIS. Metronamica enables interactive simulations to assess the effects of various external factors (e.g., macro-economic shifts, population growth) and policy interventions (e.g., land use zoning, conservation policies, densification strategies) on the regional development of urban, regional, national, or continental areas on an annual basis.

Model Structure

The core of Metronamica is a CA-based land use allocation component that simulates land use changes over time using a 'competition for space' principle. In this model, different actors - depending on their economic and political power - compete to occupy the most desirable locations. Planning and policy interventions can support or mitigate these competitive dynamics to achieve a more favourable future. Land use changes are modelled by considering various driving factors.

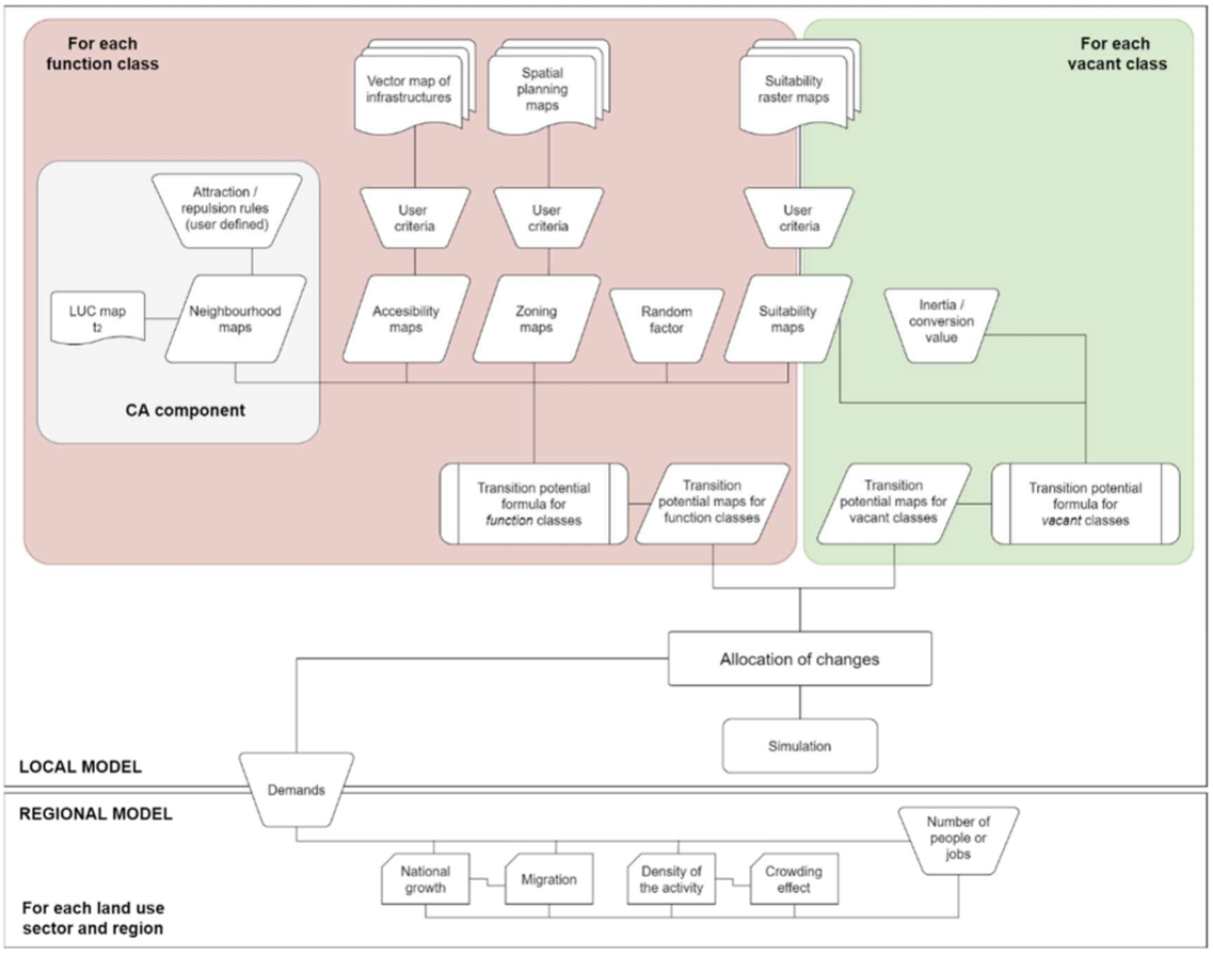

Figure C.1: Graphic representation of the Metronamica Land Use Change modelling framework.

Firstly, external influences, such as population growth and the reduction of natural areas, affect the demand for different land uses. Population and employment are distributed across regions based on their attractiveness to residents and businesses, influenced by factors such as existing activities and regional characteristics like accessibility. Within each region, the allocation of land use for specific locations is determined by a combination of socio-economic factors (e.g., the potential success of a business at a particular site), policy considerations (e.g., regulations restricting new housing developments), and biophysical factors (e.g., the suitability of soil for agriculture).

A key feature of Metronamica is its modularity, which allows several independent modules to integrate, enabling the model to seek an optimal solution at the system level rather than focusing solely on maximizing economic, social, or ecological aspects. Each module requires its own specific data inputs, as outlined below:

1. Physical suitability, represented by one map per land use function modelled. The term suitability is used here to describe the aptness of a cell to support a particular land use function and its associated activity.
2. Zoning or spatial planning, represented by one map per land use function modelled. For different planning periods, the map specifies which cells can and cannot be taken in by the particular land use and how strict or flexible the various plans are.
3. Accessibility, represented by one map per land use function modelled. Accessibility is an expression of the ease with which an activity can fulfil its needs for transportation, mobility and other facilities in a particular cell, based on the proximity to infrastructure networks.
4. Human behaviour, represented by spatial interaction rules simulating the preferences of various actors for certain locations based on the land uses surrounding the location, including their power to occupy the most desirable locations.

If the potential of a location is sufficiently high, a particular function will occupy that space; if not, it will seek

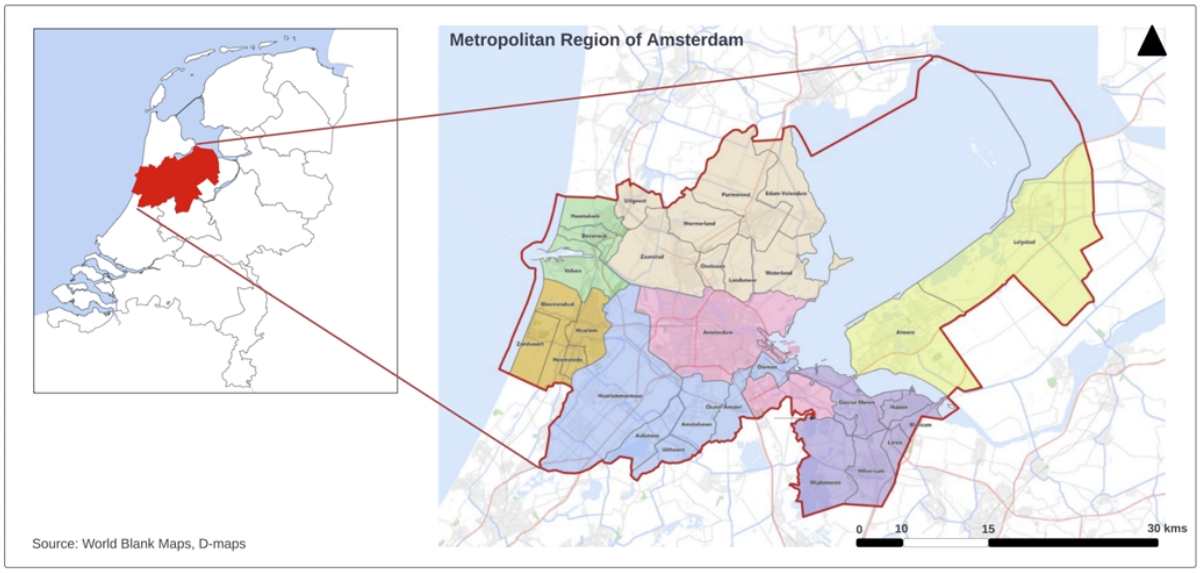

Figure C.2: Location and Map of the modelling area - the Metropolitan Region of Amsterdam (MRA), the Netherlands

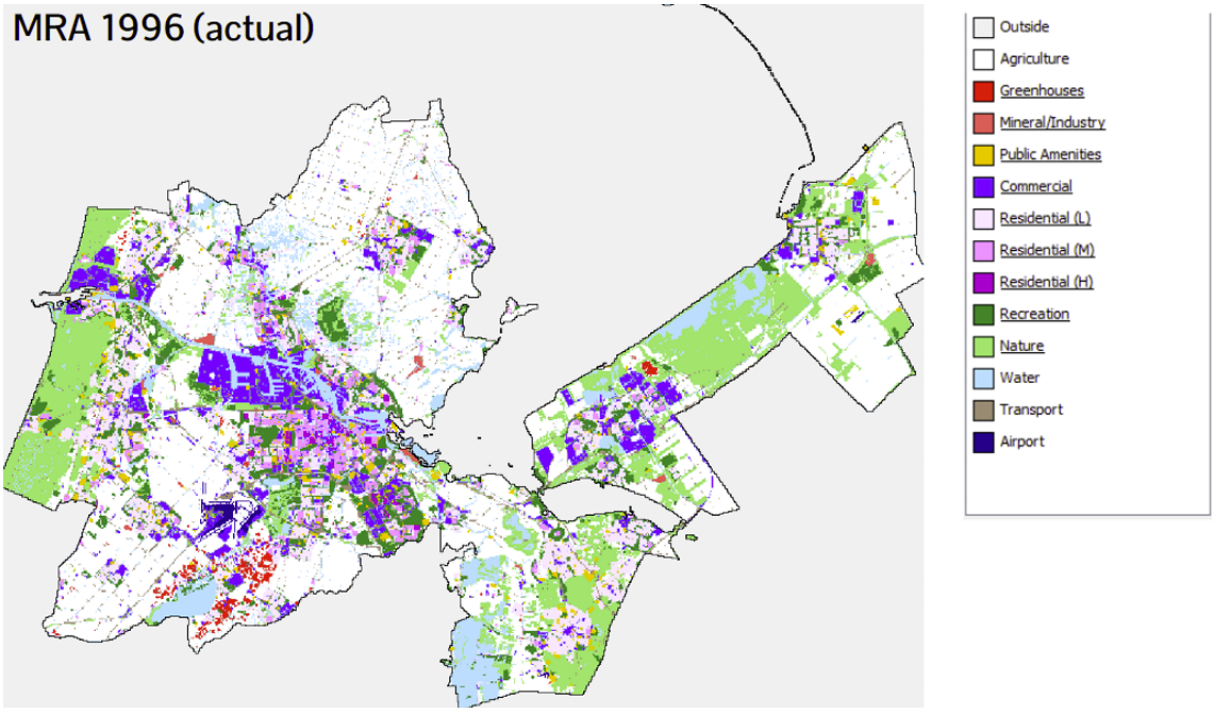

Figure C.3: Initial Land Use Map of the MRA (1996), starting point of the calibration

out more attractive areas. As new activities and land uses emerge in a neighborhood over time, they alter the attractiveness of existing activities and other potential land uses searching for space. This process contributes to the model's highly non-linear behaviour.

Data Inputs and processing

Region Map: This map forms the basis of the model, whereby the geographic scope of the study area is specified. The region map is a raster map of the exact resolution as the landuse map (100x100m), where each cell contains a value of 0 (outside the modelling area) and 1 (inside the modelling area). Every map input into

Metronamica is overlaid on top of the region map. For every cell for which its underlying value in the region map is 1, that cell will be included in the transition potential calculation and excluded otherwise.

Preparing Land use Raster Maps

Land Use maps in Metronamica are input as raster maps. The original landuse maps are first clipped to the MRA boundaries (extent of the region map). The original landuse map (one that has not been processed or regrouped for the model yet) was procured from CBS, which had 37 LUs. We extracted maps for the following years: 1996, 2006, 2016. However, as every landuse class input into Metronamica requires neighbourhood rules, accessibility, suitability and zoning values associated with it, including a large number of classes (more than 15) makes the calibration process cumbersome given the resources of this project. Hence, the original 37 subclasses are regrouped into 13 broad LUCs.

A resolution of 100 by 100 meters was selected because detailed land use categories (LUCs) were available at this scale, and it was considered appropriate for modelling the dynamics of the Amsterdam region. The value assigned to each cell corresponds to the 'Value' of the associated category, which must remain consistent across all maps. Fig C.3 shows the raster file generated for 1996 with the regrouped LUCs.

The dataset includes as many LUCs as possible; however, for the model, these are regrouped into broader categories to meet the project's requirements and reduce the computational resources needed for simulations. The LUCs to be input into Metronamica are classified as follows:

- Vacant: These are classes that other LUCs can potentially take over if the latter expands in growth in future years. This is also determined by other restrictions such as land Suitability and Zoning policies.. Examples: Agriculture, barren land, open nature, etc.
- Functional: These are dynamic classes and the most important from an urban growth perspective. These include LUs subject to change by external factors such as socio-economic changes, climate impact, and active change through the years. These include Residential (High, Medium, and Low density), Mineral/Industrial, Commercial, Public Amenities, and Recreation, including smaller water bodies and selected Nature reserves.
- Feature: These are LUCs that remain more or less fixed over time and have the least potential for change. These include major water bodies, airports, and transport infrastructures such as roads and railways.

Splitting Residential Classes

The original dataset featured only a single residential class. However, research shows that low- and medium-density residential areas have distinct land use dynamics, which are essential for accurately capturing urban behavior. To account for these differences, we subdivided the residential land use (LU) into three categories - low-density, medium-density, and high-density - by combining population data with information on residential areas. The steps taken were as follows (Fig C.4):

- Spatial Data of Population: Population counts for 1996 (used for calibration) were obtained at a 500x500m grid level for the MRA region.
- Overlay: The population grid was overlaid on the residential land use patches extracted from the original land use map. The area of each polygon was calculated and added to the attribute table.
- Spatial Join: A spatial join was performed between the two layers so that each 500x500m population grid contained the total residential area.
- Residential Density Calculation: Residential density was calculated using the population data in each grid and the corresponding residential area.
- Classification: The Fisher-Jenks classification method was employed to identify natural breaks in the residential densities. After several iterations, three breaks were established, resulting in low, medium, and high-density residential classes.
- Merge: Shapefiles for the three LUCs were generated and merged into the primary land use file for regrouping.

This process was repeated for the years 2006 and 2015.

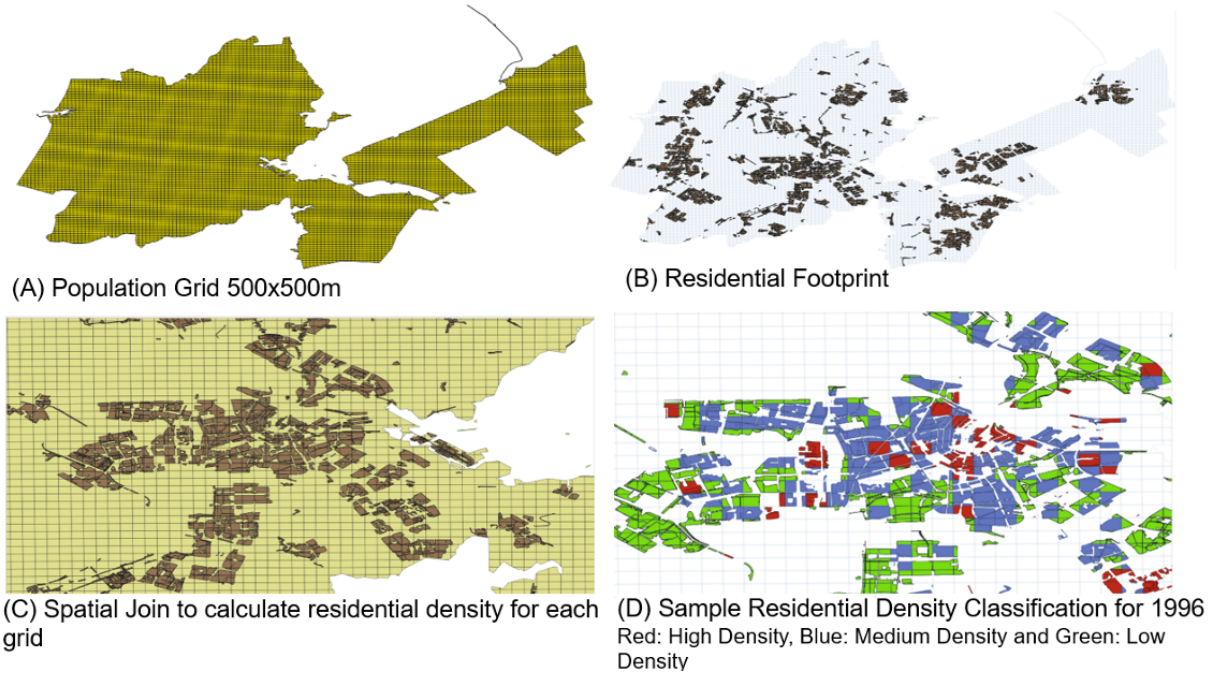

Figure C.4: The process of breaking down a single residential LUC into low, medium and high-density LUCs

Suitability

The suitability factors that we used (and were also recommended in Metronamica) are Digital Elevation Map (DEM), Slope and Soil Quality. The soil categories are derived from two soil maps available from PDOK (Netherlands Platform for Geodata) [‡]. The categories were based on the type of urban coverage and soil texture. The soil texture describes its relative fineness or coarseness regarding sand, silt, and clay. This composition determines how well the soil holds water, its Cation Exchange Capacity (CEC) level and its buffering capacity. We combine both maps to produce the categories enlisted in Table C.3. The DEM is obtained from the AHN - Current Elevation File of the Netherlands [§].

Accessibility and Attractors

Accessibility builds on the network layers and network nodes in an urban system. Through accessibility, the influence of each of these networks on the LUCs around them and their ability to attract or repel certain LUCs is modelled. For example, residential areas would not crop up next to major highways or railways, but industries would. Unlike the landuse maps, the network layers were unavailable as time series. The static map was used throughout the model runs. For MRA, we grouped existing infrastructure networks as follows:

1. Networks
   - Highways: motorway, motorway link, primary, primary link, trunk, trunk link, rail, secondary, secondary link, tertiary, tertiary link
   - Secondary Roads: tram, miniature railway, monorail, narrow gauge, subway, funicular.
   - Residential Roads (introduced when simulating the 15 MIn City scenario): residential, Other Roads, bridleway, cycleway, path, pedestrian service, living street, footway, steps.
   - Other Roads: steps, tract, track grade1, track grade2, track grade3, track grade4, track grade5, unclassified, unknown.
   - Railways
   - Navigable waterways
   - Non-navigable waterways
2. Nodes: Main Railway Stations, Secondary Railway Stations, Motorway Junctions, Bus Terminals.

[‡] https://www.pdok.nl/-/de-bodemkaart-van-nederland-beschikbaar-bij-pdok
[§] https://www.ahn.nl/

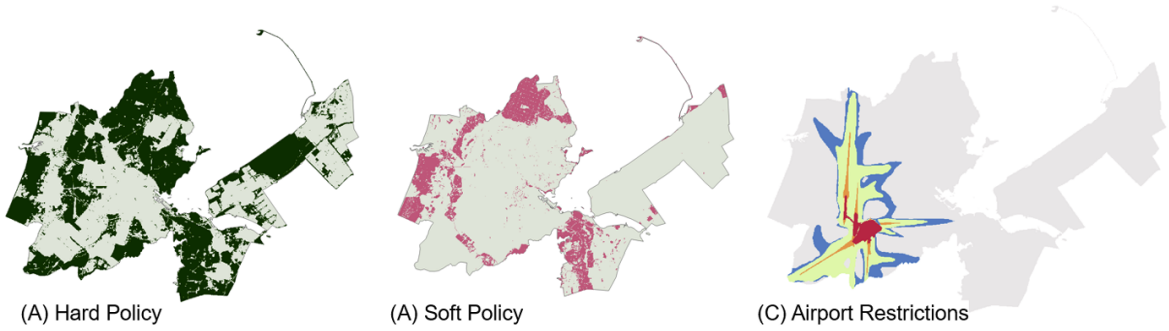

Figure C.5: Zoning Maps added to the land use model indicating (A) Soft policy regime; (B) Hard landscape regime; (C) Levels of restrictions around Schiphol airport

Zoning

Zoning maps serve as external policy or regulatory measures that can significantly influence land use categories (LUCs) changes. These maps are typically derived from planning documents provided by national or regional planning authorities and may include information on ecologically valuable and protected natural areas, cultural landscapes, buffer zones, noise and pollution control areas, future growth zones, and more. In Metronamica, each zoning input is added as a 'layer' to assess its impact on each LUC, determining whether it actively stimulates growth, weakly restricts it, strongly restricts it, or has no impact. For our calibration and validation period (1996-2016), incorporating these regulations is crucial to accurately reflect urban growth patterns over the past decades. Accordingly, the zoning inputs are categorized into two main groups (see Fig C.5):

1. Planning restrictions and government landscape protection regimes
   - Soft Policy Regime (rijk zacht): Heritage (New Dutch Waterline, Roman Limes, World Heritage Beemster, World Heritage the Defense Line of Amsterdam), UNESCO areas, Outdoor Places/ Buitenplaatsen, City and village views/ Stads en dorpsgezichten and Archaeological Monuments.
   - Hard Policy regime (beperk): Hard nature protection includes Natura2000, Nature Network Netherlands (NNN), Houtopstand Wood Stand, Wadden Sea/IJsselmeer and Kustfundament/ Coastal Foundation (Fig C.5).
2. Restrictions around Schiphol Airport:
   - Building restrictions (beperking bebouwing): These are based on noise-sensitivity and density.
   - Benchmark for height restrictions (maatgevende kaart toetshoogtes)
   - Restriction on attracting birds (Beperking antrekken vogels)

Model Calibration

- Study area: Metropolitan Region of Amsterdam (MRA).
- Period of calibration: 1996-2006
- Period of Validation: 2006-2016
- Year of future simulation: 2050
- Type of calibration: Manual, semi-automated

The calibration of Metronamica is based on historical land use changes, which are extrapolated to simulate future land use developments. The current situation and historical trends are analyzed to fine-tune model inputs, ensuring that the simulated land use patterns closely mirror real-world dynamics. This process involves examining temporal changes in the total area of various land uses and changes in landscape structure. Metrics such as the clumpiness index are employed to visually assess development patterns, while the enrichment factor is used to analyze the over- and under-representation of specific land uses in the vicinity of altered land uses [638]. Calibration is not merely about replicating an urban model; rather, it involves training the model to achieve a growth pattern similar to observed trends. Once calibration is complete, planners can use the model to experiment with different scenarios, policy options, and external influences, such as spatial

zoning plans, road network expansion, or population growth scenarios. The calibration process involves the following steps:

Raster Comparison & Change Detection

We conducted a basic raster comparison of the starting and ending points of our calibration period: 1996 and 2006. This presents the big picture of actual changes in the urban landscape. This also allows us to compute the 'demand' values for each LUC in Metronamica. Detailed code and maps can be accessed at `https://github.com/aarsundaram/amsterdam_metronamica.git`

Enrichment Curve

Enrichment factor is a value that characterizes the neighbourhood effect between LUCs [633]. The enrichment factor is the over- or underrepresentation of land use in the neighbourhood of a particular location relative to the average land-use distribution over the entire modelling region. Enrichment factors range from -1 to 1. An enrichment factor of 0.25 means that the specific land-use class is represented 25% above the average allocation of the class in the entire region.

Enrichment factors were calculated for both observed and simulated land-use changes to compare differences in neighborhood interactions among various land use categories (LUCs). These enrichment factors for 2006 were plotted as a distance decay function, an example of which is shown below. The enrichment factor at a distance of 0 reflects the inertia or conversion effect of a particular land use, while enrichment factors at distances greater than 0 indicate the attraction or repulsion effects exerted by neighboring land uses. The observed enrichment factors were then used to calibrate the neighborhood rules in Metronamica. Calibration begins by focusing on the curves with the most significant deviation, adjusting the interaction rules to achieve the closest possible match.

Although repetitive visual comparisons are required, this approach allows the modeler to explore local patterns in detail, relying more on area-specific knowledge than on the data alone. Unlike automatic calibration methods that depend solely on statistical techniques, qualitative/manual calibration offers significant advantages by incorporating spatial forms and patterns unique to the modeled area [114].

In Metronamica, land use is classified; some are modelled dynamically, while others remain static.

- Vacant states are LUCs that only change due to other land use dynamics.
- Functions are LUCs that are actively modelled.
- Features are LUCs that are not supposed to change in the simulation

Land use changes are simulated using various drivers, including external factors (such as population growth or reduction in natural areas), population distribution (based on the attractiveness of regions to residents and businesses), local characteristics (like accessibility), socio-economic factors (e.g., the potential success of a business in a particular location), policy options (e.g., zoning regulations that restrict new housing developments), and biophysical factors (e.g., soil suitability for agriculture).

During calibration, parameter values are established and refined, and the model's behavior and outcomes are evaluated, often using a historical calibration period for comparison. Challenges in calibrating CA-based land use models typically involve managing the large number of parameters that need adjustment, the limited availability of time series data for land use maps, and the difficulty of developing objective methods to evaluate calibration quality.

Neighbourhood Rules

For each LUC, a set of neighbourhood rules that are modelled using splines (manually input during the calibration phase). Each spline determines the degree to which the landuse class is attracted or deflected by other neighbouring landuse classes. Each spline is defined using the following rules:

Table C.3: List of model inputs, associated datasets and sources

S.no.	Model Block	Layers	Format	Sources
1	Land Use Map	Regrouped Categories: Agriculture, Greenhouses, Mineral/Industry, Public Amenities, Commercial, Residential (low, medium, high density), Recreation, Nature, Water, Transport, Airport	Raster Maps	Statistics Netherlands (CBS)[a]
2	Suitability	Digital Elevation Map (DEM)	x	Current Elevation File of Netherlands (AHN)[b]
		Soil: Water, Built-up area, Highly elevated terrain, Unsuitable area/protected area (dike, upland, swamp, highly excavated terrain), Sand (sand + light sand + coarse sand), Loamy sand (moderately fine sand + fine sand + loamy and weak loamy fine sand), Clay (clay+ light clay), Heavy clay, Others (including all the soil categories that are not easy to be integrated into other soil category groups)	Raster Maps	Netherlands Platform for Geodata (PDOK)[c]
3	Accessibility	Highways, Secondary roads, Navigable waterways, Non-navigable waterways, Railways	Vector Maps	OpenStreetMap, Statistics Netherlands (CBS)
4	Zoning	Hard Policy regime (beperk): Hard nature protection includes Natura2000, Nature Network Netherlands (NNN), Houtopstand Wood Stand, Wadden Sea/IJsselmeer and Kustfundament/ Coastal Foundation	Raster Map	Netherlands Environmental Assessment Agency (PBL)[d]
		Soft Policy Regime (rijk zacht): Heritage (New Dutch Waterline, Roman Limes, World Heritage Beemster, World Heritage the Defense Line of Amsterdam), UNESCO areas, Outdoor Places/ Buitenplaatsen, City and village views/ Stads en dorpsgezichten and Archaeological Monument	Raster Map	Netherlands Environmental Assessment Agency (PBL)[e]
		Restrictions around Schiphol Airport: Building restrictions (beperking bebouwing), Height restrictions (maatgevende kaart toetshoogtes), Restriction on attracting birds.	Raster Map	GeoApp North Holland[f], Plan Viewer NL[g]

[d] https://www.cbs.nl/en-gb
[d] https://www.ahn.nl/
[d] https://www.pdok.nl/
[d] https://www.pbl.nl/en
[d] https://www.pbl.nl/en
[d] https://geoapps.noord-holland.nl/
[d] https://www.planviewer.nl/

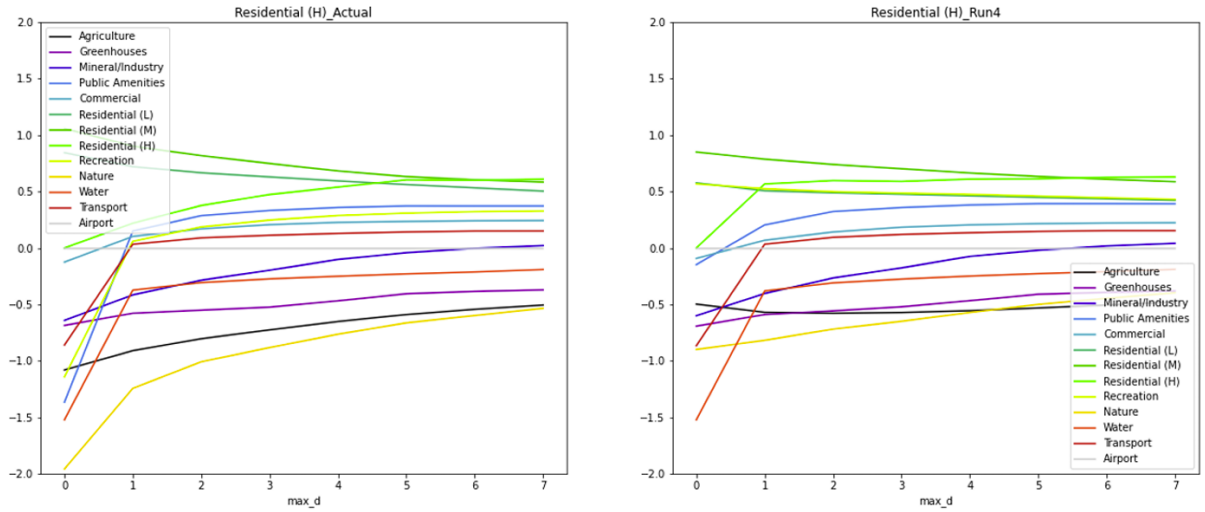

Figure C.6: Enrichment curves for Residential (High-density) plotted for Observed 2006 map (left) v/s Simulated 2006 map (right)

- Inertia value: the inertia value is the value of the spline at x=0. This value determines the strength of the landuse class to remain in its current state at its location in the next timestep. It also determines its strength to take over another landuse in the neighbouring cell.
- x=1: the second value is at x=1, which determines the strength of this landuse class in its ability to take over other landuses. If the value is negative, it means the landuse is repelled.

Suitability

These factors determine the 'suitability' of a cell to host or transition into a specific land use function. For example, the presence of agricultural land use categories (LUCs) in an area can be influenced by factors such as soil quality, elevation, and slope. Suitability, therefore, is a metric that reflects the inherent characteristics of an area and how favorable it is for a particular land use category. Individual maps will be created for each chosen factor (such as slope, aspect, soil quality, pollution, etc.) for every land use function class. Each land use cell on these maps will have a value between 0 and 1, where 0 indicates complete unsuitability for that class, and 1 indicates high suitability.

Accessibility

All network features in this model are input in vector format, with an additional attribute column labeled 'ACCTYPE' containing a value from 1 to X. In the model, a numeric value ranging from 0 to the total number of network layers (4 in this case) is assigned based on the number of network features to be utilized. Each accessibility type is thus assigned an 'ACCTYPE' value, which Metronamica uses to differentiate between the layers. Accessibility parameters need to be calibrated separately for each land use function.

- Implicit Accessibility refers to transportation features of landuse classes embedded within the landuse layer and not included in the network layers. For example, many small streets are not included in the network layer as a separate layer in residential areas. Values for this parameter range from 0 (no access) to 1 (full access). So if the landuse class is a residential layer, a built-up area value of 1 is used, assuming that residential areas are always connected to a road.
- Explicit Accessibility: this makes some land uses passable (1) or 0 (impassable), such as water bodies. Accessibility parameters are assigned to each network layer concerning the LUC.
- Relative Importance: a value ranging from 0 (not important) to 1 (important) is assigned. So for a residential class, the network layer of secondary roads will be very important, with a value of 1 assigned. The highways layer will be less important than the secondary layers (0.7). This will be the opposite for industries' landuse class: highways will be more critical connectors than secondary roads.
- Distance Decay: is used to model the decrease in importance of the transport feature with increasing distance. This is input regarding the number of cells (as a distance measure). The values can be negative: for example, residential areas will have negative distance decay with railway networks, as people would not prefer to reside within proximity of a railway track.

C.4.1 Assessing the Quality of Calibration

The quality of calibration is evaluated by assessing 'predictive accuracy' (how accurately the model predicts changes) and 'process accuracy' (how well the simulations align with real-world dynamics). This evaluation involves four steps: (1) Visual map comparison, (2) Kappa Statistics, (3) Comparison with neutral models, and (4) Clumpiness Index. All assessments are conducted using the Map Comparison Kit (MCK).

Visual Map Comparison:

We use the MCK's Map Comparison algorithm to visualize the differences in the allocation of LUCs between two maps - in our case, Observed and Simulated changes. This allows us to inspect obvious dissonances in allocating LUCs and focus on fixing them (see Fig.C.7).

Kappa Statistics:

Kappa is the goodness of fit between 2 maps. Kappa statistics are widely applied in geographical problems to assess the similarity between observed and simulated results. It is a cell-to-cell comparison approach that checks each pair of cells on the simulated map and actual maps to see if they are equal (Table C.5).

1. Kappa Index: Kappa Index shows the proportion of cells that are equal in the simulated map and the actual map[637]. The calculation of Kappa is based upon the contingency table (sometimes also referred to as confusion matrix). Kappa is classified into Khisto (similarity of quantity) and Klocation (similarity of spatial allocation). Kappa index is the multiply of the two measures.
2. Kappa Simulation: The issue with Kappa Index is that if there is little change in the simulations, the Kappa index will be high despite the poor quality of the model. Hence, we use Kappa Simulation to compare the cell-to-cell consistency of the two maps by correcting for the amount of change[638]. Kappa Simulation is based on the distribution of "class transitions", which is regarded as one kind of conditional probability: the chance of finding a particular class at a location will depend on the class initially there. The Kappa Simulation value indicates how accurate the land-use change process is, and reduces the pitfall caused by the high Kappa index due to the small changes [636].

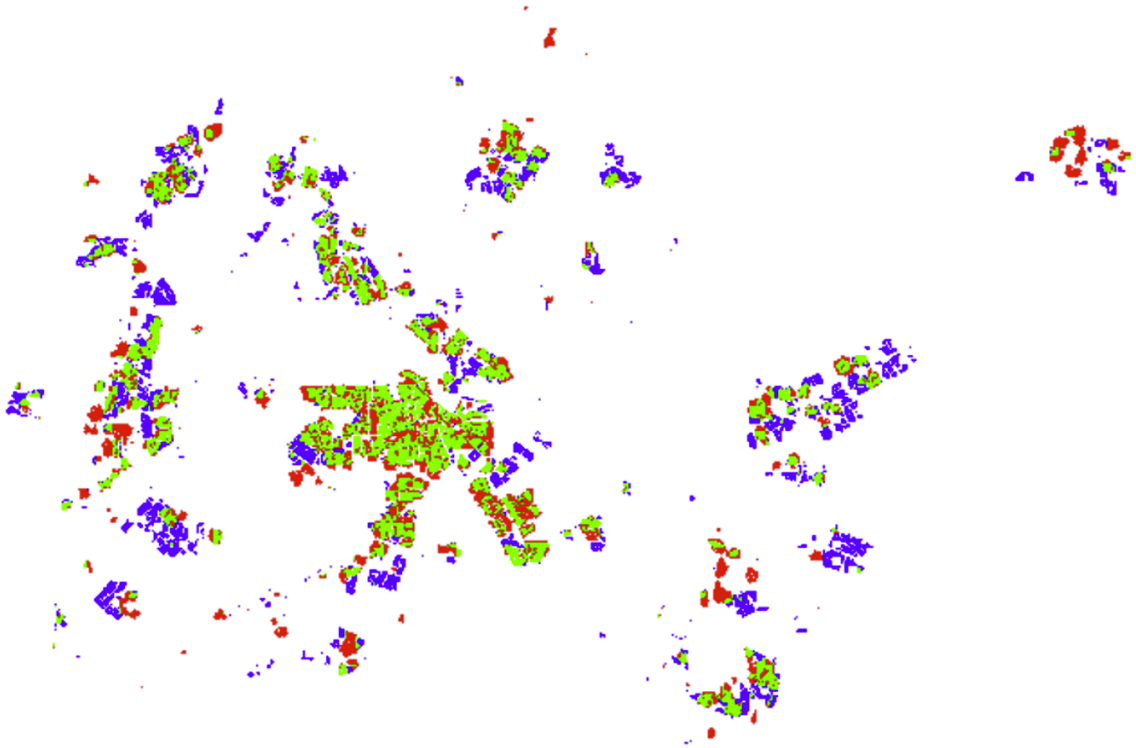

Figure C.7: A sample map indicating a comparison of the Observed (blue) and Simulated (red) changes for Residential (high density). The green patches refer to nature cells consistent in both maps.

3. Fuzzy Kappa considers the two kinds of fuzziness: 1) the vague distinctions of LUCs and 2) the proximity of similar cells. For example, in our land-use classes, there are high, middle and low residential areas, but the boundaries of these categories may contain some vagueness. Also, one cell is not necessarily occupied by one land-use type and the neighborhood cells around one cell could add some fuzziness. Therefore, a membership vector is adopted in Fuzzy Kappa instead of giving one single category or value for every cell.

After the cell-by-cell comparison, a similarity map is generated. In this similarity map, each cell has a value between 0 (fully distinct) and 1 (fully identical). The results of this similarity map will finally be aggregated into one overall Fuzzy Kappa index. Calculations of the three Kappa-related measures can be made via MCK.

C.4.2 Comparison with Neutral Models

Arriving at a Kappa index by comparing the Observed and Simulated maps does not present a benchmark for how well the model performs. For example, a Kappa index of 0.8 may appear excellent, but the map may not perform as expected visually. Therefore, we need to set a benchmark against the goodness-of-fit of the simulated model that can be compared. To do this, we compared the simulated model with two neutral models: (1) Random Constraint Match and (2) Null Model. The Simulated model must outperform the Kappa indices of both these neutral models.

Random Constraint Match (RCM)

An RCM model will introduce the same quantity of errors as in the Simulated model - but at random locations. It will first calculate how many cells have changed from the initial map to the end condition and then randomly distribute these cells on the initial map[634]. As a result, the Random Constraint Match model creates a new map by minimally adjusting the initial map, giving it the same frequency distribution of the categories as the simulated map.

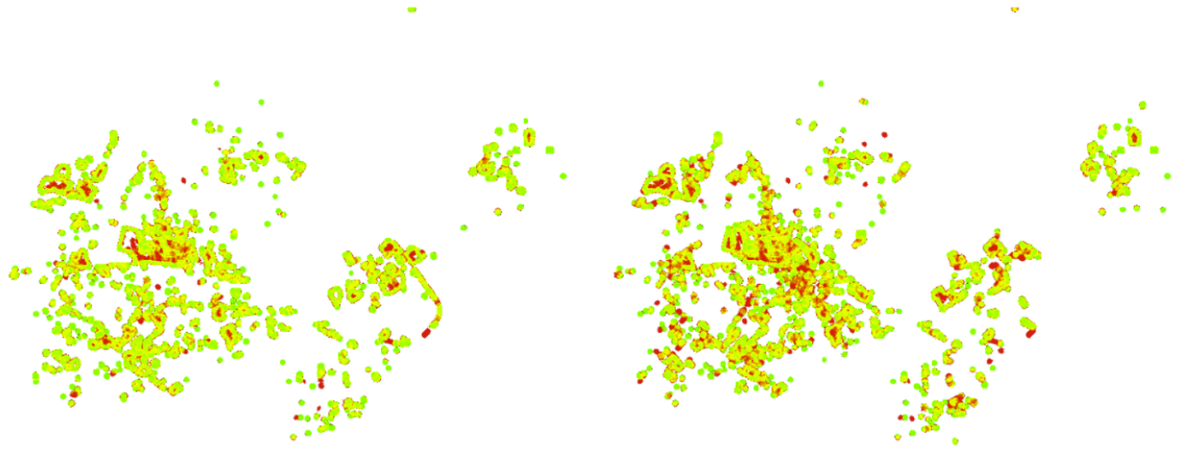

Figure C.8: A sample map indicating a comparison of the Observed (blue) and Simulated (red) changes for Residential (high density). The green patches refer to nature cells consistent in both maps.

Table C.5: Comparisons between the manually calibrated model with the two neutral models

	Kappa	**Kappa Simulation**	**Fuzzy Kappa**
Calibrated model	**0.866**	**0.076**	**0.899**
Neutral model 1: Random Constraint Match	**0.848**	**0.309**	**0.873**
Neutral model 1: Null Calibration	**0.797**	**0.038**	**0.822**

Null Model:

Null Model Null calibration is an almost uncalibrated version of our model that only contains very basic neighbourhood rules. Specifically, the inertia of all the functional land-use classes will be set to 100, whereas all the conversions are to 1. When distance is more than 0, the influence will also be reduced to zero, which means there is no attraction or repulsion and most places will stay in their current location. No other input layers are added.

C.4.3 Clumpiness Index

Clumpiness Index is a widely used landscape pattern metric [635] that has been applied in land-use modeling studies. It is a measure of adjacency indicating the extent of clumps or fragmentations in urban growth. These values range from -1 (complete disaggregation) to 1 (maximal aggregation), and values near 0 indicate the random distribution of patches.

To assess the landscape pattern structure, the average of the absolute category level clumpiness error between Observed and Simulated maps is used. MCK has an inbuilt algorithm to calculate the Clumpiness Index and visually illustrate the values (Fig. C.8).

Model Validation

Validation is the process of assessing the model's prediction capability over a separate dataset that has not been applied to the calibration. Thus, the model validation time is set from 2006 and 2015. The simulated and actual maps of 2015 are compared to check if the high agreements are satisfied. The two neutral models, Random Constraint Match and Null calibration are also adapted and simulated for the validation time. The Kappa index, Kappa simulations and Fuzzy Kappa are used to quantify the similarity between the simulated maps and the actual maps for the three models. Table **??** provides the comparison results. An overall Kappa index of 0.882 and a Fuzzy Kappa value of 0.908 suggest a high level of agreement between the simulation results and the reality. Additionally, it can be observed that the performance of the working model is better than the two neutral models in the validation process in terms of the Kappa statistics, meaning the current model can be applied to further uses.

As part of the validation, the model's behaviour and results, based on the parameters and settings obtained during the calibration, are assessed over a data set independent of the one used in the calibration. This usually results in evaluating the model's behaviour over a different historical period. Metronamica learns land use transition rules and tests them against actual data. It consists of four significant modules guiding land use changes: neighbourhood rules (N), Accessibility (A), Suitability (S), and Zoning (Z) [631]

Table C.7: Comparisons between the validated model with the two neutral models

	Kappa	**Kappa Simulation**	**Fuzzy Kappa**
Validated model	**0.882**	**0.035**	**0.908**
Neutral model 1: Random Constraint Match	**0.859**	**0.028**	**0.891**
Neutral model 1: Null Calibration	**0.863**	**0.019**	**0.887**

Curriculum Vitae | D

Supriya Krishnan is an urban development and strategy specialist whose work bridges climate resilience, geospatial intelligence, and infrastructure systems. With over a decade of experience spanning architecture, policy, and urban resilience, she has collaborated with governments, UN agencies, and academic institutions to advance approaches for resilient cities. Born in Mumbai, India - one of the most climate-vulnerable cities globally - Supriya's lived experience, from India to the Netherlands and now to the USA, continues to shape her understanding of how planning, technology, and governance intersect in addressing climate and development goals. Her early professional experience as an architect evolved into a focus on systems-scale urban resilience, culminating in her work to establish the interim secretariat of the Coalition for Disaster Resilient Infrastructure (CDRI), where she helped establish its global mandate and mobilize multi-country partnerships for infrastructure resilience.

Supriya holds a Masters of Science in Urbanism (Honours) from Delft University of Technology, where her thesis titled "The Middle Ground Spatial Planning Under Uncertainty" received a perfect 10 score (top 2.1% theses in the Netherlands). The thesis modeled transport networks risks and recovery patterns during a disaster to inform a risk-informed master planning strategy and became an inspiration to set out the scope for this PhD: "The Future Ground". Her Bachelors thesis at University of Mumbai titled "Connecting the Dots" focused on strengthening transit-oriented growth between Mumbai and sister city Navi Mumbai by targeted design interventions.

Her research and practice are grounded in rigorous theoretical and empirical work combined with computational modeling, geospatial analytics, and scenario planning methods, building evidence for actionable long-term planning and policymaking. Recognized with the Allianz Climate Risk Award (2024), CDRI Fellowship (2021), TU Delft Global Fellowship (2021) and C40 Women4Climate Mentorship (2022), her work continues to promote equitable, data-informed, and forward-looking approaches to urban resilience and planning.

Journal Articles & Book Chapters (peer-reviewed)

2025 [in preparation] Krishnan, S., Aydin, N.Y., van Delden H., Comes, M. "Planning for the extreme: Assessing Preparedness for Extreme Flood Events in the Metropolitan Region of Amsterdam."

2024 [Under Review] Krishnan, S., Aydin, N.Y., van Delden H., Comes, M. "FutureScape: Blending Computational Models and Scenario Narratives to Design Urban Futures" *Environment & Planning B.*

2024 Krishnan, S., Aydin, N.Y. and Comes, T. TIMEWISE: Temporal Dynamics for Urban Resilience-theoretical insights and empirical reflections from Amsterdam and Mumbai. *npj Urban Sustainability: Policy and Practice*, 4(1), p.4. doi:10.1038/s42949-024-00140-5

2023 Krishnan, S., Aydin, N.Y. and Comes, M. RISE-UP: Resilience in Urban Planning for Climate Uncertainty: Empirical insights and

theoretical reflections from case studies in Amsterdam and Mumbai. *Cities* doi: j.cities.2023.104464

2022 Aydin, N.Y., Krishnan, S., Comes, M. and YU, H. An integrated framework for incorporating climate risk into urban land-use change modeling. *(Proceedings of the 32nd European Safety and Reliability Conference (pp. R25-01). ESREL.* doi: j.cities.2023.104464

2021 Krishnan, S., Aydin, N.Y. and Comes, T. Planning Support Systems for Long-Term Climate Resilience: A Critical Review. In: *Urban Informatics and Future Cities*, (pp.465-498), edited by S. C. M. Geertman, Christopher Pettit, Robert Goodspeed, Aija Staffans: Springer.

Grants and Awards

2024 **Winner:** Allianz Climate Risk Award. Recognized for research on proactive urban planning for catastrophic resilience (full essay: Riding Out the Storm: Strategic Urban Planning for Managing Extreme Weather, see Appendix).

2022 C40 Cities Women4Climate Mentee. 1 of 25 next-generation climate leaders for Mumbai.

2021 Coalition for Disaster Resilient Infrastructure (CDRI) Fellow. Grant for mainstreaming resilience in urban planning for Mumbai.

2021 TU Delft Global Fellow. Grant for resilient urban planning framework for Mumbai.

2015 TU Delft Full Scholarship, Justus and Louis van Effen Grant offered to 16 international students across the university (€43,500).

2018 Young Scientist, Integrated Research on Disaster Risk (IRDR), International Science Council & UNDRR.

2018 The Dutch Research Council (NWO) PhD Award for outstanding Masters students, offered to 27 researchers in the country. *Received exceptional review; finalist at interview stage.*.

2015 UK Chevening Scholarship and German DAAD Scholarship. *Declined to accept the TU Delft scholarship.*

Conference Activity

Talks

2024 Data-rich vs. Data-poor? Developing Land-Use Models for Urban Resilience. International Workshop on Climate-Resilient Development in Southeast Asia, Harvard University. Boston, MA.

2024 Temporal Dynamics for Urban Resilience: Insights from Amsterdam and Mumbai. International Conference on Resilient Systems, National University of Singapore.

2024 RISE-UP: Resilience in urban planning for climate uncertainty-empirical insights and theoretical reflections from case studies in Amsterdam and Mumbai. Reinventing the City, Hosted By: AMS Institute, Amsterdam, Netherlands.

2023 Predicting Land-use for Urban Resilience: The knowledge divide between the Global North and Global South. International Conference on Resilient Systems. Mexico.

2023 Risk to Resilience: Dealing with Uncertainty in Urban Planning. Global Coastal Cities Summit. Mumbai, India.

2022 When to Plan? Understanding temporality for urban planning for an uncertain future. Society for Decision Making under Deep Uncertainty. Tecnológico de Monterrey, Mexico.

2022 Risk-informed Urban Planning and Infrastructure Resilience. DRI Technical Conference. New Delhi, India.
2022 Geospatial Tools for Urban Resilience. Geospatial World Forum. Amsterdam, Netherlands.
2022 Risk-informed Urban Planning and Infrastructure Resilience. DRI Technical Conference. New Delhi, India.
2021 Planning for a Resilient Mumbai. Dutch Answers to Flood Management & Land Subsidence. Netherlands Consulate Mumbai & Municipal Corporation of Greater Mumbai. India.
2021 Planning Support Systems for Long-Term Climate Resilience. 17th International Conference on Computational Urban Planning and Urban Management. Finland.
2020 Towards a framework for long-term climate resilience in complex urban environments. Joint Resilience Engineering Conference. Delft, Netherlands.
2019 The uncertainty space in urban planning. Society for Decision Making under Deep Uncertainty. TU Delft, Netherlands.

Sessions Organized/ Moderated

2022 **UN Habitat's World Urban Forum.** Designed and Led a training event titled 'Resilience for All' : Scientific tools at the intersection of resilience and equity. Katowice, Poland.
2023 **Risk to Resilience: Dealing with Uncertainty in Urban Planning.** Global Coastal Cities Summit, Mumbai, India.
2023 **The Dutch Way to Coastal Resilience.** Workshop with Municipal Corporation of Greater Mumbai and Netherlands Consulate. Mumbai, India.
2021 **Masterclass on Urban Resilience.** International Conference on Disaster Resilient Infrastructure. New Delhi, India.

Consultations, Masterclasses and Guest lectures

2023 **Resilience Lab, TU Delft.** Designed and Led a Workshop on Exploring Resilient Land-Use Scenarios for the Metropolitan Region of Amsterdam (MRA). Amsterdam, Netherlands.
2024 "How Architecture can address Climate Change?" Columbia University School of Professional Studies, New York, USA.
2023 Exploring Resilient and Equitable Urban Scenarios. TU Delft Summer School on Planning and Designing the Just City, Netherlands.
2022 "Measuring and modelling urban resilience". Cities and Climate Change Summer School, University of Southern Denmark.
2021 Urban resilience. Part of TU Delft core course on "Understanding International Grand Challenges", for students of the Masters in Engineering and Policy Analysis program, Netherlands.
2020 **International Conference on Disaster Resilient Infrastructure.** Co-organised the thematic session on Urban Resilience. New Delhi, India.

Student and Research Supervision

2023 Sayali Lokare, Researcher, Resilience Lab, Faculty of Technology, Policy and Management, TU Delft. Merging Spatial Data and Local

Insights for Developing Land Use Models for Mumbai (in collaboration with Abhijit Lokare, Adjunct Associate Professor, School of Environment and Architecture, Mumbai, India).

2022 Quint La Fleur, Masters Thesis Project, Faculty of Technology, Policy and Management, TU Delft. Assessing future flood resilience of the Mumbai Metropolitan Region: A land-use modelling case study.

2022 Marya Al Malki, Honors Project, Faculty of Technology, Policy and Management, TU Delft. Understanding Urban Growth and Impacts of Climate Risk for the Mumbai Metropolitan Region.

2022 Aydin, N.Y., Krishnan, S., Yu, H. and Comes, M., 2022. An integrated framework for incorporating climate risk into urban land-use change modeling. In Proceedings of the 32ND EUROPEAN SAFETY AND RELIABILITY CONFERENCE (ESREL 2022) Article R25-01-258 (Proceedings of the 32nd European Safety and Reliability Conference). ESREL.

2021 Aarthi Meenakshi Sundaram, Honors Project, Faculty of Technology, Policy and Management, TU Delft. Setting up a Computational Land Use Model to simulate future growth for the Metropolitan Region of Amsterdam.

List of Figures

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Thank you both for being the guiding lights of this PhD.

Hedwig van Delden - for being the rock behind the land-use modelling components of this PhD (far more than what made it into this final draft, and I hope it all sees the light of day in the coming years). Thank you for training this so-called "non-modeller" through the labyrinth of a fully functional computational model; for the endless troubleshooting sessions, resources, encouraging words, and limitless patience. I couldn't have done it without you.

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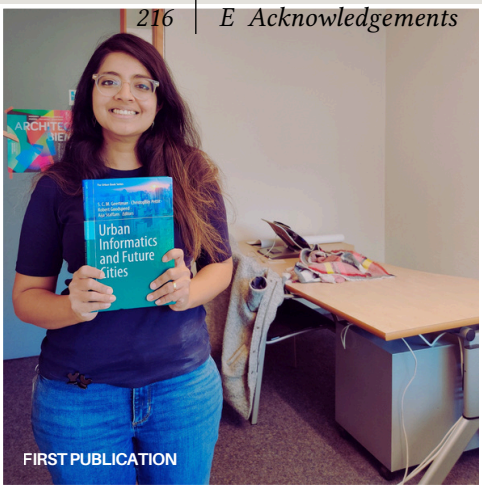
To my little boy Sid: I've been waiting to say this: *Now that the PhD is done, here's to finally doing life together!*



FIRST PUBLICATION

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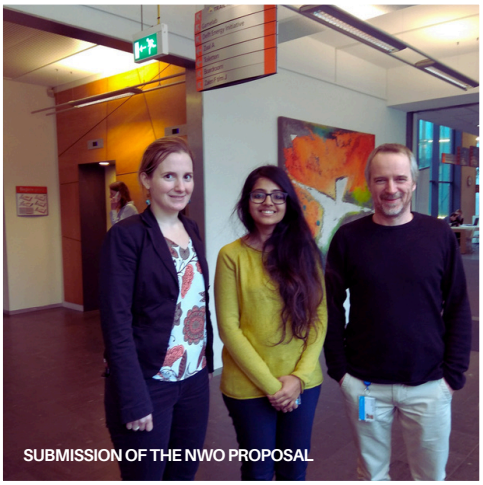
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FIRST OFFICE MATES

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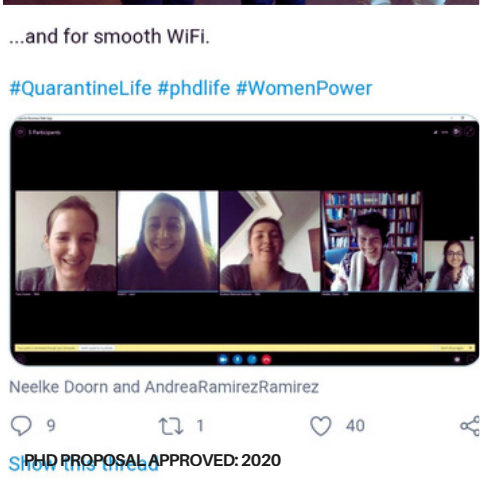

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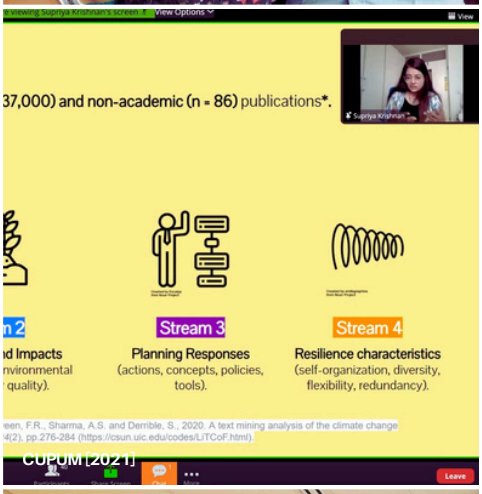

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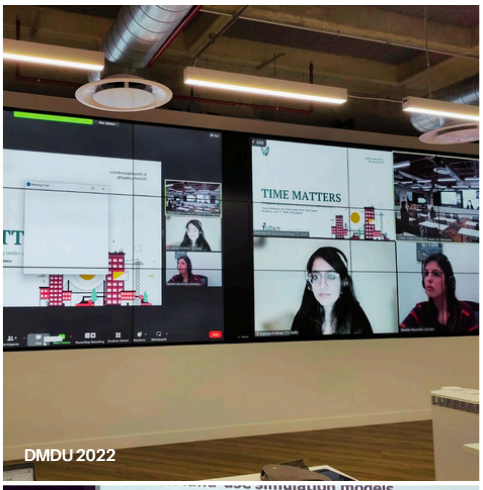

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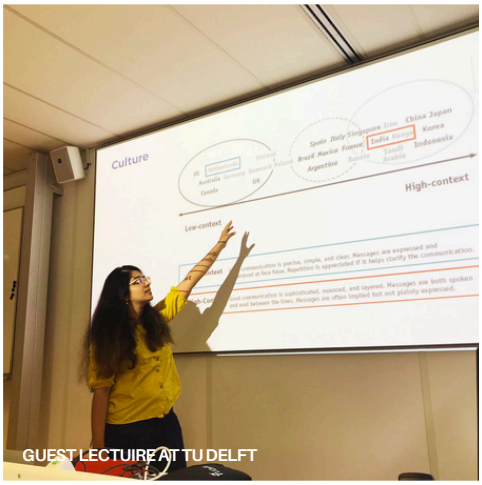

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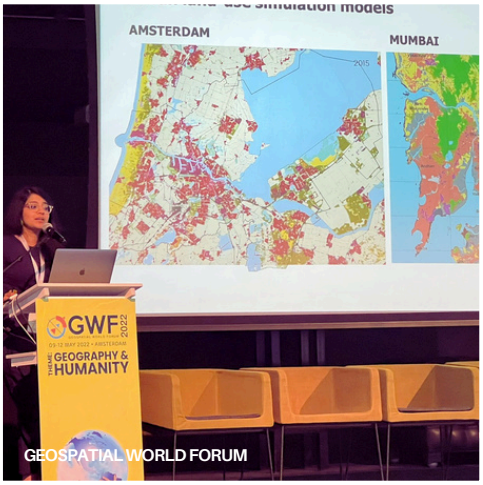

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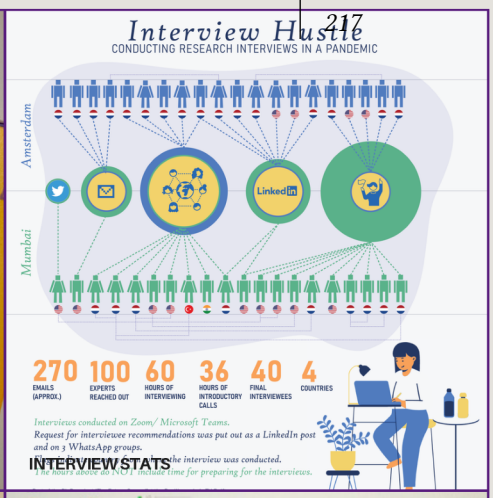
HOME FOR 4 YEARS

PHD JOURNALS



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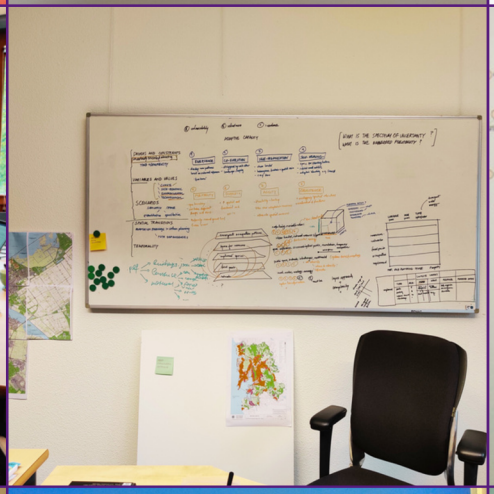
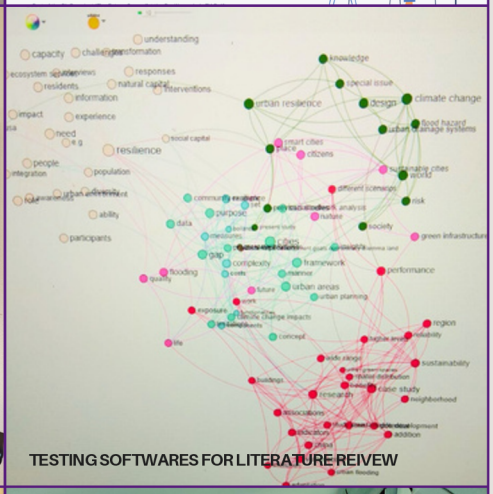
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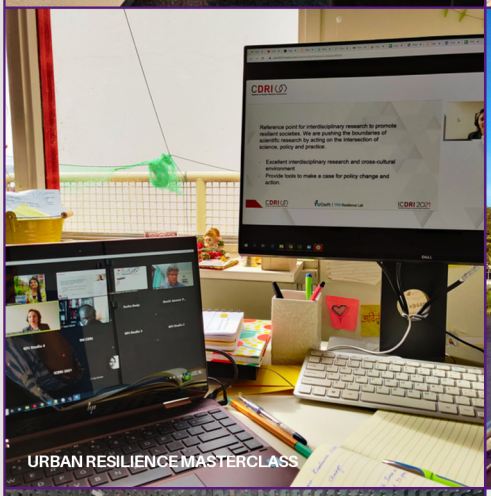
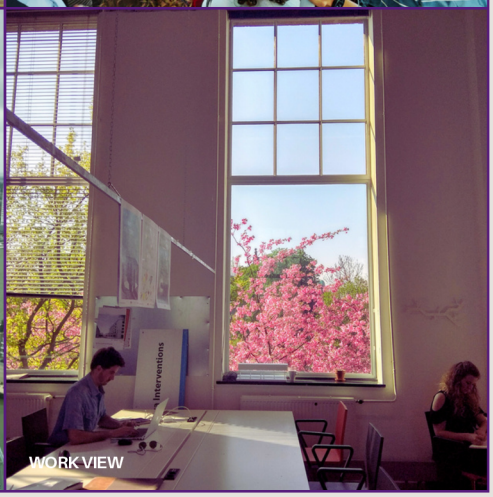

URBAN RESILIENCE MASTERCLASS


DAILY ROUTE TO OFFICE

DAILY COMMUTE


GUEST LECTURE AT TU DELFT SUMMER SCHOOL


RESEARCH MEETINGS


WORK VIEW

PHD WORK-LIFE