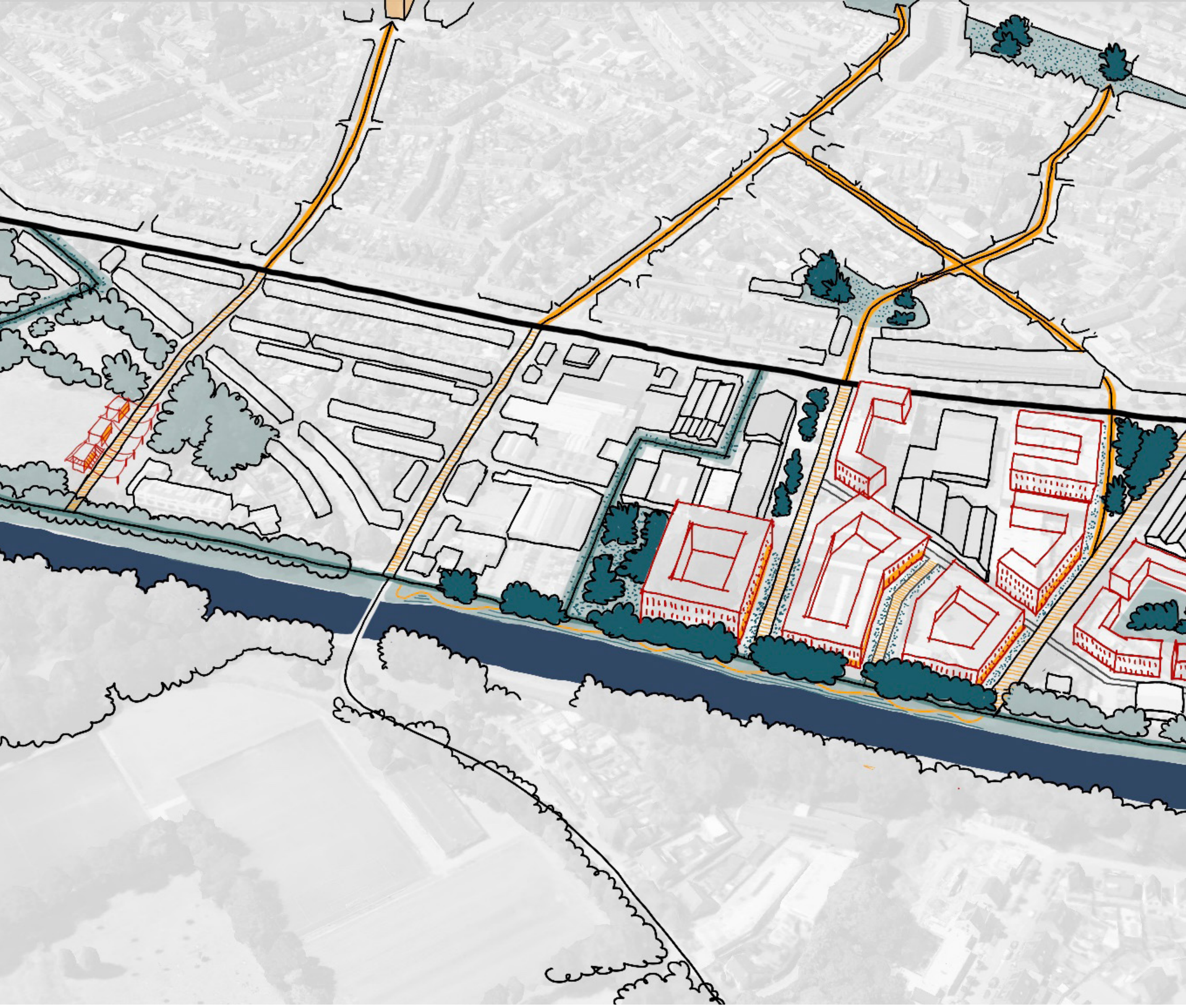


Towards a Resilient Port-Cityscape:

Identifying waterfront transformation potential in industrial inland port cities in transition in the hinterland of Port of Rotterdam

Author: Yaying Hao
Student Number: 5496950
Cluster: Data-Informed Strategies for Sustainable Urban Futures
Mentor: Claudiu Forgaci, Daniele Cannatella

Preface

Motivation

The intellectual genesis of this thesis is rooted in the fascination with the symbiotic relationship between urban waterscapes and human well-being. Having grown up near a canal forest park in China, my weekend walks along the water became a foundational lens through which I perceived urban space. Upon coming to the Netherlands, the canals of Utrecht evoked a profound aesthetic resonance. Although morphologically distinct from the landscapes of my hometown, the riparian environment offered me with a familiar sense of psychological restoration and spatial tranquility. This personal experiential connection underscores a universal urban truths: waterfronts are not merely functional corridors, but vital socio-ecological assets that anchor collective memory and emotional well-being.

Concurrently, this thesis is driven by an aspiration to advance computational and quantitative methodologies in urbanism. The future of granular, high-precision urban governance imperatively demands the integration of spatial data and analytics. Particularly in the current era of technological acceleration, embracing data-informed frameworks is no longer optional, but essential to uncovering the complex, latent spatial dynamics that traditional qualitative design methodologies often fail to capture.

Overview

This thesis establishes a multi-scalar, data-informed research framework tailored for post-expansion industrial port cities within the the critical hinterland of the Port of Rotterdam. By systematically identifying the transformation potential of waterfronts, this study aims to optimize these riparian hubs into a more resilient, adaptive regional logistics network and provides actionable design strategies to re-integrate underutilized waterfront resources into the surrounding urban fabric. Ultimately, this research seeks to reconcile development trajectory at macro-scale with local liveability, pioneering a balanced approach to the sustainable evolution of contemporary port cities.

All the maps in this report use the projection of EPSG: 28992.

Abstract

Over the past three decades, the regionalization of the Port of Rotterdam has decentralized functional logistics upstream, driving significant industrial waterfront expansion across inland industrial port cities (IIPCs) in the Netherlands. Concurrently, these host municipalities have experienced pronounced residential growth, precipitating acute spatial conflicts along the port-city waterfront interface. In the contemporary post-expansion era, this spatial friction necessitates an urgent re-evaluation of waterfront adaptive reuse. This thesis investigates how waterfront zones within IIPCs can be spatially optimized to cultivate a resilient port-cityscape, balancing multi-dimensional urban performance with structural adaptability toward future transitions.

Conceptually rooted in port-city interface literature and urban resilience theory, this study deploys quantitative urban morphology as its primary analytical approach, translating spatial and functional characteristics into measurable parametric indices. Executed through a multi-scalar context–assessment–design framework, port-cities are studied both as nodes on the inland waterway network at the macro-scale, and further divided into spatial units at the meso- and micro-scale, where urban waterfronts are delineated into river corridor segments. At the macro- and meso-scale, transformation potential is identified based on the development model adapted from Anyport model by Bird (1963). At the micro-scale, a typology of distinct morphological identities is established, and the types exhibiting high transformative potential are then subjected to a diagnostic urban performance framework to uncover latent structural imbalances and generate data-informed spatial strategies. Finally, these strategies are translated and demonstrated through site-specific urban design interventions.

By bridging the gap between spatial data analytics and urban design, this research establishes a structured, reproducible methodological framework. Ultimately, it contributes actionable design strategies for cultivating coherent, adaptive, and resilient port-cityscapes in post-expansion inland port territories.

Keywords

Port-city relationships, waterfront transformation, quantitative urban morphology, urban resilience, industrial inland port city

Index

Index of Tables

Index of Figures

1. Problem Statement

Economic activities fundamentally shape the spatial configuration of human settlements, a dynamic most vividly manifested within the historical evolution of port-cities. During the preceding era of rapid industrial intensification and physical expansion, the waterfront of industrial inland port cities (IIPCs) became primary sites of acute spatial competition, characterized by friction between industrial demands and residential landuse requirements. In the contemporary transition into the post-expansion era, this deep-seated landuse conflict has generated an urgent demand to comprehensively re-evaluate waterfront regulatory frameworks, structural configurations, and spatial qualities.

Fig. 1, Inland barge routes from port of rotterdam and their connections with major industrial zones

1.1 Problem Analysis

1.1.1 Influence of Rapid Expansion of Industrial Ports on Port-Cityscape

Over the past three decades, global trade has grown significantly, accompanied by profound transformations in the global industrial landscape. As the principal maritime gateway for imports and exports of the European Union, one of the world's most important economic player, the Port of Rotterdam has experienced continuous growth in both throughput and strategic importance. At the same time, driven by technological development, energy transition, and the increasing demand for circular economic development, the functional allocation of the Port of Rotterdam within its limited spatial capacity has been forced to undergo upgrading and restructuring (Port of Rotterdam Authority, 2023). As a consequence, a number of inland ports with inland waterway connections to Rotterdam have absorbed part of the port's transferred functions during this period (Port of Rotterdam Authority, 2022). These ports are further connected to their hinterlands through multiple transport modes, meaning that the Port of Rotterdam exists less and less as an isolated entity, but rather acts as the core of a multimodal transport network extending across the Netherlands and even throughout Northwestern Europe (Fig.1).

Within this logistics network, inland waterway transport (IWT) occupies a critical position, which is particularly pronounced in the Dutch context. According to logistics data from the report on the Rhine–Alpine Corridor (European Commission, 2017), IWT accounts for approximately half of total freight transport in Northwestern Europe. As a key transport corridor connecting the Port of Rotterdam with major European industrial hinterlands, such as Germany's Ruhr region and northern France and Belgium, Dutch inland waterways have always played a crucial role in the circulation of goods across Europe. Based on an analysis of industrial data from Informatiesysteem Bedrijventerreinen (IBIS)(Rijksdienst voor Ondernemend Nederland, 2024) and landuse data for the Netherlands from Bodemgebruik - Land Cover (INSPIRE geharmoniseerd) (Kadaster, 2024), inland ports and their surrounding industrial areas have experienced pronounced growth over the past thirty years.

At the same time, inland waterway transport exerts tangible influences on surrounding urban morphology through the spatial medium of ports. These ports are not isolated industrial enclaves; rather, they interact with surrounding cities and residential areas in diverse spatial forms, both shaping and being shaped by them. This relationship of mutual shaping can, to a certain extent, be captured by a generalized paradigm, which is the "Anyport Model" (Bird, 1963). This model originally focused on seaports, which are different to inland ports in the sense that they are able to freely reclaim land from water in order to access better routes and relocate function. However, by situating the inland ports into an interconnected waterway network, the reclamation of lands to relocate the ports can be replaced by shifting of ports and related industries between different municipalities that are connected at the network scale. Consequently, this way of recognizing the ports not only based on their administrative boundaries but also considering the related urban texture can be understood as examples of the "Port Cityscape" as articulated by Carola Hein (2019).

In the pre-modern phase, ports and cities coexisted through a mixture of functions and forms; subsequently, ports gradually expanded away from city centers and developed more specialized functions; finally, in the industrialized phase, ports became largely detached from urban centers, characterized by monotonous functions. In the Dutch context, the port is often managed by administrative bodies separated from those governing the city. This institutional separation ultimately resulted in infrastructural disconnection and spatial segregation between port and city (Hein, 2023).

With this generalized model examined within a more specific context mentioned above, the combined effects of the functional relocation from the Port of Rotterdam and the spatial separation characteristic of modern port–city relations lead to particularly significant spatial implications. When it comes to specific cases, the outcomes of this superimposition vary across inland port cities due to different urban morphology and transportation positioning. In some cities, such as Alblasserdam and Tilburg, newly developed large-scale port areas are almost completely separated from the urban fabric by infrastructure, while smaller ports that are closer to city centers have stagnated.
In cities such as Nijmegen and Eindhoven, industrial functions in the major port have been intensified within designated industrial zones, while some waterfronts have been significantly transformed into urban use. In others, such as Venlo, port expansion has not yet produced substantial morphological impacts on urban structure; however, due to their roles as regional transport and logistics hubs with development potential, they may face landuse and planning challenges in the future. (Fig. 2)

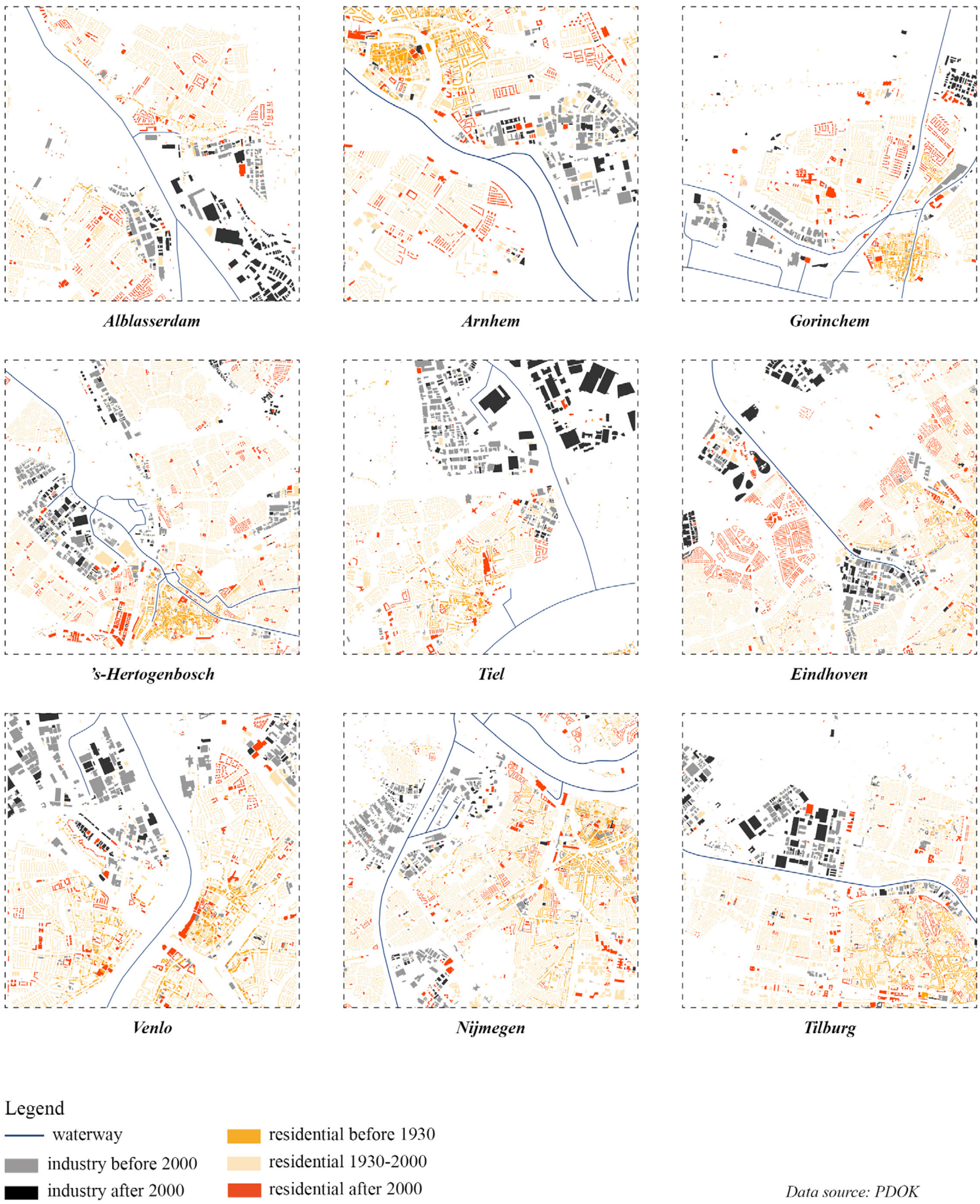


Fig. 2, Expansion of industrial and residential areas in IIPCs in the Netherlands

1.1.2 The Spatial Conflicts Caused by Synchronized Rapid Expansion

However, port expansion has not been the only significant development in these cities over the past thirty years. During the same period, housing construction in the Netherlands has expanded rapidly, leading to a substantial increase in residential areas across numerous cities. Driven by institutional planning frameworks, this synchronized expansion shaped the urban morphological structure, which ultimately manifested as materialized spatial quality perceived by inhabitants. Throughout this process, this rapid, parallel expansion generated two major conflicts: lagging landuse regulation and sub-optimal urban performance.

The lag in landuse regulation represents a critical conflict between contemporary urban form and its institutional precursors. During the era of rapid expansion, numerous waterfront plots were designated for industrial use due to their peripheral locations at the time. However, as cities transition into the post-expansion era, the adaptation of regulatory planning heavily lags behind the pace of natural urban evolution. Consequently, several industrial blocks, which are now in close proximity to urban cores and exhibiting high urbanity, remain legally and institutionally "locked-in" as industrial land. This institutional inertia not only stifles land market vitality and urban transformation but also severely compromises the perceived spatial experience of the waterfront.

Concurrently, sub-optimal urban performance stems from the conflict between macro-urban structures and micro-spatial quality. The synchronized, rapid expansion has resulted in the chaotic coexistence of residential and industrial functions in some urban areas, failing to reserve adequate buffer zones or preserve qualitative conditions for public waterfront experiences. This deficiency creates a severe morphological rupture between the established urban fabric and the riparian space, leaving valuable waterfront resources critically underutilized and detached from daily urban life.

While these conflicts have already produced spatial planning challenges in IIPCs, neither urban nor port development will remain static. Moreover, the future is unlikely to simply replicate the patterns of the past three decades. As global economic structures and patterns evolve, the trajectory will shift away from an era of rapid, incremental expansion toward a post-expansion era characterized by qualitative optimization. To address this shift, planning and policy institutions at multiple levels, from the European Union to the Dutch government and the Port of Rotterdam, have articulated higher ambitions for sustainable and resilient development. Future development is increasingly oriented towards creating a more coherent environment that integrates natural systems, human settlements, and economic activities.

In practical terms for IIPCs, this implies that future development will no longer involve the indiscriminate expansion of all ports. Instead, based on a comprehensive assessment of the overall transport system, priority for infrastructural investment will be allocated to ports demonstrating robust potential for industrial development and expansion. For regional logistics hubs lacking physical expansion capacity, integrating multi-functional programming and pursuing internal densification within existing industrial footprints represents the optimized trajectory. Conversely, ports confronting a trajectory of shrinkage can be strategically repurposed and transformed into alternative urban functionalities, a process that must be meticulously contextualized within their specific localized urban structures.

This systematic process of evaluation and adaptive repurposing necessitates a comprehensive synthesis of planning policies, landuse regulations, urban morphological structures, and indicators of urban performance, thereby generating evidence-based spatial strategies.

1.2 Problem Statement

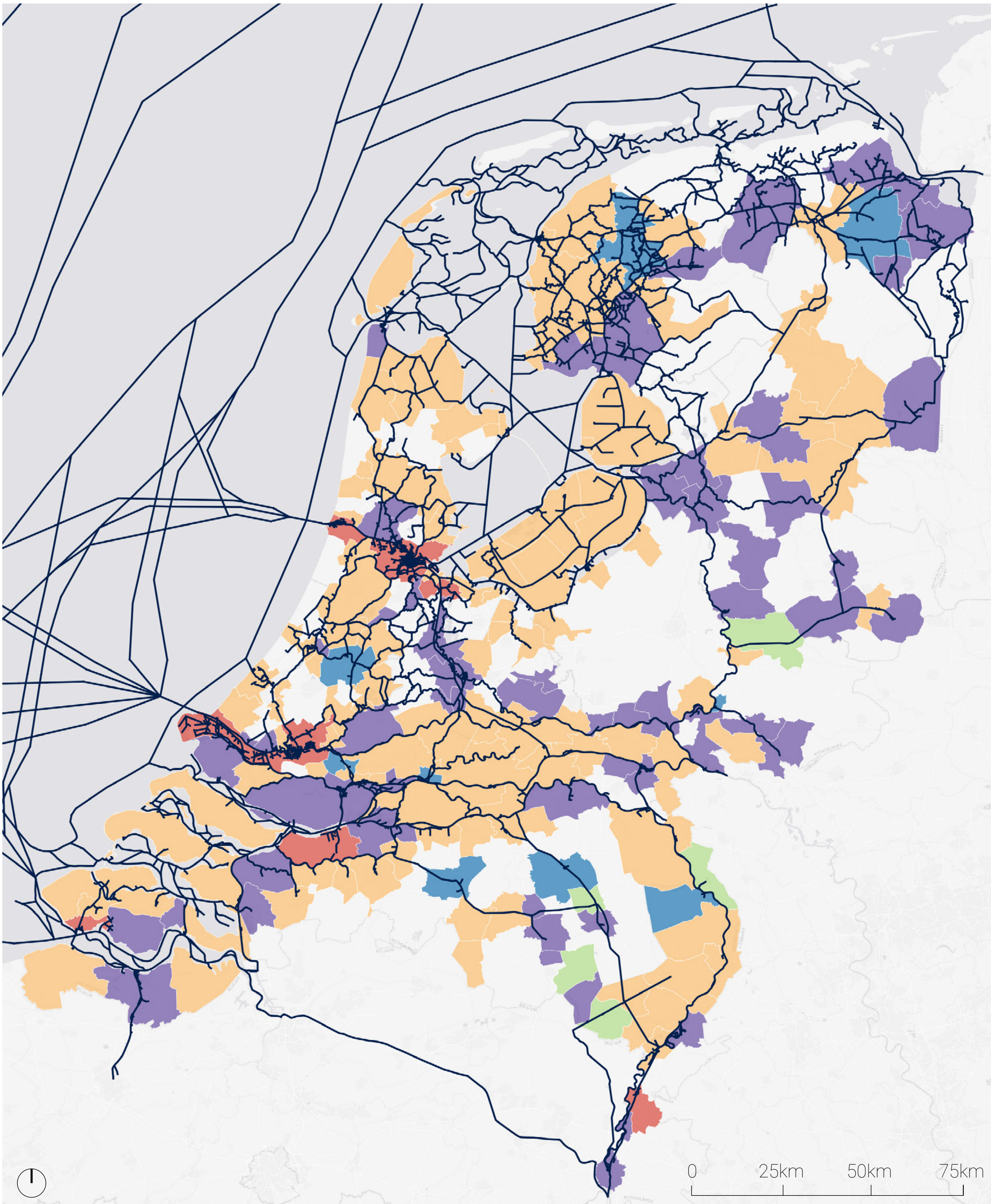
During the era of rapid expansion, the synchronized development of residential and industrial areas in IIPCs generated critical conflicts among urban morphological characteristics, landuse regulations, and urban performance. Consequently, valuable urban waterfronts remain underutilized and structurally detached from the surrounding urban fabric. While waterfront transformation has been widely discussed, existing literature predominantly relies on qualitative approaches and tends to examine individual cities or specific waterfront areas in isolation, lacking a systemic integration with the broader regional network. To address these gaps, this study aims to establish a multi-scalar, data-informed framework to identify the spatial transformation potential derived from these two types of conflicts, ultimately proposing targeted urban design strategies.

1.3 Objectives

The overarching objective of this research is to construct a multi-scalar framework with the process of context–assessment–design. By leveraging a data-informed methodology, this framework aims to bridge the analytical gap between regional and port-city level development projections at the macro- and meso-scale and localized urban design interventions at the micro-scale, thereby providing transferable insights for future evidence-based urban renewal.

The major goal of such a re-evaluation and transformation potential identification is to harmonize competing socio-economic and ecological imperatives. By optimizing the foundational components of urban morphology, which are landuse pattern, street network, and building block (Whitehand, 2001) this approach seeks to cultivate the inherent spatial adaptability necessary to absorb and navigate future socio-spatial transformations.

This thesis specifically focuses on the IIPCs situated within the interconnected IWT network bridging the Port of Rotterdam with the industrial hinterlands of Northwestern Europe (Fig. 6). These municipalities occupy a highly strategic position within this vital logistical network; consequently, transformations within their industrial configurations and urban fabrics exert direct and indirect structural impacts throughout the wider region. Furthermore, the imperative for post-expansion qualitative optimization is uniquely critical for IIPCs, which grew rapidly before and are now navigating a structural transition away from simple expansion. Investigating waterfront transformation within these specific urban contexts and formulating corresponding spatial design strategies is therefore of profound contemporary and practical significance.



Legend *Source: CBS*

chemical industry port
container port
large multifunctional port
sand/gravel port
agriculture port
transportation waterway

Fig. 3, All municipalities with inland industrial ports in the Netherlands categorized by major cargo throughput

1.4 Research Questions

In summary, this thesis on waterfront spaces in IIPC identifies potential arising from the urgency of transformation, offering pathways for future development towards a more resilient port-cityscape. The main research question guiding this study is therefore:

How can waterfront transformation potential in industrial inland port cities be identified through a multi-scalar framework to cultivate a more adaptive and resilient port-cityscape?

In alignment with the research and design process, several sub-questions must be addressed in order to answer this overarching question:

1. What are the development prospects of IIPCs in the network in the hinterland of Port of Rotterdam according to their current spatial, economic and social condition?

2. What are the transformation potentials indicated by spatial configuration patterns based on IIPC development model?

3. What is the urban morphological identity of the waterfronts in those cities?

4. What are the transformation potentials indicated by imbalances between urban morphological identity and urban performance?

5. What are the appropriate design strategies for transformation potentials indicated in the multi-scalar framework?

6. To what extent can the data-informed strategies balance context-specificity and transferability in providing waterfront urban design solutions?

1.5 Relevance

The societal relevance of this research lies in its focus on IIPCs. In a contemporary context where social, economic, and ecological values are increasingly expected to be integrated in pursuit of sustainable development goals, the comprehensive design of urban waterfront spaces is gaining growing importance. In IIPCs, however, tensions arising from the incompatibility between modern industrial activities and living environments make the analysis and design of waterfront spaces particularly critical. Ongoing industrial and energy transitions further intensify these tensions, while simultaneously opening up opportunities to explore alternative and more balanced spatial solutions.

The scientific relevance of this study is reflected in its attempt to construct a multi-scalar data-informed framework through the combined application of multiple research methods, and to validate assessment outcomes through concrete spatial design proposals. The methodology integrates qualitative and quantitative approaches and relies on open-source data and algorithms in order to maximize reproducibility. Moreover, at each analytical scale, the study seeks to distill generalizable patterns, with the intention that the proposed analytical and evaluative framework can be extended and applied to a broader range of IIPCs. Furthermore, this thesis also contributes to evidence-based design in design-driven research.

1.6 Scope

This research primarily investigates how IIPCs in the hinterland of the Port of Rotterdam can remediate the conflicts caused by previous synchronized expansion of industrial and residential functions and optimize waterfront spaces in the post-expansion era. The ultimate goal is to foster resilient urban development through a multi-scalar data-informed framework. Within this context, the scope of this study is defined by the following perspectives:

Geographical and Morphological Context:
The study focuses on Dutch IIPCs from the perspective of urban morphology. These cities exhibit the average morphological characteristics of Dutch cities, including road networks, density, and landuse patterns. Consequently, they can be analyzed collectively, and a generalized clustering method can used to construct typology. Should this research be expanded to include cities in other countries, certain parameters and clustering criteria would require further evaluation and adjustment.

Analytical Focus:
The clustering is primarily based on urban morphology, analyzing and drawing conclusions from a spatial perspective. While other factors significantly influencing urban development, such as demographic and economic dynamics, are acknowledged, they are not the central focus of this study. Furthermore, although property rights and development costs are critical considerations in urban renewal, they fall outside the scope of this research.

Functional Focus:
The study concentrates on sensitive zones where industrial and urban functions interface, examining how industrial parcels with redevelopment potential can enhance spatial quality and urban performance, thereby elevating the overall quality of the urban waterfront. While certain industrial sites could be converted into ecological green spaces, such an approach is not the primary focus of this research.

Design Scale:
In terms of design, this study examines how the derived spatial strategies can be translated into concrete spatial designs. These designs focus primarily on public space networks and the urban facades, incorporating density and functional elements which are required to enclose public spaces. Architectural design at the individual building scale is beyond the scope of this study.

2. Literature Review

In order to address the sub-research questions, this study is grounded in three main fields, and establishes a multi-layered conceptual framework at their intersection.

Together, these three dimensions of theory and analysis constitute the conceptual framework of this report: the investigation of port–city relationships through the lens of quantitative urban morphology, guided throughout by the normative orientation of urban resilience.

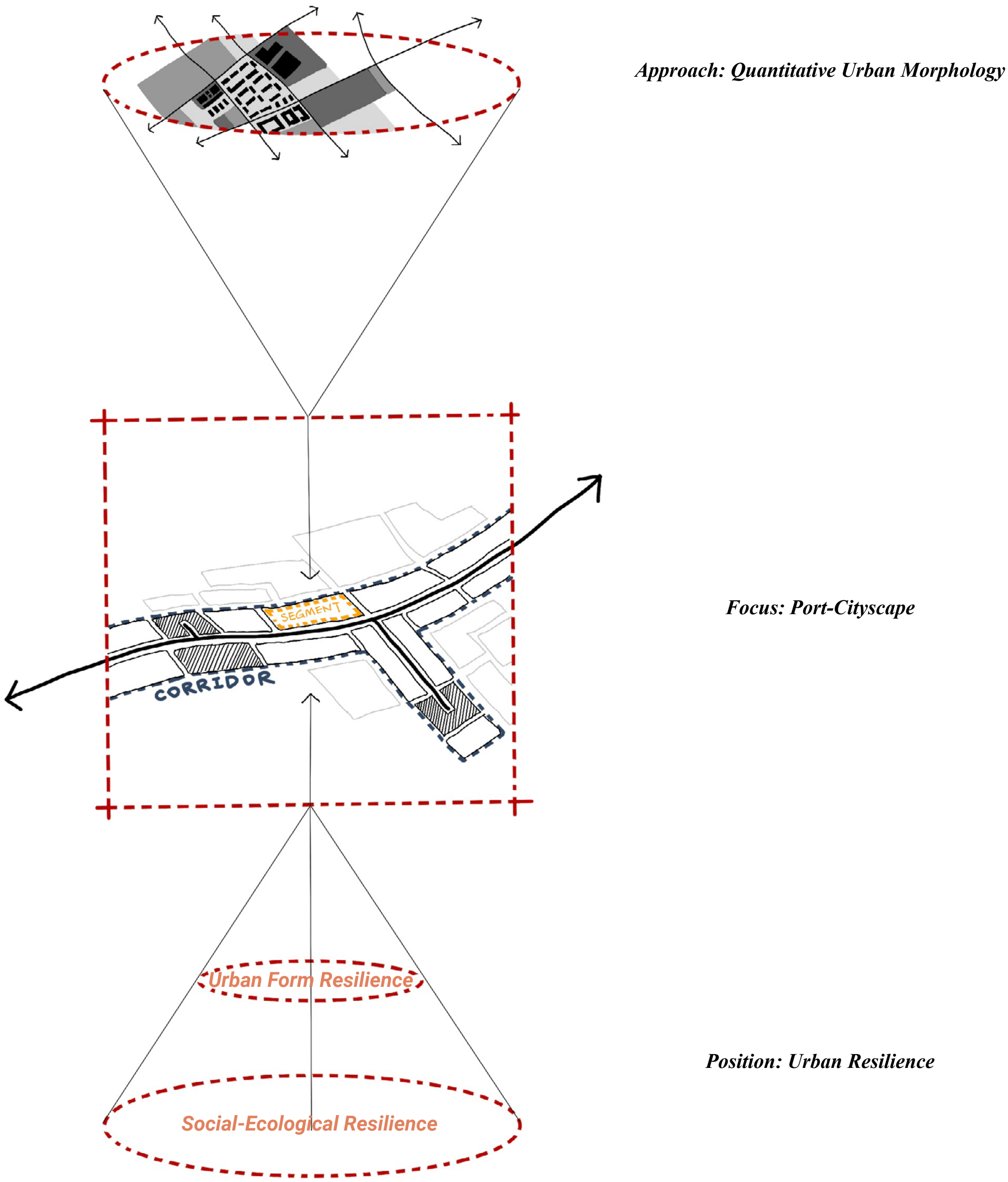


Fig. 4 Conceptual framework

2.1 Focus: Port-Cityscape

The focus and topic of this research is the port-city relationships, and more specifically, the manifestation of port–city relationships within waterfront spaces. Ports function as nodal points between cities and wider regions, connecting distant and extensive transport networks while simultaneously exerting a profound influence on the spatial structure of local cities. Due to the network-based nature of ports, studies of port cities can be structured across three interrelated scales: poly-centric ports within a regional network, the relationship between an individual port and its associated city, and specific waterfront spaces (Patrick, 2025).

At the port–city scale, according to Bird's "Anyport Model" (1963), the era of industrialization, modernization and containerization has resulted in a complete separation between ports and cities in both morphology and connectivity. In the Dutch context, ports and cities are often governed by different administrative institutions, which has gradually transformed them into two confronting entities, entirely disconnected in terms of function and urban fabric (Hein, 2023). This separation renders the port virtually invisible within the city center and in everyday urban perception. Nevertheless, ports continue to shape urban form and spatial organization in multiple ways. In response to this paradox, Hein introduced the concept of the port-cityscape, emphasizing that the presence of the port extends far beyond a clearly bounded industrial landscape, and instead shapes the city through pipelines, transportation infrastructures, port-related industries, etc (Hein, 2019). When combined with the Port of Rotterdam's hinterland strategy (Notteboom, 2026) and the crucial role of IWT in the Netherlands, this concept becomes particularly significant for analyzing the development potential of Dutch inland port cities from a systemic and network-based perspective.

Emerging from this separation between port and city, the study of the port–city interface also becomes essential. Hein proposed the notion of port-city porosity, arguing that an appropriate degree of functional mixing between port and city is necessary to bridge their dichotomy, thereby enhancing the resilience and adaptability of port cities in processes of transformation and transition (Hein, 2021). Moretti (2020) further developed this discussion through the concept of the port-city threshold, suggesting that once the existence of such interfaces is acknowledged, the port city should be understood as a dynamically evolving forma urbis, and studied as an organic whole. In parallel, the concept of port–city symbiosis emphasizes that ports and cities should be regarded as co-evolving ecosystems (Hein, 2023). Through multidimensional resource analysis, this perspective seeks to identify shared values that allow both port and city to benefit mutually, rather than one entity merely parasitizing the other.

In addition, the transformation potential of waterfront spaces in port cities has long been a central topic in urban studies. Waterfronts are spaces where multiple layers of social and ecological interactions are most intensely manifested (Forgaci, 2018), which simultaneously endows them with significant transformative potential. In major Dutch seaport cities such as Amsterdam and Rotterdam, extensive research has been conducted (Van Den Berghe, 2023, Harteveld, 2021b) and numerous waterfront redevelopment projects have been implemented. However, port redevelopment is not always universally supported by all stakeholders. Van den Berghe et al. (2023) examine the timeline of waterfront redevelopment in Amsterdam and highlights how diverging ambitions between port and urban authorities have shaped project outcomes, further demonstrating that institutional fragmentation between port and city governance can result in a lack of clear and consistent direction in urban planning. Pinto (2020), by synthesizing factors behind both successful and failed waterfront projects worldwide, identifies appropriate functional programming, scale, and the optimization of connectivity across three dimensions, namely lateral, longitudinal, and vertical, as key determinants of success. Other studies on waterfront redevelopment place greater emphasis on ecological dimensions, presenting a wide range of nature-based transformation possibilities (Prominski, 2012). Furthermore, qualitative researches on waterfront design methods have provided additional inspiration for the design strategies for these important urban public spaces (De Martino et al., 2023; Harteveld, 2021a, 2021b).

2.2 Approach: Quantitative Urban Morphology

The lens and methodological approach used by this research is mainly quantitative urban morphology. Quantitative urban morphology transforms the traditional, descriptive analysis of urban environments into objective, highly scalable spatial metrics, and seeks optimal urban design solutions through analysis using computational tools. Widely applied methods include Space Syntax (De Koning et al, 2017; van Nes, 2018), Space Matrix (Berghauser Pont et al, 2023), and Form Syntax (Ye et al, 2017). Ultimately, quantitative urban morphology promises reproducibility and allows the design strategies to be transferred with predictable outcomes.

Quantitative urban morphology has already been extensively employed in studies of port cities and urban waterfronts. In research on urban river corridors, Forgaci argues that urban morphology, understood as a tangible manifestation of urban form resilience, can help define crucial criteria for analyzing and designing more resilient waterfront spaces (Forgaci, 2018). Huang and Wu aim to identify spatial factors influencing waterfront vibrancy in order to inform waterfront design through a quantitative morphological analysis of highly rated coastal tourism cities worldwide (Huang et al, 2022; Wu et al, 2025). Aouissi's research quantifies port and waterfront geometries to investigate the transformation potential of different spatial forms, offering a valuable foundation for waterfront typologies construction(Aouissi et al, 2023). Huang and Zheng further demonstrate the potential of quantitative urban morphology by combining it with machine learning algorithms to automatically generate high-performance design solutions for waterfront areas in New York with redevelopment potential, highlighting the future value of this approach for urban regeneration (Huang & Zheng, 2022).

The quantitative urban morphology methodology primarily applied in this research is the Form Syntax approach proposed by Ye and van Nes (Ye et al., 2017). In their study, they integrated Space Syntax, the Floor Space Index (FSI), and the Mixed-Use Index (MXI) to correspond to the three morphological elements defined by the Conzenian school: the street network, the building block, and the landuse pattern. Their proposed method categorizes the results of Space Syntax, FSI and MXI analysis into high, medium, and low tiers, suggesting that redevelopment potential exists in areas where a misalignment or imbalance occurs among the three indicators. This paper primarily draws upon the selection of quantitative morphological indicators and the "natural urban development theory" that links transformation potential to such imbalances. Building upon this foundation, this thesis incorporates additional variables relevant to the specific research objectives and adapts the concept of "imbalance" to better align with the analytical goals.

2.3 Position: Urban Resilience

Finally, the normative position and value framework adopted in this report is urban resilience, which informs the stages of analysis, classification, and strategy formulation.

Urban resilience refers to an urban system's capacity to cope with short-term disturbances and long-term stresses. In Meerow's definition, urban resilience not only denotes the ability of an urban system to rapidly recover from acute shocks, but also its capacity to adapt to long-term changes and to transform systems with low adaptive capacity (Meerow, Newell & Stults, 2016). The latter aspect is of particular relevance to this research. As discussed earlier, the long-term pressures faced by IIPCs include the competition for waterfront spaces resulting from the simultaneous expansion of industrial and residential areas, demands of adapting their urban configuration in the post-expansion era, and the challenge of balancing economic, ecological, and social objectives in order to achieve symbiosis.

Within the broader discourse on urban resilience, this study places particular emphasis on two branches: social–ecological resilience and urban form resilience, both of which align closely with the methodological principles of quantitative urban morphology.

According to Folke, social–ecological resilience refers to the capacity of complex social–ecological systems to change, adapt, and transform in response to stress (Folke, 2006). This definition conceptualizes such systems as inherently dynamic rather than static. From this perspective, two modes of resilience emerge within urban planning: reactive and proactive. The reactive mode focuses on a city's ability to return to former equilibrium after acute shocks, whereas the proactive mode emphasizes anticipatory adaptation to future change (Vale, 2014). Given the core concern with long-term spatial development and resource allocation of the discipline of urban planning, the proactive mode is of particular analytical value and constitutes the primary focus of this study.

Urban form resilience, in turn, addresses the capacity of a city's spatial composition and configuration to adapt to change. According to Davis and Uffer, key attributes of a resilient urban form include appropriate density, functional mix, morphological diversity, and the presence of flexible and adaptable public spaces (Davis & Uffer, 2013). As a normative theoretical framework, urban form resilience identifies desirable spatial characteristics that can be operationalized through urban morphological analysis, translated into quantifiable parameters, and applied to guide design and planning toward more resilient urban forms.

3. Methodology

The methodology of this study has two principle dimensions (Fig. 5). The first is a multi-scalar approach, moving from the port-city-region network level, to the corridor-segment on port-city level, and finally to the level of selected specific waterfront segments.
The second concerns the research process, which follows a sequence of context – assessment – design: first understanding the problem, then analyzing properties, and finally deriving patterns or design principles that inform spatial interventions. The three levels and the three procedural steps embedded within the two trajectories together form the methodological matrix that underpins this research.

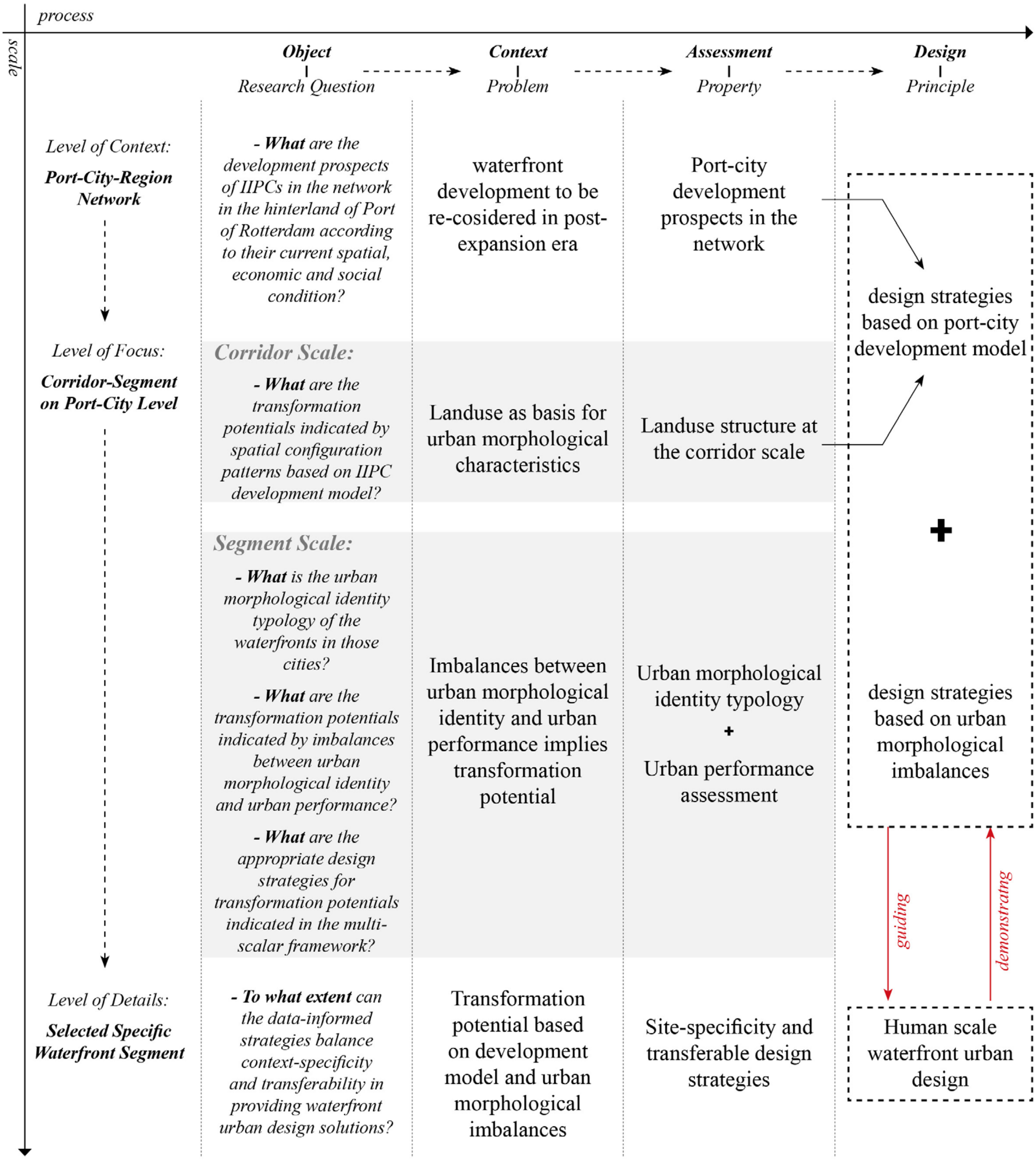
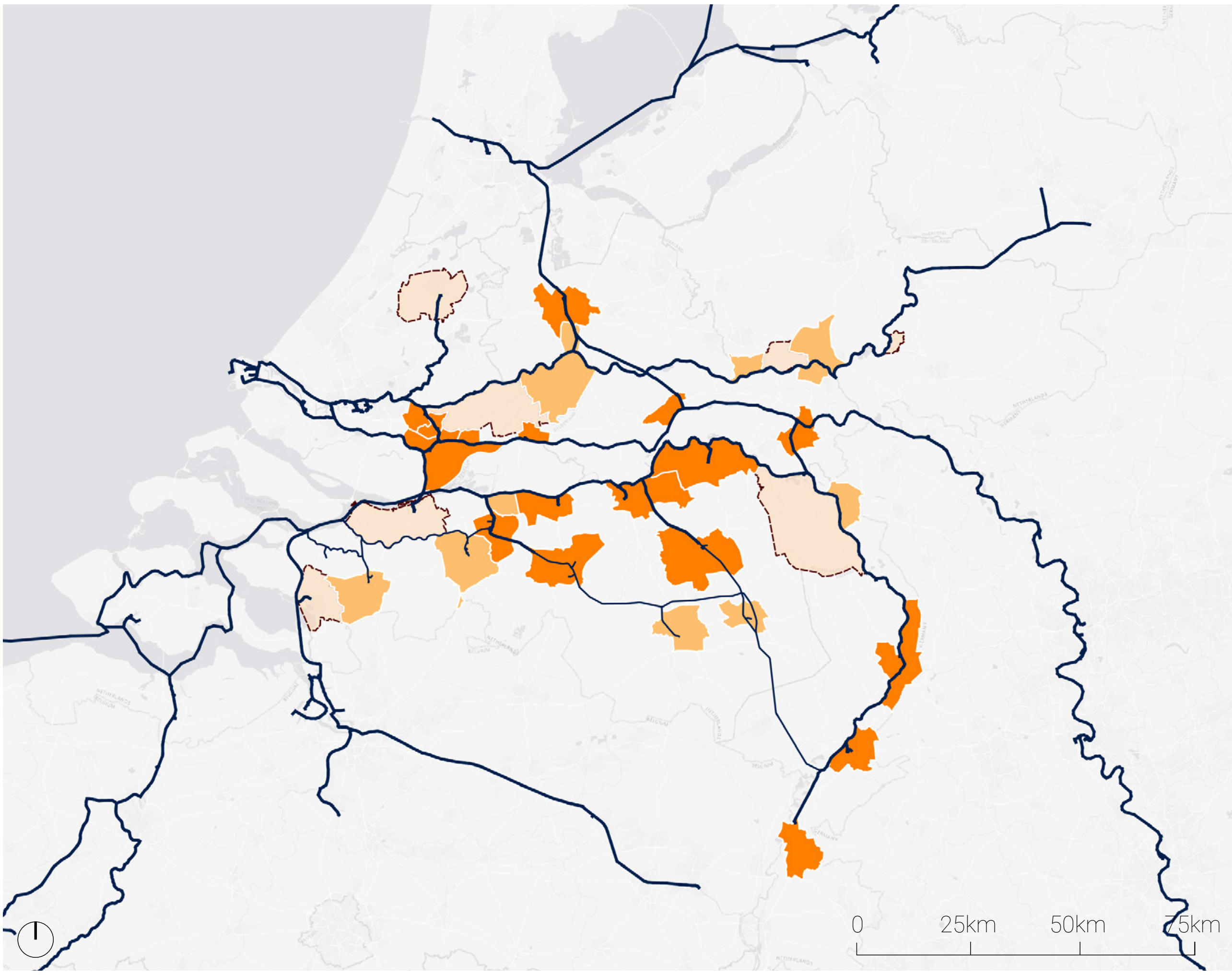


Fig. 5, Methodological framework

Within this framework, the study adopts Turner and Gardner's three-level hierarchy method (Turner & Gardner, 2015), defining the first level as the level of context, dealing with the network scale, whose conditions constrain the lower levels. The second level is the level of focus, containing two scales, corridor scale and segment scale, which constitutes the core analytical part of the thesis. From those two levels and three scales (network, corridor and segment), two layers of transformation potentials are derived. The third level is the level of details, which serves to elaborate and substantiate the overlapped transformation potentials drawn at the first two levels.



Legend

Source: Port of Rotterdam Authority

- selected IIPCs with direct barge route connection with Port of Rotterdam
- IIPCs selected with other inclusion rules
- IIPCs excluded based on exclusion rules
- barge route connection with Port of Rotterdam
- secondary transportation waterway

Fig. 6, Selected IIPCs for study

3.1 Case Selection

The selection of the port-cities in this study is primarily based on the barge route connection to the Port of Rotterdam and also follows the basic rules as shown in table 1. In the upper part of the table, several rules of including port-cities are stated, then, according to the rules listed in the bottom part of the table, a few port-cities are excluded for they are not relevant to the topic of this thesis.

In the end, out of the 26 port-cities with direct barge route connection to Port of Rotterdam, 20 was selected as study case (77.0%). In total, 30 cities are selected for further research and analysis out of the 205 dutch municipalities with ports (14.6%) (Centraal Bureau voor de Statistiek, 2025). In the table, the data sources are also stated.

Included port-cities	
a. **Ports with direct barge link with the Port of Rotterdam (Port of Rotterdam Authority, n.d.), and their associated municipality (Kadaster, 2024)**	Ridderkerk, Alblasserdam, Dordrecht, Moerdijk, Berg op Zoom, Alphen aan de Rijn, Utrecht, Doesburg, Gorinchem, Tilburg, Oss, Sittard-Geleen, Roermond, Nijmegen, ’s-Hertogenbosch, Tiel, Venlo, Wanssum, Meierijstad, Oosterhout, Waalwijk, Cuijk, Hendrik-Ido-Ambacht, Zwijndrecht, Papendrecht, Sliedrecht
b. **Ports along the three major waterways (Lek-Nederrijn, Waal, Maas) which are not in *a*, and their associated municipality (Kadaster, 2024)**	Arnhem, Molenlanden, Vijfheerenlanden, Nieuwegein, Wageningen, Renkum, Geertruidenberg, Gennep
c. **Ports with both canal link and major highway connection to port-cities in *a* and *b* (OSM, n.d.)**	Eindhoven, Breda, Helmond, Roosendaal
Excluded port-cities	
d. **Seaports (OSM, n.d.)**	Berg op Zoom
e. **Ports not relevant with the connection from the Port and Rotterdam to upstream industrial hinterland**	Alphen aan de Rijn, Doesburg
f. **Ports and urban areas isolated by considerable distance**	Wanssum
g. **Municipalities with urbanization area size not sufficient for this study**	Wanssum, Moerdijk, Molenlanden, Cuijk, Renkum

Table 1, Rules of inclusion and exclusion of IIPCs

3.2 Spatial Unit Delineation

This study is structured upon a multi-scale methodological framework, wherein data collection primarily involves two spatial units of analysis: the municipality and the segment.

Level of Context: Municipality

At the network scale, the designated spatial unit is the municipality. Analysis at this scale primarily examines the development projections of different IIPCs, with relevant spatial, economic, and social data aggregated at the city level. To minimize the confounding effects of other urban economic activities, data related to the port economy are isolated and focused on the port itself whenever possible. Furthermore, in cases where a municipality contains multiple industrial ports, their data are not disaggregated but are instead consolidated into a single municipal unit.

Level of Focus: Segment

At both the corridor and segment scales, the primary spatial unit of analysis is the segment. The definition of a segment in this study adopts the RCRISP methodology (Fig. 8, Forgaci and Nattino, 2025). Through two primary spatial operations, buffering and splitting by infrastructure (Fig. 7), the urban fabric within the zone of waterfront influence is divided into distinct segments bounded by major road and rail infrastructure.

Fig. 7, Corridor and segment delineation example - Utrecht

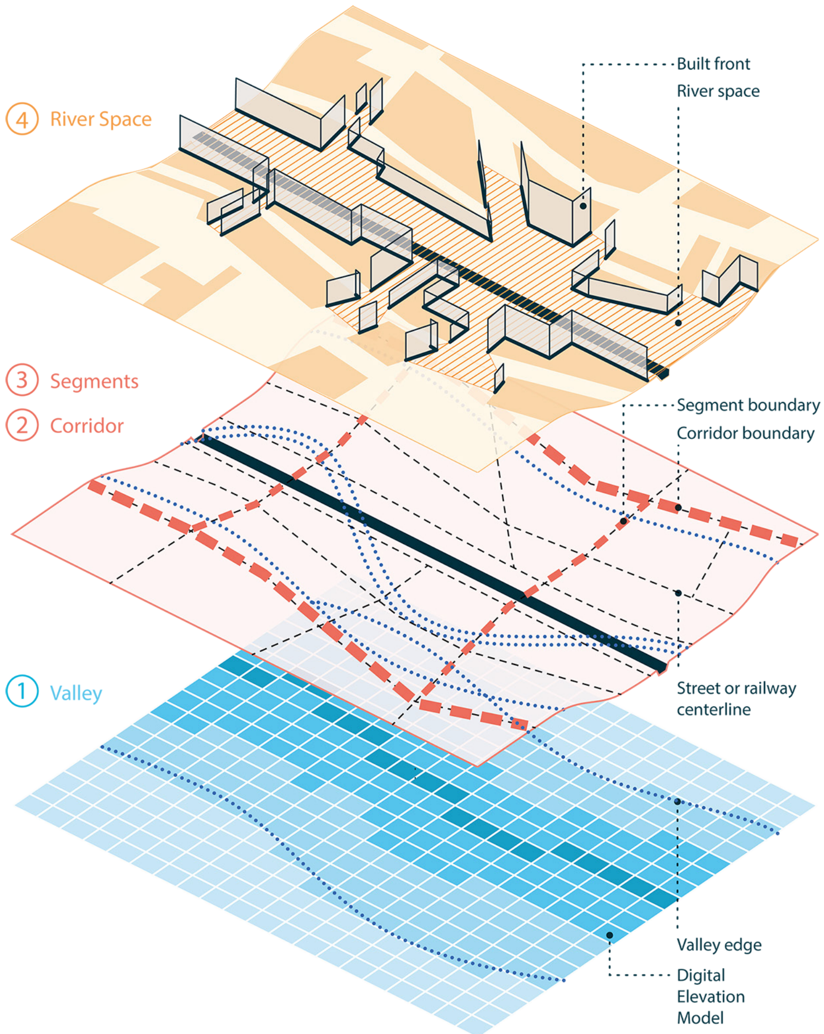


Fig. 8, Forgaci, C., & Nattino, F. (2025). rcrisp: Automate the Delineation of Urban River Spaces [Computer software]. Zenodo. https://doi.org/10.5281/zenodo.15793526.
Rcrisp overcomes the challenge of arbitrary urban river corridor delineation by providing a reliable workflow to produce morphologically grounded spatial analytical units. Rcrisp is adopted in this thesis so that there is a consistent and automatic standard of corridor and segment delineation for all the 30 selected port-cities, providing a common ground for later typology construction.

At the corridor scale, the land-use attributes of these segments are analyzed to determine their positions and roles within the IIPC development model. The conclusions derived at this scale are synthesized with the city-level development projections from the network scale to identify the waterfront transformation potential from the development model.

At the segment scale, the urban morphological characteristics of these delineated segments are examined, thereby revealing the waterfront transformation potential from urban morphological imbalances.

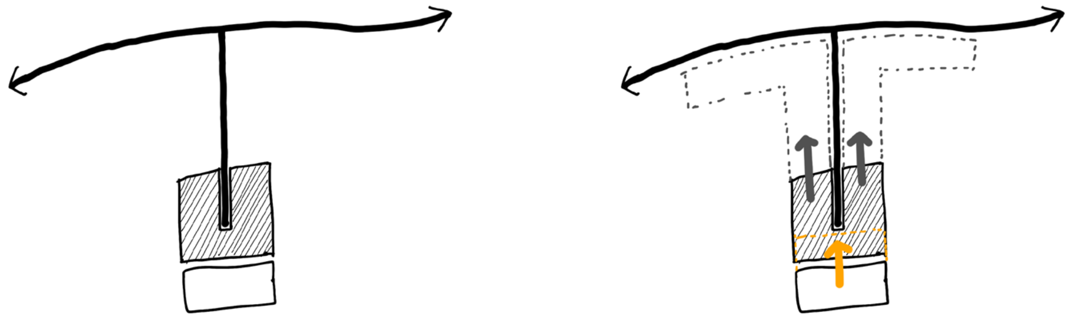
3.3 Definition of Transformation Potential

3.3.1 Identifying Waterfront Transformation Potential from IIPC Development Model

The transformation potential defined and proposed in this study is two-fold. Firstly, based on the Anyport Model by Birds (1963) adapted to IIPC, it is related to both the growth trend of the port-city and the relative location of the area in the city. In Bird's model, in the industrialized and containerized era, the city and the port, having distinct fabrics and structures, can not be integrated anymore. As a result, the port gradually grows farther away from the city (Fig. 9). In this process, the old ports located near the urban center are gradually abandoned and replaced by urban functions. Thus, the first step of identifying transformation potential in this study is to locate those areas according to the development model of the IIPCs.

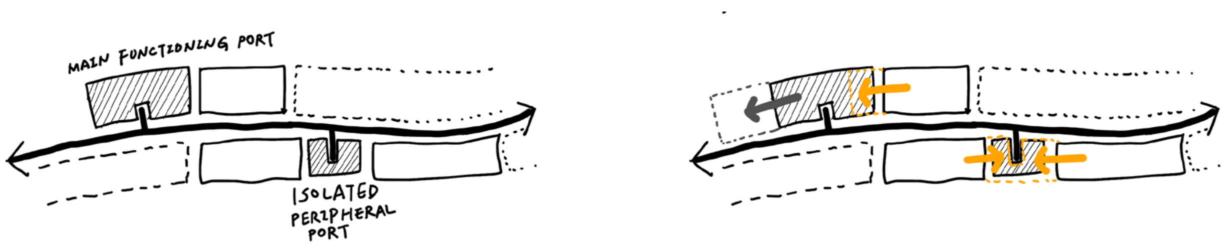
This step is accomplished by categorizing the different development trajectories of the selected port-cities at the network scale and recognizing the urban landuse structure at the corridor scale. Specific methods used at those two scales will be introduced in section 3.4 and 3.5.2.

Port Type 1: Terminal Port



configuration *development direction*

Port Type 2: Passing-Through Port



configuration *development direction*

Legend

Fig. 9, Anyport model adapted to IIPC

3.3.2 Identifying Waterfront Transformation Potential from Urban Morphological Imbalances

Secondly, the potential comes from the imbalances among urban morphological identity, landuse regulation, and urban performance based on the theory of natural urban transformation process proposed by Ye and van Nes (2014). In their study, they argued that the three fundamental elements of urban morphology, namely, street network, density and functional mix, influence each other in a sequential way. A dense street network better formulates dense building fabric, which promotes higher level of functional mix. As a result, the imbalance of the performance of the three elements leads to potential for transformation, which is part of the natural urban transformation process (Fig. 10).

The definition of imbalance proposed in this thesis is adapted from the study of Ye and van Nes, with the sequence reorganized, in order to cope with the two conflicts mentioned in the problem statement (Fig. 14). As mentioned previously, there are two major conflicts caused by the rapid synchronized development of industry and housing: the lag in landuse regulation and sub-optimal urban performance.

Based on the observation of Dutch town planning, landuse regulations play an important role in influencing the urban structure and performance of the cities. Consequently, landuse regulation is recognized as a base ground influencing the urban structure. With this logic, the landuse regulations could be adjusted according to new requirements or conditions of the city and thus influence the urban morphology.

Table 2. The definition of various categories in the final combination of space syntax, spacematrix and MXI

Types of urban areas	The values of Space Syntax, Spacematrix and MXI belonging to each type	Degree of Balance
1) Suburban	L/L/L, M/L/L, L/L/M, L/M/L	Balanced with low-values
2) Low-urban	L/M/M, M/L/M, M/M/L	
3) In-between (low)	H/L/L, L/H/L, L/L/H	Unbalanced with mixed-values
4) In-between (medium)	H/M/L, M/H/L, L/M/H, H/L/M, L/H/M, M/L/H	
5) In-between (high)	H/H/L, H/L/H, L/H/H	
6) Medium-urban	M/M/H, M/H/M, H/M/M, M/M/M	Balanced with high-values
7) Highly-urban	H/H/H, H/M/H, M/H/H, H/H/M	

L = Low value, M = Medium value, H = High value

Fig. 10, Urban Morphological imbalances identified in the study of Ye and van Nes

Additionally, the urban morphological identities present characteristics of the urban structure of a certain area. However, when it comes to the perceivable spatial experience, there might be mismatches between morphological identity and urban performance. Thus, it is necessary to examine the tangible urban performances that are related to waterfront space qualities, namely integration, accessibility and connectivity (Forgaci, 2018).

This aim is achieved by constructing a typology of waterfront urban morphological identities and establishing an assessment framework to diagnose the urban performance at the segment scale, and finally to inform different types of intervention strategies. The methods adopted at this scale is introduced in the section 3.5.3.

3.3.3 Overlapping of Multi-Scalar Transformation Potential

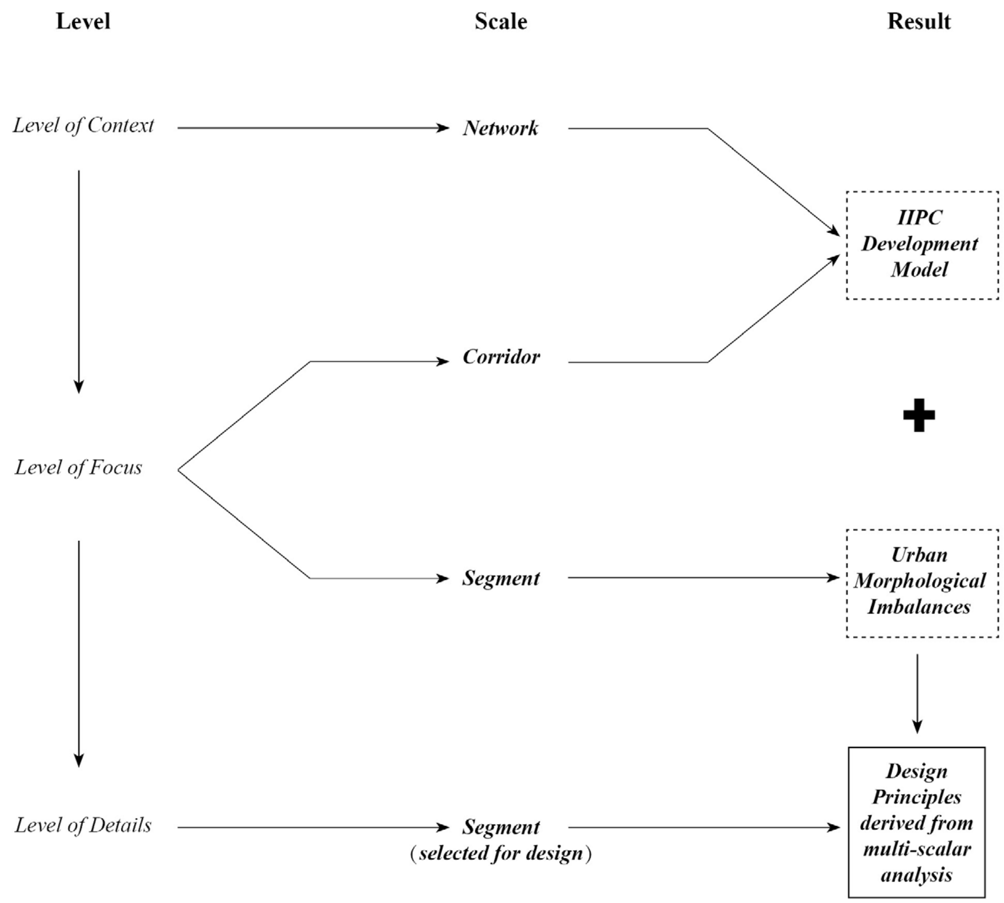


Fig. 11, Scalar framework

The "transformation potential" defined in this study is derived by overlapping the two aforementioned transformation potentials. The former is established based on the integrated conclusions drawn from the scale of regional network and corridor, whereas the latter emerges from the urban morphological analysis conducted at the segment scale. Consequently, a correspondence is established between the first two levels and the three scales within the methodological framework (Fig. 11).

Potential identification derived from the development model not only places greater emphasis on the spatial positioning of a segment with redevelopment potential within the broader network and its host city, but also regards the development of these cities as a dynamic process. This step is essentially to address the question of “where to”.

Conversely, while potential identification stemming from urban morphological imbalances also accounts for locational factors, it focuses more closely on the inherent morphological characteristics of the eligible segments, dealing more with the question of “how to”. By quantifying, summarizing, and refining these characteristics, this approach yields guidance for transformation strategies that prioritize the localized spatial experience.

Ultimately, advancing to the level of details, the design phase for specific segments predicated on the analytical conclusions of the preceding two scales, necessitates the integration of site specificity. Accordingly, the final design strategy is synthesized from three core components: the projections derived from the IIPC development model (Fig. 9), the optimization recommendations generated by urban morphological imbalances, and the more qualitative considerations informed by site specificity (Fig. 12).

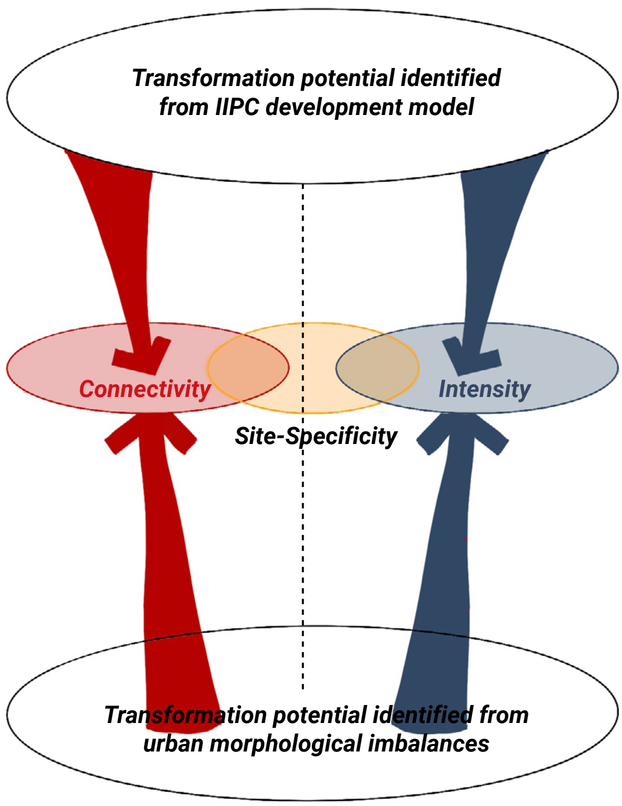


Fig. 12, Three design strategy and their relation with assessment conclusions

3.4 Level of Context: Port-City-Region Network

At this level, the research examines the network of IIPCs located along strategically significant inland waterways connecting the Port of Rotterdam with the industrial hinterland of Northwestern Europe. As discussed previously, this network is expected to undergo a more differentiated and prioritized development process, evolving into a system with a clearer hierarchy of port-cities with different development prospects and an enhanced capacity to adapt to future transformations. Within this network, cities differ in port type, industrial and economic conditions, and expansion capacity, resulting in divergent development dynamics and, consequently, varying spatial implications. By clustering the selected cities and analyzing this divergent development dynamics, the research at this level aims to prepare the base for identifying transformation potential based on IIPC development model.

Accordingly, the key research question and objectives at this level is:

1. *What are the development prospects of IIPCs in the network in the hinterland of Port of Rotterdam according to their current spatial, economic and social condition?*	**Objective 1.1**	Identify perspectives of port and urban area development
	Objective 1.2	Categorize IIPCs according to development prospects
	Objective 1.3	Analyze development dynamics in the network

Table 2, Research question and objectives at the level of context

3.4.1 Context

To address the sub-question, contextual analysis involves the interpretation of relevant policies at the level of EU (European Commission, 2021), Dutch national government (Government of the Netherlands, n.d.; IenW, 2024; Ministry of Infrastructure and Water Management et al, 2023; PBL, 2025), and Port of Rotterdam (Port of Rotterdam Authority, 2023, 2024&2025), from which future development directions for the inland port logistics system are derived, providing proof for analyzing the clustering result.

Aspects	Criteria	Unit
Social criteria	Population growth dynamics	Municipality
Economical criteria	Port type GDP trend	Port
	Multimodal connection availability	Port
	Functional diversity of port	Port
	Scale of the port	Port
	Sector GDP trend of the port	Port
Spatial criteria	Port expansion dynamic	Port

Table 3, Variables for clustering at the level of context

3.4.2 Assessment

As assessment, the thirty selected case municipalities are categorized based on variables from three aspects: spatial, economic, and social (Table 3). k-prototypes algorithm is used in the process, which has the capacity to handle mixed data types across a multi-variable dataset, thereby yielding highly objective and scalable conclusions that facilitate the detection of latent patterns. To validate the structural integrity and robustness of this clustering, box-plot analyses of the results are subsequently interpreted based on the conclusions drawn from policy and planning documents, and the typology is expected to contain three clusters of different development trajectories (Table 4).

Categories of IIPC	Description	Strategic Implications
Expansion	Future urban expansion hotspot in the logistics network: occupy strategic positions, enjoy priority in infrastructure investment; in turn stimulating the expansion of surrounding residential areas and intensifying competition for waterfront spaces	An expansion direction of industrial ports should be planned along the waterfront; The social and environmental performance should be enhanced in the rest of the waterfront space
Consolidation	Ports located close to the city, with constrained expansion possibility, can be transformed into urban circularity hubs; waterfront spaces with non-core industrial uses offer potential for mixed-use redevelopment	The waterfront space in-between the current port-in operation and the urban core can accommodate mixed-use development to enhance the system performance
Shrinkage	small, mono-functional ports may face functional transformation and redevelopment	The industrial waterfront can be transformed into other use

Table 4, Categories of IIPCs at the level of context

3.4.3 Design

No specific design intervention is developed at this scale, as it functions primarily as a context and works together with the result of scale of corridor to form the transformation potential based on development model. Yet, the cluster result is mapped across the region, with the dynamics analyzed to demonstrate that it would promote a more resilient network.

Sub-question 1	*What are the development prospects of IIPCs in the network in the hinterland of Port of Rotterdam according to their current spatial, economic and social condition?*		
Objective 1.1	Identify perspectives of port and urban area development	**Method**	Policy analysis
Objective 1.2	Categorize IIPCs according to development prospects	**Method**	Data collection, k-prototype clustering
Objective 1.3	Analyze development dynamics in the network	**Method**	Mapping

Table 5, Objectives and methods at the level of context

3.5 Level of Focus: Corridor-Segment on Port-City Level

The analysis at this level concentrates on spatial characteristics and operates across two scales: the corridor and the segment. The corridor scale examines waterfront spaces within a port city as continuous spatial systems, while the segment scale focuses on spatially meaningful, discrete units delineated through urban morphological method, which is based on the rcrisp method (Forgaci and Nattino, 2025).

This level constitutes the central focus of the study and addresses the following research questions and objectives:

2. *What are the transformation potentials indicated by spatial configuration patterns based on IIPC development model?*	**Objective 2.1**	Delineate corridor and segment of IIPCs
	Objective 2.2	Map the landuse structure and identify potential spatial configuration patterns
	Objective 2.3	Propose strategies for potential based on IIPC development model
3. *What is the urban morphological identity of the waterfronts in those cities?*	**Objective 3.1**	Collect data for selected variables and cluster to construct urban morphological identity typology
	Objective 3.2	Analyze cluster result and identify the clusters with potential
4. *What are the transformation potentials indicated by imbalances between urban morphological identity and urban performance?*	**Objective 4.1**	Diagnose the clusters with potential with urban performance assessment framework
	Objective 4.2	Identify imbalances
5. *What are the appropriate design strategies for transformation potentials indicated in the multi-scalar framework?*	**Objective 5.1**	Propose design strategies by overlapping the multi-scalar transformation potentials

Table 6, Research question and objectives at the level of focus

3.5.1 Context

In contemporary urban development, landuse planning serves as a critical determinant that guides and influences urban morphology; to a certain extent, it constitutes the cornerstone of urban form (Gallagher et al, 2023). While landuse planning and urban morphology do not necessarily share a direct causal relationship, they generally exhibit a significant degree of correlation. Observations of Dutch industrial port cities reveal that port and associated industrial zones typically feature a high GSI and a low FSI, coupled with a relatively sparse road network. In contrast, predominantly residential areas are characterized by a high GSI, a high FSI, and a denser road network.

However, the impact of landuse planning on the evolution of urban morphology inherently involves a certain temporal lag. During the transition of industrial zones and the gradual transformation of urban structures, some former industrial areas may possess significant redevelopment potential, yet their designation remains restricted to industrial use, thereby constraining the emergence and development of alternative spatial functions. Alternatively, certain areas may be formally designated as mixed-use zones for industrial and residential purposes; however, due to various factors, their morphology continues to exhibit typical industrial characteristics, which significantly impairs the living experience of local residents. These inherent contradictions represent the very foundation of the transformation potential within urban waterfront. Consequently, to identify this type of transformation potential, one must first comprehend the urban structure from the perspective of landuse structure.

3.5.2 Assessment and Design at Corridor Scale

To answer sub-question 2, landuse structure of the selected port-cities are analyzed at the scale of corridor. This thesis collects landuse data from Kadaster (2025) to calculate the area proportions of three primary landuse categories within each segment: industry, public facilities, and residential. The latter two categories are subsequently aggregated into an "urbanity" index. By determining which landuse type constitutes the majority (i.e., exceeding 50%) within each zone, the blocks are classified into distinct types. Then, spatial configuration patterns with potential for transformation are identified (Fig. 23). Together with the development prospects analysis at the level of context, these patterns help identify the transformation potential based on IIPC development model.

3.5.3 Assessment and Design at Segment Scale

To answer sub-question 3, at the segment scale, urban morphological identity typology is formulated using k-means clustering algorithm. For sub-question 4, The segments in the cluster which presents the morphological identity of great transformation potential are then diagnosed using an assessment framework. Finally, to answer sub-question 5, appropriate design strategies are proposed according to the overlapping of transformation potential from both the IIPC development model and the urban morphological imbalances.

This thesis adopts K-means clustering as the method to identify urban morphological identities. It is widely applied in the field of urbanism for typology construction (Schirmer and Axhausen, 2019), primarily due to its exceptional capacity to discern multi-dimensional, hidden patterns within complex spatial datasets. Concurrently, it offers a highly scalable and reproducible methodological framework, allowing researchers to efficiently analyze vast amounts of spatial data while ensuring that findings can be rigorously tested and replicated across different urban contexts.

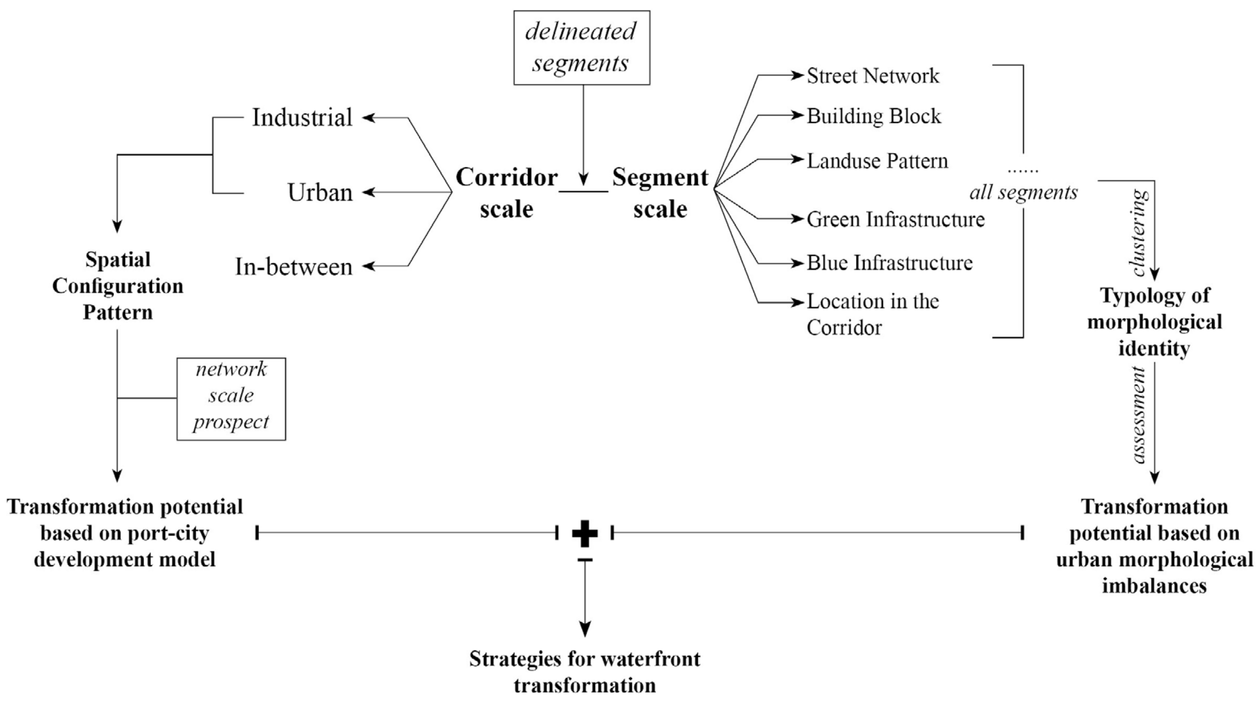


Fig. 13, Methods at the level of focus

Variables for clustering	Description	Aspect
Accessibility of each segment	Using space syntax to calculate the weighted sum of angular choice result (800m) of each segment	Street network
FSI	Using the data from Rudifun dataset from the dutch government, indicating the built density of the segments	Density
Mixed-use index	Using the data from Rudifun dataset from the dutch government, indicating how mix-used are the segments	Function
Average NDVI	Using satellite image to calculate the average NDVI of the area, indicating the health and density of vegetation	Green infrastructure
Waterway ratio	Using waterway data from PDOK to calculate the ratio of waterway length and perimeter of each segment, indicating the amount of accessible waterfront	Blue infrastructure
Center reachability	Using QNEAT to calculate how much area of each segment is within 15min walkable distance from the urban center	Location in the corridor

Table 7, Variables for clustering at the scale of segment

Dimensions of assessment	Description	Aspect
Industrial landuse ratio	For segments already having an identity of higher waterfront transformation potential, the landuse regulation could be adjusted if industrial ratio is too high	Landuse regulation
Residential landuse ratio	For segments with higher residential land ratio but categorized into lower urbanity cluster, an integrated intervention is required	Landuse regulation
Amenity density	Segments with higher waterfront transformation potential but with lower amenity density may need more multi-function development	Function performance
Built density	Segments with higher waterfront transformation potential but with lower built density could be densified	Density performance
Lateral connectivity	Segments with higher waterfront transformation potential but with lower lateral connectivity may need intervention on street network	Connectivity performance
Waterfront path density	Segments with higher waterfront transformation potential but with lower waterfront path density may need more waterfront pedestrians	Connectivity performance

Table 8, Dimensions of assessment framework at the scale of segment

3.5.4 The Relation between Typology Construction and Performance Assessment

The variables selected for clustering in this study can primarily be categorized into six dimensions: street network, density, function, green and blue infrastructure, and location within the corridor (Table 7). This selection is grounded in the Conzenian school of urban morphology, which conceptualizes urban form through the tripartite framework of street systems, building blocks, and landuse patterns. Building upon this foundation, the waterway ratio serves as an indicator of the potential waterfront space surrounding each block, effectively identifying waterfront areas with high redevelopment potential. Furthermore, the inclusion of the Normalized Difference Vegetation Index (NDVI) integrates the ecological value of these waterfront spaces into the evaluation. Finally, the accessibility from each block to the city center reflects its spatial location within the corridor. Consistent with preceding analyses and findings, blocks situated closer to the city center exhibit higher redevelopment potential and priority.

Together, these variables comprehensively capture the morphological characteristics of the blocks, leading to the derivation of urban morphological identity through clustering. However, there may be a discernible mismatch between urban morphological identity and more specific, tangible urban performance indices. For instance, a high level of landuse diversity (e.g., high Mixed-Use Index) does not necessarily translate to an abundance of accessible amenities for local residents. Similarly, high accessibility within the road network (presented as high value in angular choice analysis) does not automatically guarantee high lateral and longitudinal connectivity within the block. The former indicates a block's underlying capacity, whereas the latter is more tangible and directly linked to the lived spatial experience.

Based on the preceding analysis, following the clustering process, this study will establish an assessment framework with dimensions derived from the variables adopted in the previous analysis (Fig. 14). This framework will evaluate the segments within clusters that exhibit high potential or distinct spatial contradictions, thereby identifying the specific blocks that hold significant potential yet require targeted interventions. The subsequent design strategies and interventions will then be formulated specifically for these designated blocks.

This study utilizes a rigorous quantitative approach to diagnose these imbalances. The specific values of each individual segment across the selected indices are statistically benchmarked against the overarching distribution of their respective cluster. If a segment's metric deviates from the cluster centroid by more than one standard deviation (confidence interval = 68.27%), it signifies that the segment falls within the top or bottom 15% threshold of the entire cluster, confirming a statistically significant imbalance.

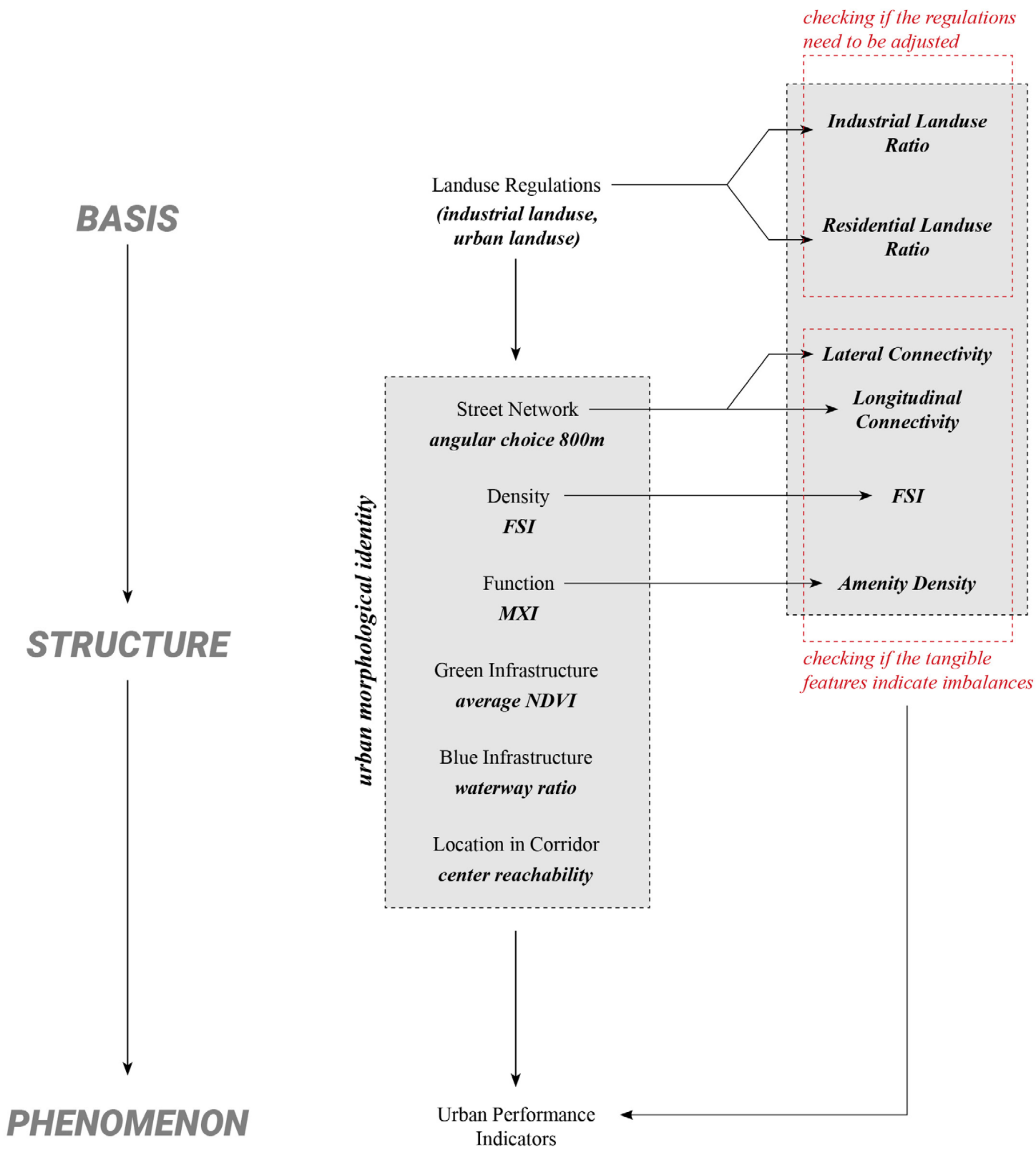


Fig. 14, Methodological framework to assess urban morphological imbalances

Sub-question 2	*What are the transformation potentials indicated by spatial configuration patterns based on port-city development model?*		
Objective 2.1	Delineate corridor and segment of IIPCs	**Method**	Rcrisp
Objective 2.2	Map the landuse structure and identify potential spatial configuration patterns	**Method**	mapping
Objective 2.3	Propose strategies for potential based on port-city development model	**Method**	Design
Sub-question 3	*What is the urban morphological identity typology of the waterfronts in those cities?*		
Objective 3.1	Collect data for selected variables and cluster to construct urban morphological identity typology	**Method**	DBSCAN, satellite image processing, urban data analysis, k-means clustering
Objective 3.2	Analyze cluster result and identify the clusters with potential	**Method**	Statistical analysis, box-plot, PCA analysis
Sub-question 4	*What are the transformation potentials indicated by imbalances between urban morphological identity and urban performance?*		
Objective 4.1	Diagnose the clusters with potential with urban performance assessment framework	**Method**	Urban data analysis, Statistical analysis, radar chart plotting
Objective 4.2	Identify imbalances	**Method**	Statistical analysis
Sub-question 5	*What are the appropriate design strategies for transformation potentials indicated in the multi-scalar framework?*		
Objective 5.1	Propose design strategies by overlapping the multi-scalar transformation potentials	**Method**	Analysis and design

Table 9, Objectives and methods at the level of focus

3.6 Level of Details: Selected Specific Waterfront Space

The level of details focuses on design strategies implemented into specific cases. Building on the design strategies derived from the level of focus, this scale tests to what extent can the strategies derived from transferable data-informed approach be implemented in site-specific urban designs. Three design cases are selected presenting the three spatial patterns identified at the corridor scale, with the segment chosen as design site from both of the clusters with transformation potential and showing four different types of imbalances to better demonstrate the feasibility of the constructed typology and recognized patterns from the multi-scalar methodological framework.

The key research question and objective at this level is:

6. *To what extent can the data-informed strategies balance context-specificity and transferability in providing waterfront urban design solutions?*	**Objective 5.1**	Analyze site-specificity for each design case
	Objective 5.2	Propose human scale urban design for selected segments

Table 10, Research question and objectives at the level of details

3.6.1 Context

The context of this level is inherited from the analysis conclusions from the previous levels, which is the transformation potential identified from based on both the IIPC development model and the urban performance imbalances.

3.6.2 Assessment

The assessment of this level is two-fold. First, before design intervention, the site-specificity is assessed using qualitative methods to decide how the transferable strategies can be applied to a specific case. Second, the urban performance is again assessed after design intervention to demonstrate the effect of the design.

Sub-question 6	*To what extent can the waterfront typology balance context-specificity and transferability in informing waterfront urban design solutions?*		
Objective 5.1	Analyze site-specificity for each design case	**Method**	Mapping and spatial analysis
Objective 5.2	Propose human scale urban design for selected segments	**Method**	Design

Table 11, Objectives and methods at the level of details

3.6.3 Design

Specific urban designs will be presented in masterplans, profile sections, birdeye views and diagrams.

As previously noted, the transformation potential identified in this study translates into three distinct considerations during the design phase: projections from the development model, optimization recommendations derived from urban morphological imbalances, and qualitative assessments of site specificity. In the lexicon of urban spatial design, these three components are operationalized into three spatial layers: ***site specificity*** corresponds to interface, and conclusions from projections from the development model and optimization recommendations from urban morphological imbalances correspond to ***connectivity*** and ***intensity*** (Fig. 12).

Interface defines the structural relationship and integration between the selected design segment and its surrounding urban fabric. This involves identifying which boundaries function as physical or psychological barriers, locating critical nodes of urban connectivity, and mapping accessible public resources and spatial assets peripheral to the segment. These localized spatial nuances are inherently generalized or obscured during the initial quantitative classification process, while actual design interventions requires a return to their empirical spatial configurations and physical distribution. Consequently, this analytical step is inherently qualitative and site-specific.

Connectivity is informed by projections from the IIPC development model and urban morphological imbalances (Fig. 25 and Fig. 37). For the projections from the development model, explicit forecasts regarding the trajectory and orientation of urban growth are presented. These developmental directions are physically manifest and reinforced through spatial connectivity. For the imbalances, some dimensions in the assessment framework are related to connectivity (Fig. 14), providing insights for the design strategy.

Intensity predominantly encapsulates two dimensions: density and functional diversity. From the potential identified based on IIPC development model, this strategy is mostly related to the network scale analysis, which informs the development projection of the port-city where the segment is located (Fig. 26). The analysis of urban morphological imbalances involves benchmarking these specific urban performance metrics to identify which segments require an increase in density or a higher concentration of amenties (points of interest). Furthermore, the introduction of new urban connections often demands a concomitant increase in surrounding intensity to elevate overall spatial quality (Jacobs, 1961; Gehl, 2001).

Through this methodological progression, the study starts from the requirement to reconsider the waterfront development of Dutch IIPCs and ultimately arrives at human-scale urban design solutions aligned with the values of urban resilience. The delineation, analysis, and clustering of waterfront spaces in port-cities constitute both the core of the research and its principal methodological contribution, within which quantitative urban morphology is most extensively applied.

4. Results

4.1 Identifying Transformation Potential from IIPC Development Model

4.1.1 Network scale

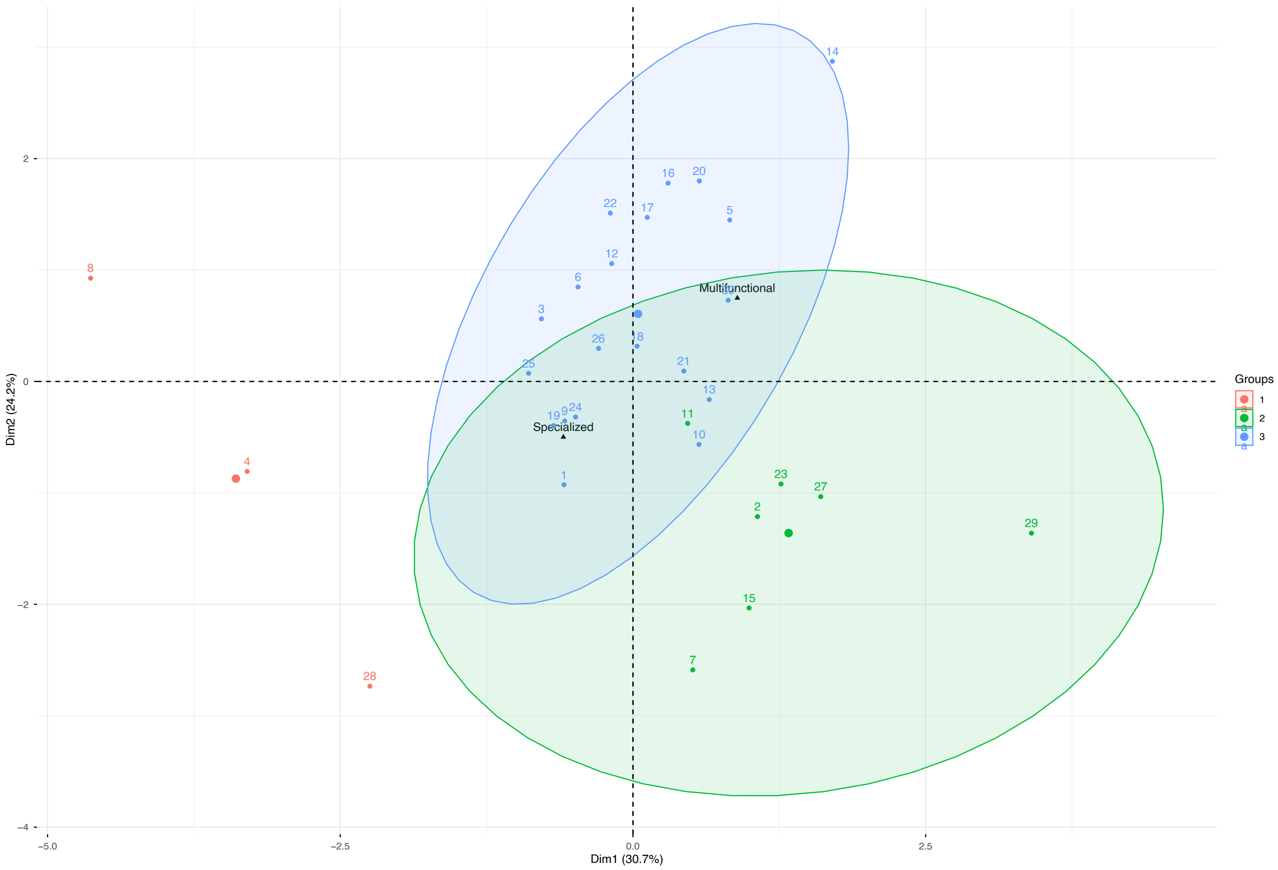


Fig. 15, K-Prototype clusterng result of development prospects of the selected port-cities

In accordance with the described methodological framework, this study initially applies k-prototypes clustering to the data compiled at the network level, thereby categorizing the thirty case cities into three primary developmental trajectories (Fig. 15). Based on the analysis of clustering result(Fig. 16a-g), the three red data points on the left represent cities categorized under shrinkage; the central blue data points denote cities assigned to the consolidation typology, with the blue ellipse delineating the 95% confidence interval; and the green data points on the right signify cities in expansion cluster.

The two axes in Fig. 15 represent the principal dimensions derived from the data synthesis, while the two black triangular markers indicate the alignment of the non-numeric (categorical) variables with the other dimensions. As demonstrated by the plot, the centroid for single-functional ports is positioned in the lower-left quadrant of the coordinate system. This indicates that the cities within the red "shrinkage" cluster predominantly feature single-functional ports. Conversely, multi-functional ports are located in the upper-right quadrant, suggesting that multi-functional ports exhibit a stronger propensity toward expansion or, at a minimum, the preservation of their existing scale and operational capacity. This observation aligns consistently with the strategic projections documented in planning frameworks and policy reports.

Furthermore, although a slight overlap exists between the consolidation and expansion clusters, their respective centroids are substantially distant and clearly differentiated. This underscores that the tripartite classification is statistically distinct and robust within the dataset.

The box-plots and barplot of the selected variables provide a more lucid and comprehensive demonstration of the distinct characteristics inherent to each cluster.

Spatial Dimension (Fig. 16a-b):
The expansion cluster exhibits the greatest physical capacity for growth, whereas the consolidation cluster displays the highest degree of variance, indicating substantial heterogeneity among the cities within this group. A similar trend is observed regarding multimodal connectivity: the expansion cluster possesses the highest mean value, while the majority of cities in the consolidation cluster lack multimodal connections. Interestingly, the spatial metrics for the shrinkage cluster consistently fall between those of the other two groups, suggesting that the primary determinants driving the clustering of these cities into the shrinkage cohort are not spatial in nature.

Economic Dimension (Fig. 16c-f):
The consolidation and expansion clusters exhibit highly comparable profiles regarding GDP growth, port typologies, and operational scales. Conversely, the shrinkage cluster diverges significantly; it is characterized exclusively by small-scale, monofunctional ports, and its GDP growth rates are substantially lower than those of the other two cohorts.

Social Dimension (Fig. 16g):
Demographic fluctuation within the host cities was selected as the primary social variable. The data reveal that the expansion cluster experiences the least pressure from population growth, which consequently yields favorable conditions for the further expansion of port and industrial zones. In contrast, both the consolidation and shrinkage clusters must contend with mounting pressures on housing demand precipitated by population growth.

In summary, it can be concluded that the expansion cluster is characterized by ample spatial capacity for port development, robust multimodal connectivity, strong economic momentum in related industries, and minimal demographic pressure. The consolidation cluster shares a similar economic profile with the expansion cluster but faces heightened population pressure coupled with constrained spatial capacity for growth. The shrinkage cluster, meanwhile, is primarily defined by the stagnation or poor performance of its associated economic and industrial sectors.

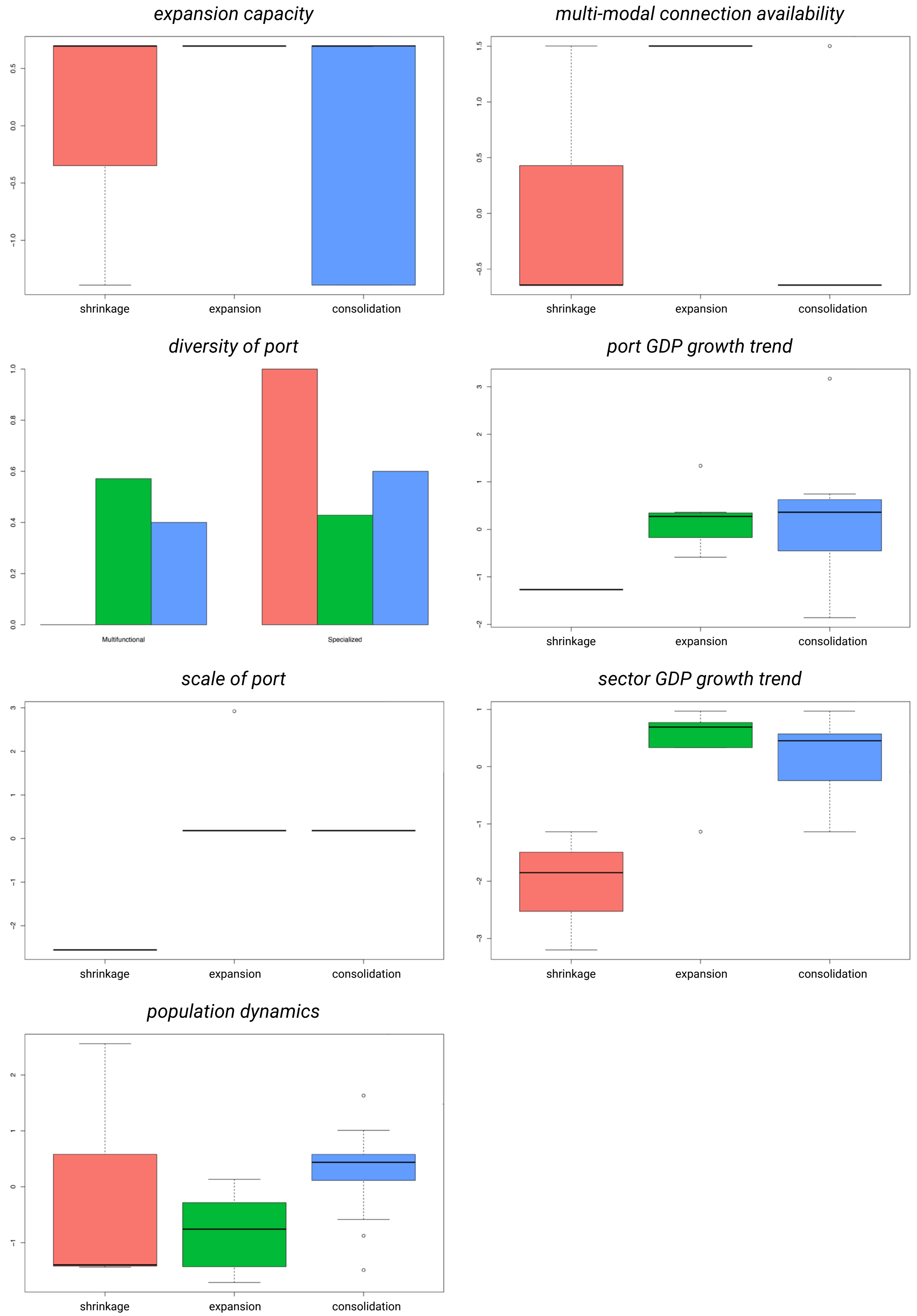


Fig. 16a-g, K-Prototype clustering result

Furthermore, supplementary visualizations corroborate the validity of this tripartite classification. Fig. 17 illustrates the strength of the correlation between the two principal axes and each of the selected variables, while Fig. 18 demonstrates that setting the number of clusters (k) to three represents an optimal statistical choice according to the elbow method (Schirmer and Axhausen, 2019).

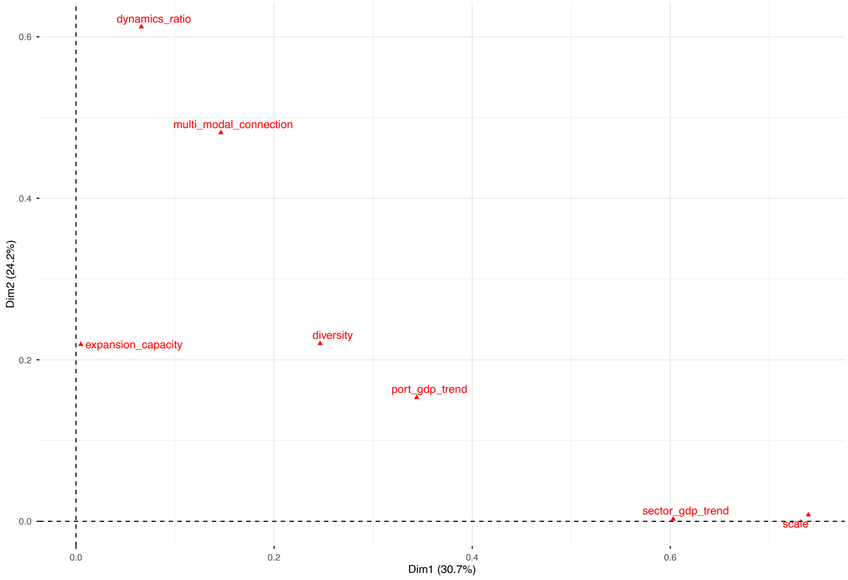


Fig. 17, Correlation between the two principal axes and each of the selected variables

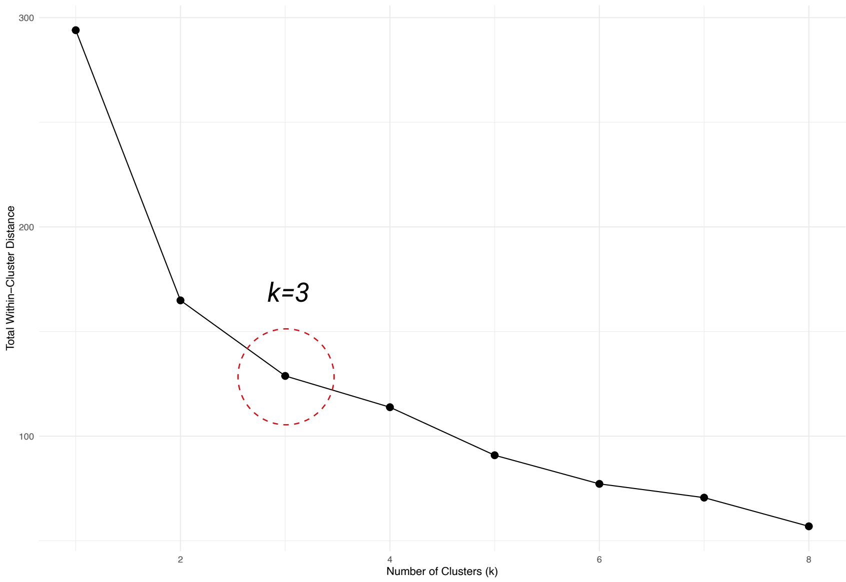
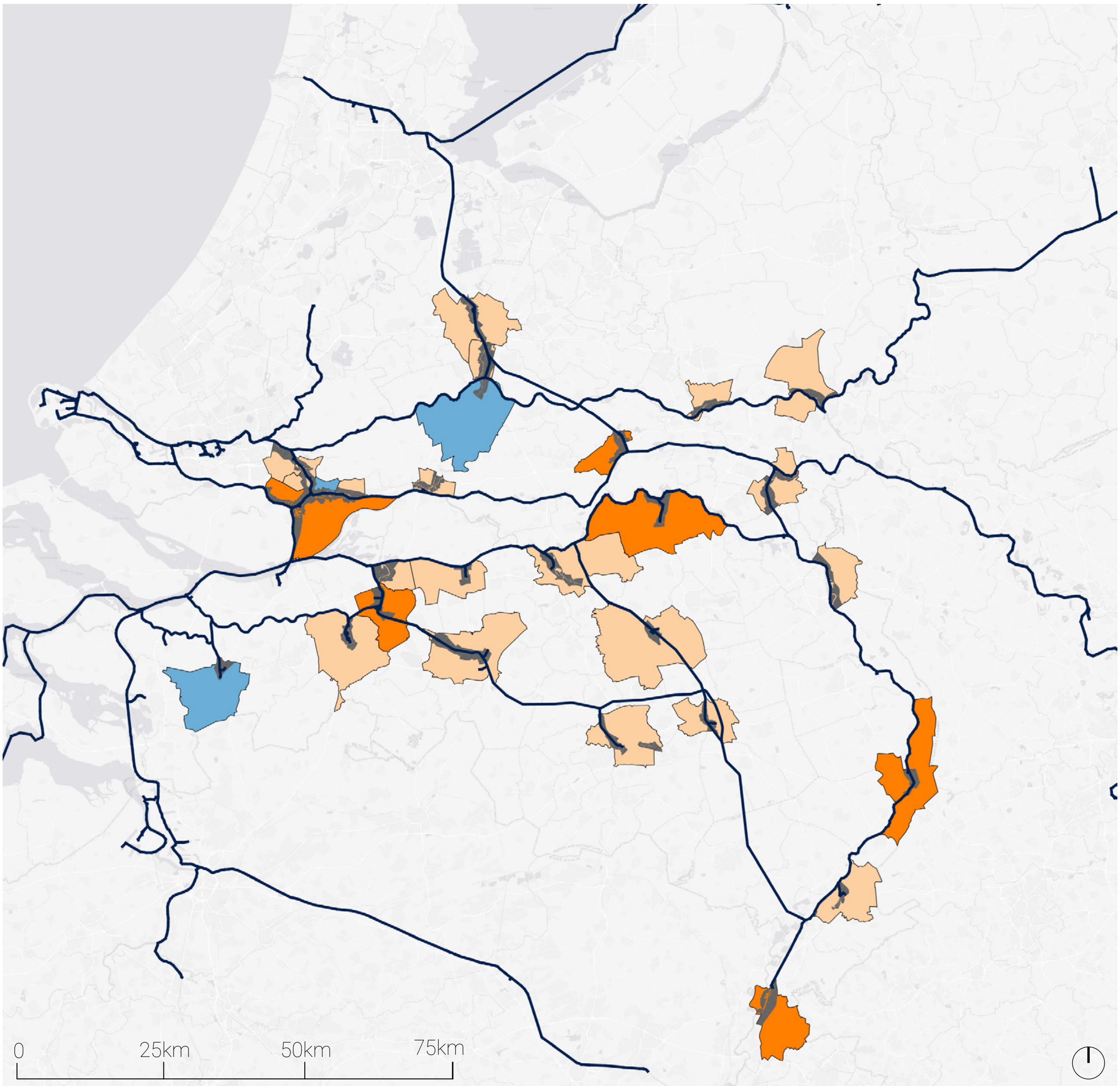


Fig. 18, Total within-cluster distance of different number of clusters



Legend

expansion consolidaton shrinkage corridor waterway

Fig. 19, Port-cities with different development projections in the network

By mapping the clustering results across the region (Fig. 19), the validity and coherence of the clustering can be further substantiated. This spatial mapping reveals that within the interconnected inland waterway network, every major shipping corridor contains at least one IIPC categorized under the expansion typology (Fig. 20). Furthermore, these expanding cities are consistently distributed at or near the strategic nodes where major waterways intersect. This spatial configuration establishes the necessary structural conditions for the formation of a resilient regional network.

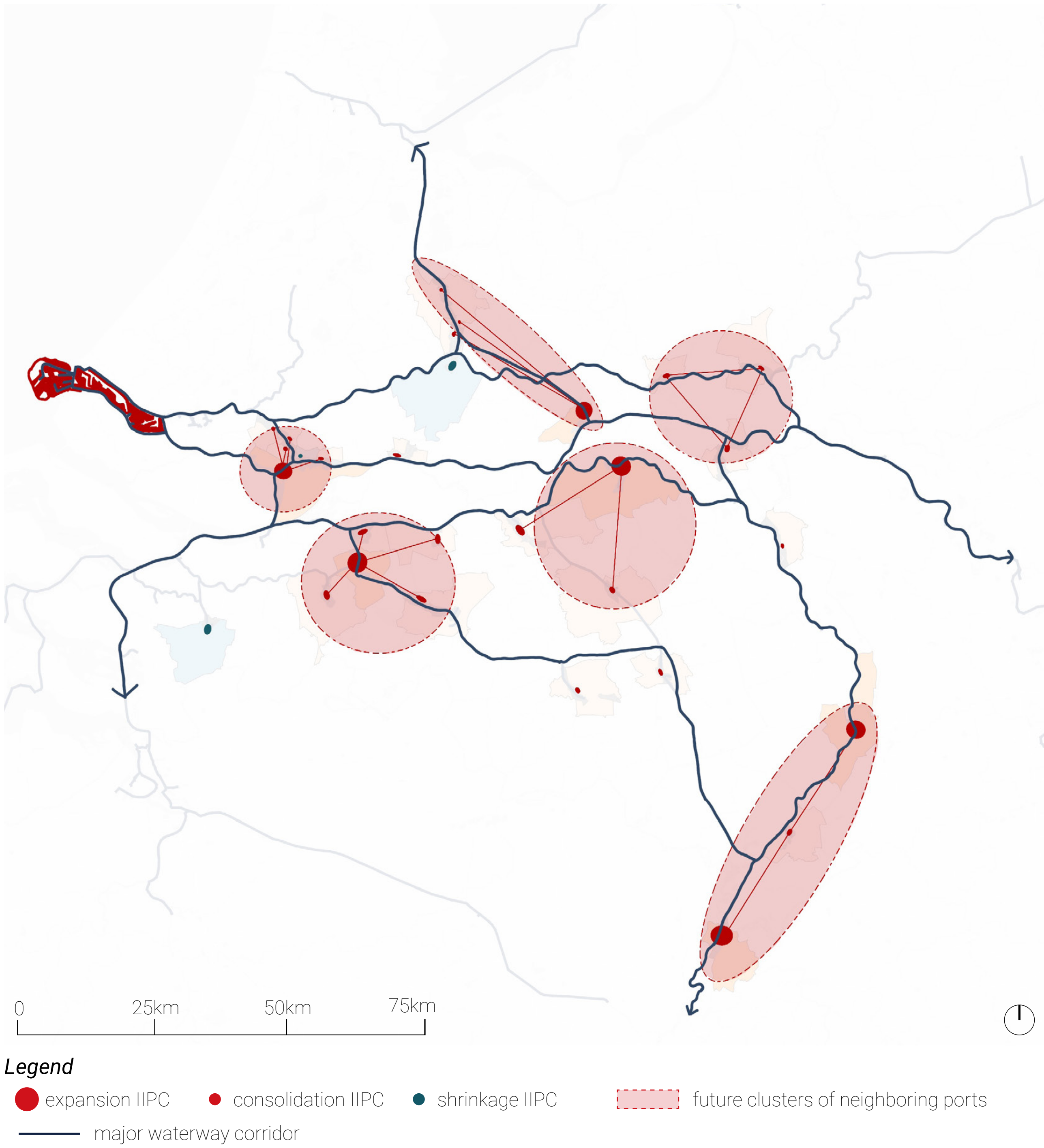
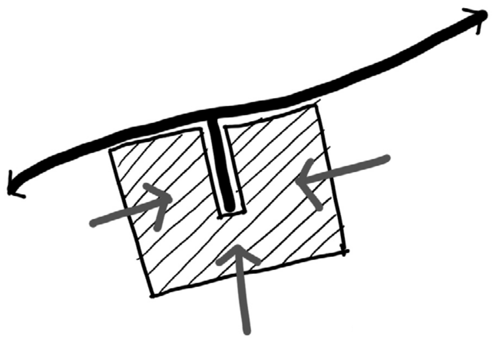


Fig. 20, Future mulyti-nodal network based on development trajectory

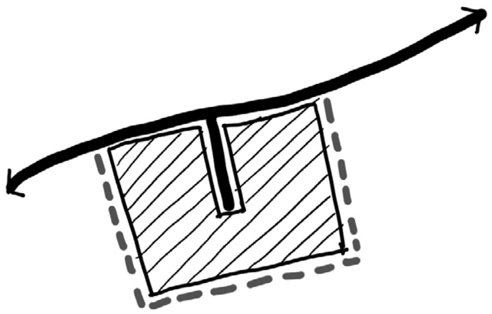
Fig. 20 illustrates the projected development of industrial port clusters within the region. Industrial sectors of ports that are adjacent or interconnected via the same inland waterway can generate mutual synergies, thereby establishing a more robust engine for economic growth. Concurrently, this multi-nodal, decentralized cluster configuration enhances the overarching resilience of the system. Consequently, this network of IIPCs, which links the Port of Rotterdam to the industrial hinterlands of Northwestern Europe, is better positioned to absorb and mitigate short-term shocks while adapting to long-term transitions.

4.1.2 Corridor scale

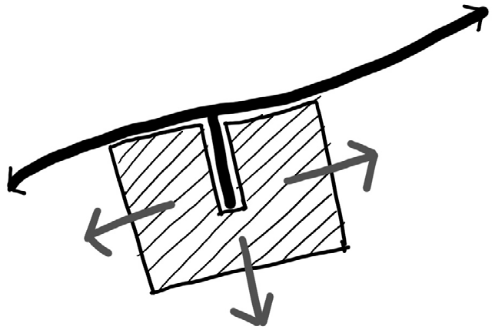
The second component of identifying waterfront transformation potential from the development model is derived from land-use analysis at the corridor scale. Bird’s Anyport model (1963) elucidates the directional trajectories of port-city development and expansion. By superimposing this theoretical model onto the three empirical urban development trajectories derived from the clustering analysis, the following hypotheses can be formulated:



Shrinkage IIPCs:
The port facilities in this category will undergo progressive redevelopment and functional conversion. The chronological sequence of this transformation will align with the direction of historic urban expansion, wherein segments adjacent to the existing urban fabric will undergo transformation first.



Consolidation IIPCs:
The ports in these cities will cease macro-spatial expansion away from the urban center, instead remaining contained within their established spatial boundaries. However, fragmented or isolated small-scale port parcels and industrial zones within these cities may face pressure for urban renewal and transformation.



Expansion IIPCs:
The ports within this cohort will continue to expand away from the urban core. Concurrently, existing port zones will primarily retain their industrial functions and will not exhibit significant redevelopment potential.

Fig. 21a-c, Spatial implication of port development trajectories

Under the premise of this hypothesis, establishing a port-city binary division becomes essential, as it provides the analytical foundation for determining the direction of urban expansion in accordance with the Anyport model (1963). The baseline for this spatial division in the current study is the dutch land-use dataset (Kadaster, 2025). Following the partitioning of the waterfront spaces across the thirty case cities into 500 distinct segments, the ratios of industrial land use to urban land use (encompassing residential and public facilities) within each segment were quantified. Consequently, these 500 segments were classified into three typologies:

1. **Industrial Segments:** Segments where the industrial land-use ratio exceeds 0.5.
2. **Urban Segments:** Segments where the urban land-use ratio exceeds 0.5.
3. **In-between Segments:** All remaining segments that do not meet either threshold.

Upon completing this classification, overarching configuration patterns can be inductively summarized from the spatial distribution of land use across the thirty analyzed cities. This study primarily focuses on three distinct spatial configurations: in-between, blocking, and next-to. From those three patterns, strategies on connectivity and intensity can thus be derived.

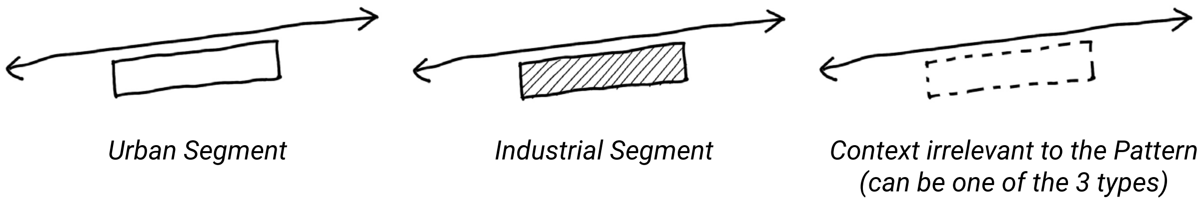


Fig. 22, Three types of segments in urban landuse structure

Pattern: Next-to

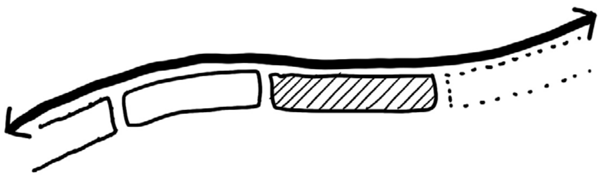


Fig. 23a, Next-to pattern

In this configuration, the industrial segment is directly adjacent to an urban segment on only one side. Morphologically, this pattern typically signifies that the port infrastructure retains sufficient spatial capacity for ongoing industrial or logistics expansion.

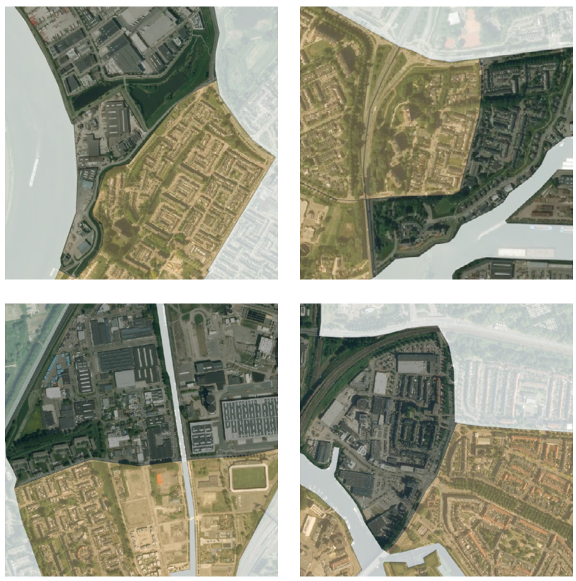


Fig. 24a-d, Next-to pattern observed in Alblasserdam, Papendrecht, Roosendaal, 's-Hertogenbosch

Pattern: In-between

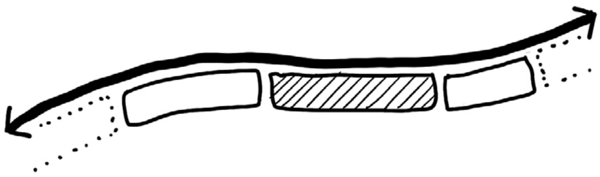


Fig. 23a, In-between pattern

Within this configuration, an industrial segment is structurally "sandwiched" between two flanking urban segments, with all three units sequentially distributed along the longitudinal axis of the waterway.

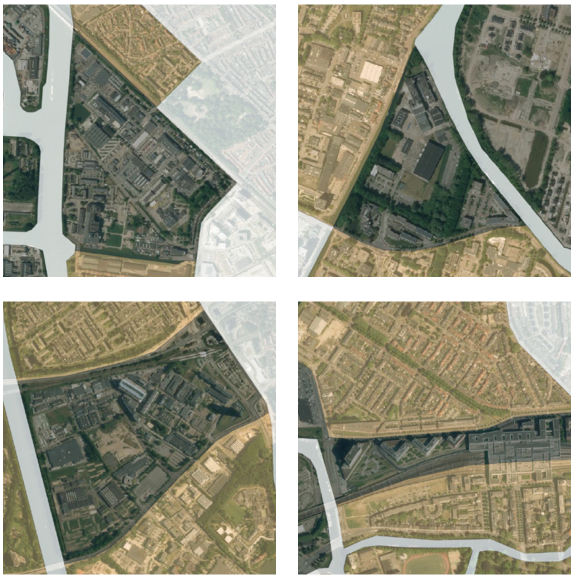


Fig. 24e-h, In-between pattern observed in Utrecht, Nieuwegein, Nijmegen, Breda

Pattern: Blocking

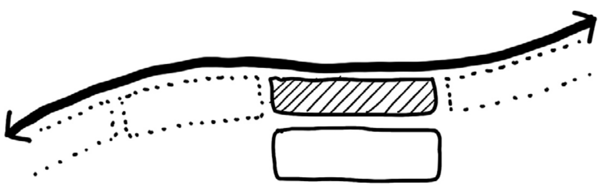


Fig. 23c, Blocking pattern

Within this configuration, the industrial segment and the urban segment are arranged perpendicular to the waterway, meaning the industrial fabric physically blocks the urban core's access to the riparian edge.

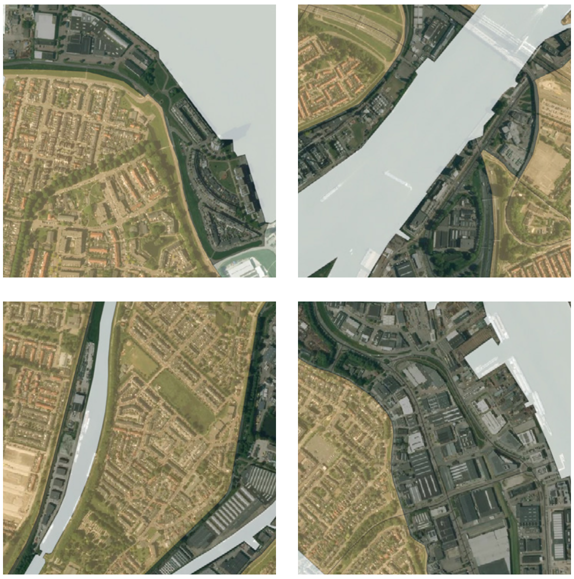
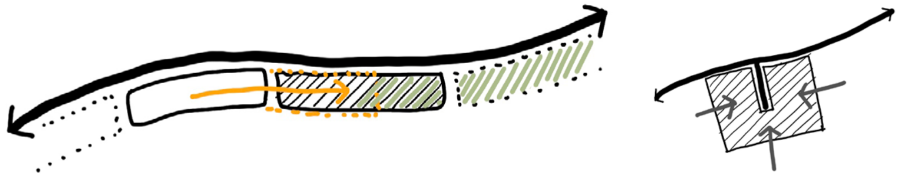


Fig. 24i-l, Blocking pattern observed in Ridderkerk, Dordrecht, Gorinchem, Hendrik-Ido-Ambacht

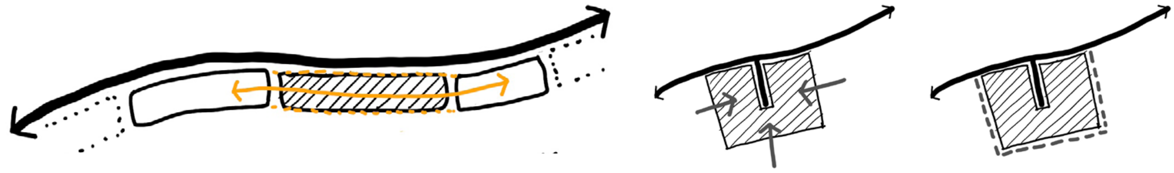
Connectivity Strategies

Next-to: Extension



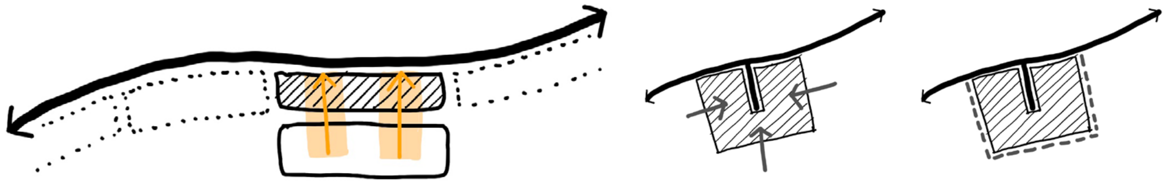
This pattern yields viable urban redevelopment potential exclusively within cities categorized under the shrinkage trajectory. In such scenarios, the spatial design strategy focuses on advancing the street network connectivity from the established urban segment into the industrial zone.

In-between: Corridor



If the host port-city is undergoing a macro trajectory of shrinkage, or if it is situated within a consolidation city but the specific site is classified as an isolated port, this industrial segment exhibits high adaptive potential. The strategic design fortifies the continuous spatial linkages between the two flanking urban zones and systematically amplifying the longitudinal connectivity.

Blocking: Penetration



The primary spatial design brief is to establish direct lateral connectivity from the interior urban fabric to the waterfront. Similar to the logic governing the in-between pattern, this configuration possesses transformation potential when situated within shrinkage port-city or when operating as an isolated port within a consolidation port-city.

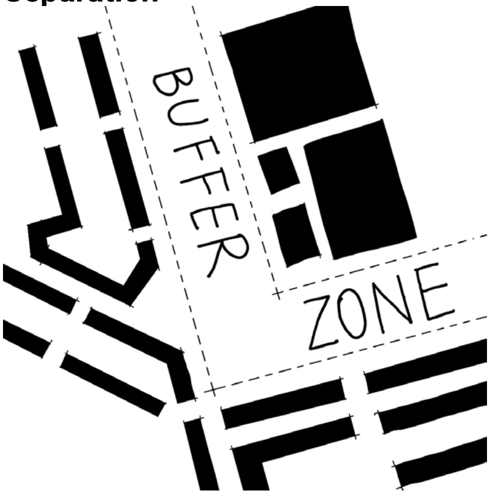
Creating Buffer Zone

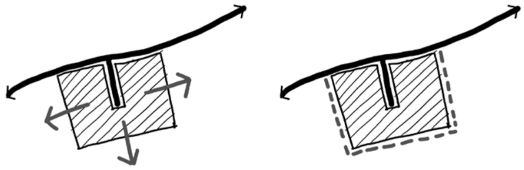
In cities with the projection of port expansion, the existing areas of industries are less likely to be transformed into urban uses. Thus, it is necessary to reserve space for buffer zone between industrial and residential area in order to minimize the disturbance.

Fig. 25, Connectivity strategy identified from IIPC development model

Intensity Strategies

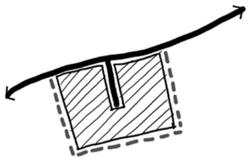
Separation





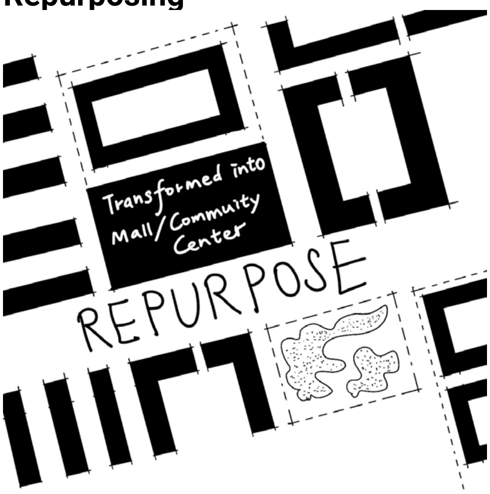
In IIPC of expansion type and for the major ports in operation in consolidation IIPCs, it is necessary to reserve space for buffer zone to separate residential and industrial areas. Adjacent to the buffer zone, both density and landuse mixture are expected to be relatively low.

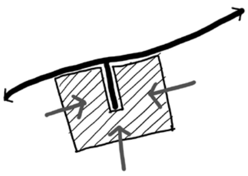
Co-existence



In peripheral or isolated smaller ports within consolidation IIPCs, moderately increasing residential and commercial density while preserving non-disruptive light industries that minimize impacts on residents' daily lives can foster an effective co-existence. This intricate mixture of functions and urban textures has been empirically proven to be beneficial in shaping vibrant, high-quality urban public spaces (Jacobs, 1961).

Repurposing





In shrinkage IIPCs, abandoned factories and warehouses can be transformed into shopping malls or community centers. Densification of housing may also happen according to requirements.

Fig. 26, Intensity strategy identified from IIPC development model

4.2 Identifying Transformation Potential from Urban Morphological Imbalances

4.2.1 Segment Scale Clustering

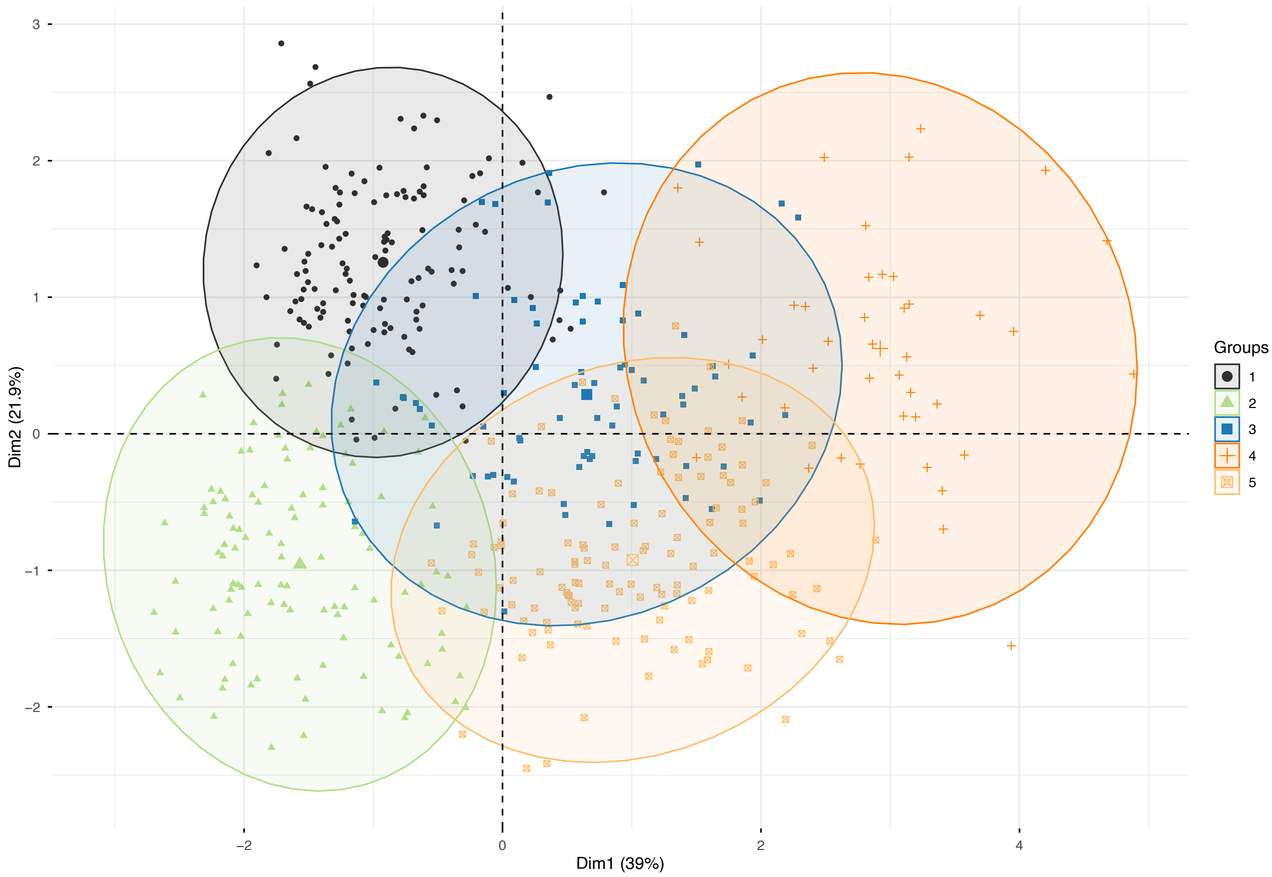


Fig. 27, K-means clustering result of urban morphological identity

The analytical outputs from the aforementioned two scales yield the primary layer of conclusions; namely, determining which segments are situated within locations that possess transformation potential based on the development model. The subsequent step, which entails the recognition of urban morphological imbalances, operates at the segment scale. Here, a k-means clustering algorithm is deployed to classify the 500 segments into five distinct types based on their urban morphological identities (Fig. 27).

In this typology, the optimal number of clusters is comprehensively determined by the trajectories of both the elbow line (Fig. 28) and the silhouette line (Fig. 29). When k = 5, the elbow line exhibits a distinct inflection point, while the silhouette line reaches a local maximum with a value of 0.25, demonstrating that the typology configured at k = 5 establishes a relatively sharp and well-defined differentiation between categories.

The clustering results depict the spatial distribution of all segments within the two-dimensional factor space. Based on the underlying variable distributions (Fig. 30), the characteristics of each cluster can be defined as follows:

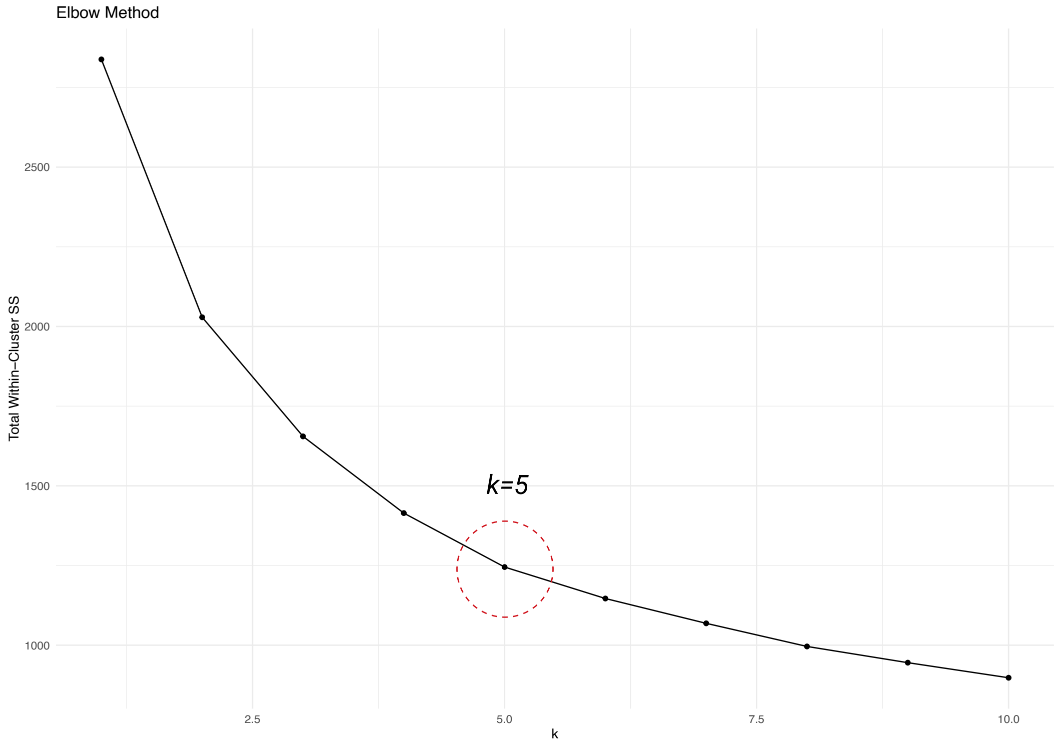


Fig. 28, Total within-cluster distance for different number of clusters

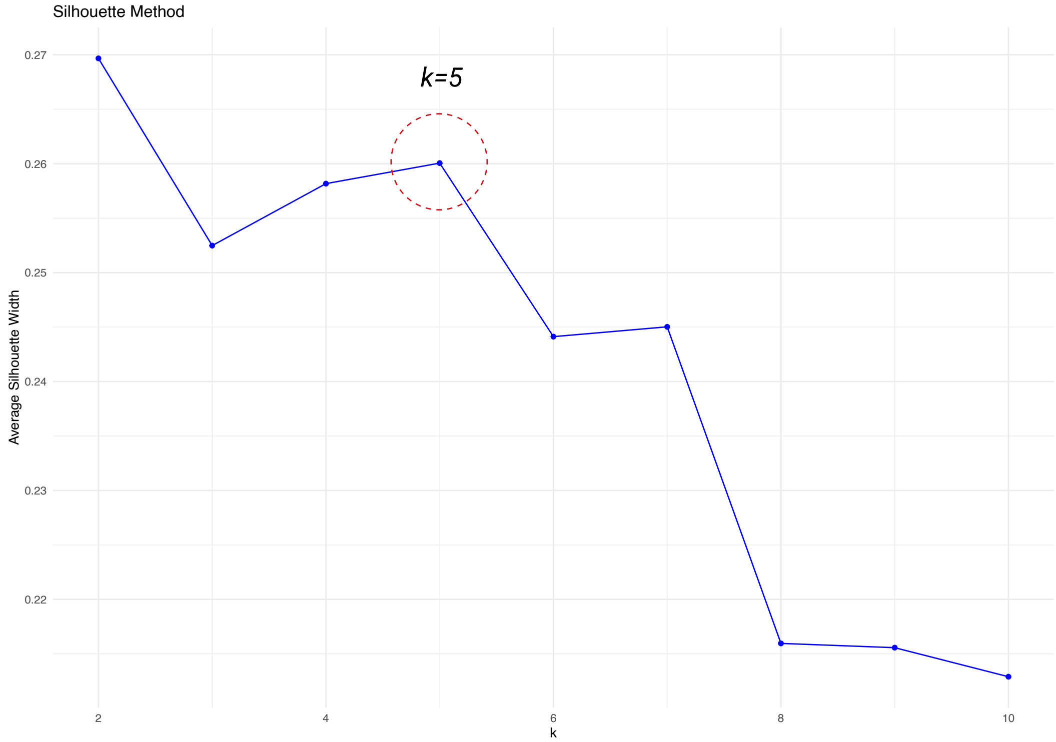


Fig. 29, Average silhouette width for different number of clusters

Cluster 1 (Fig. 32a) is characterized by low urbanity. However, because the industrial land-use ratio was systematically excluded from the clustering process, the segments within Cluster 1 are not inherently or exclusively industrial.

Cluster 2 (Fig. 32b) is predominantly characterized by high vegetation coverage (NDVI). Segments in this cluster are usually at the less-urbanized peripheral area or suburban areas with low density housings.

Cluster 3 (Fig. 32c) exhibits segments of medium to high urbanity with a high waterway-to-perimeter ratio, indicating an abundance of waterfront spatial resources. Crucially, the scatter plot demonstrates that Cluster 3 occupies an intermediate, "in-between" position, partially overlapping with other clusters; consequently, segments that exhibit features of other clusters but possess a high waterway-to-perimeter ratio are systematically assimilated into Cluster 3.

Clusters 4 (Fig. 32d) display highest urbanity among all the clusters, coupled with relatively scarce waterfront spatial resources, representing the typical urban core of the dutch cities.

Cluster 5 (Fig. 32e) contains segments that are in many ways similar to the ones in cluster 3. The urbanity of this cluster is also relatively high. However, the ones in this cluster are significantly less exposed to water.

From these findings, it is evident that within the analytical framework of this thesis, Cluster 1 and Cluster 3 constitute the two most critical cohorts for detailed inquiry.

The research value of Cluster 1 stems from its intrinsic morphological contradictions. The attribute of low urbanity shares a high correlation with port zones, meaning there's chance that these segments are situated in locations identified as having high transformation potential in the preceding analyses of IIPC development model. Concurrently, the low urbanity profile itself signifies that any prospective redevelopment must comprehensively elevate spatial connectivity, accessibility, and intensity. Furthermore, this cluster encompasses certain segments that contain a baseline residential landuse ratio yet still manifest the morphological identity of an industrial zone, thereby demanding targeted, comprehensive spatial optimization.

Conversely, the research value of Cluster 3 resides in its rich endowment of waterfront resources. While the morphological identity of segments within this cluster is defined by a moderate degree of urbanity and substantial waterfront exposure, these entities often exhibit significant variance when evaluated against more empirical urban performance indices. Consequently, instances where specific performance metrics fall substantially below the baseline average can serve as strategic entry points for design interventions. Furthermore, analytical insights from the IIPC development model can supplement this reasoning by contextualizing the urgency of transformation through the lens of structural landuse mismatches.

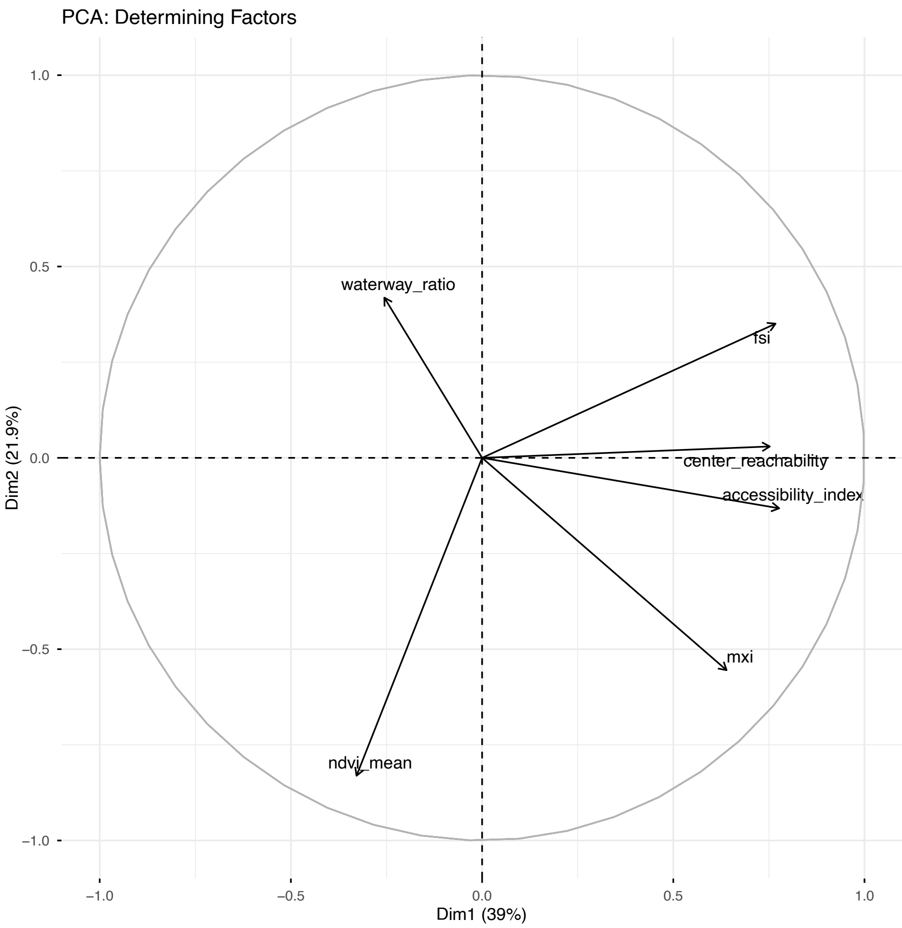


Fig. 30, Principle component analysis: determining factors

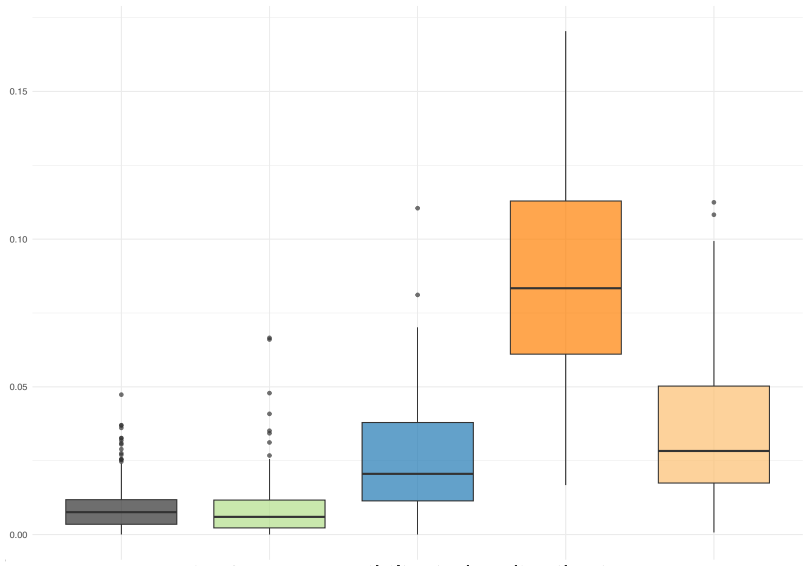


Fig. 31a, Accessibility index distribution

Accessibility Index

The Accessibility Index focuses on the street network, employing a space syntax methodology. The clustering results demonstrate that Cluster 4, representing the urban core typology, exhibits significantly higher accessibility than all other cohorts. Conversely, Cluster 1 displays low accessibility, while Cluster 3 exhibits a moderate accessibility profile.

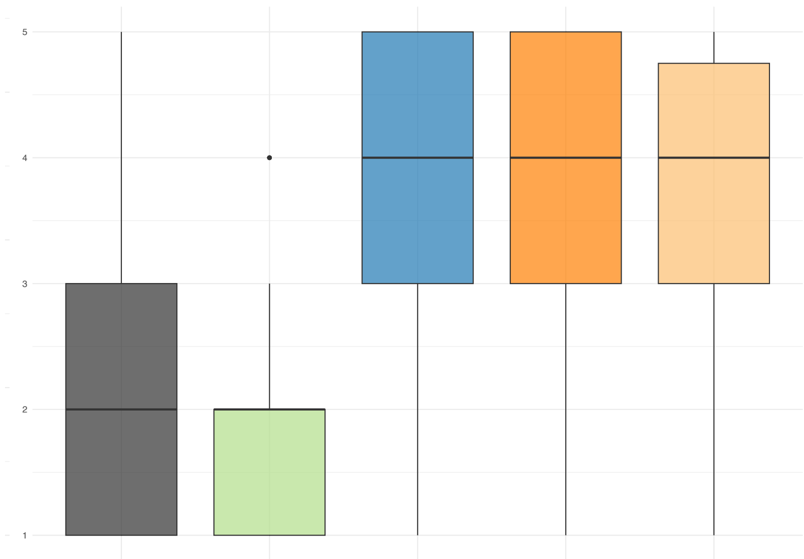


Fig. 31b, Center reachability distribution

Center Reachability

This variable measures the relative location of a segment within the corridor. The cluster results reveal that segments within Cluster 1 are generally situated further from the city center, though substantial intra-group variance exists. Conversely, Cluster 3 segments are predominantly located in closer proximity to the urban core.

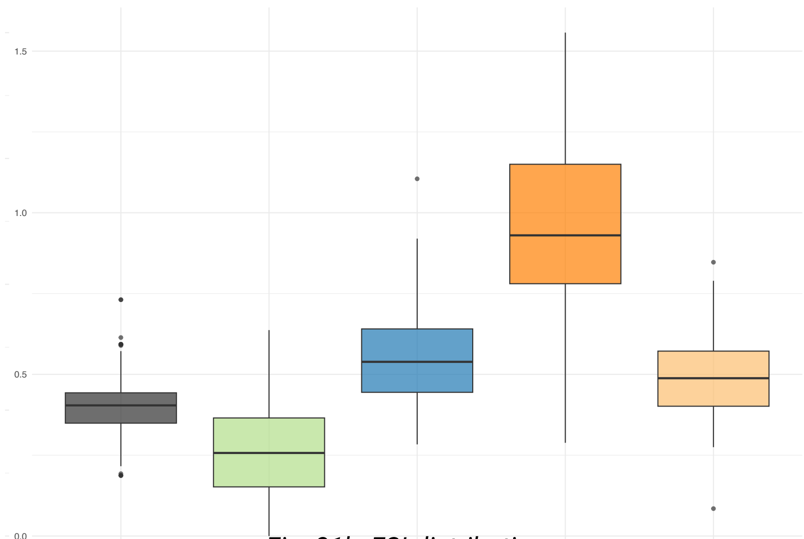


Fig. 31b, FSI distribution

Floor Space Index (FSI)

This metric serves as an indicator of built density. Cluster 1 is predominantly characterized by industrial zones. Iterative clustering trials reveal that while the Ground Space Index (GSI) of industrial areas often matches that of urban fabrics, their FSI is significantly lower due to the architectural prevalence of single-story manufacturing plants and warehouses.

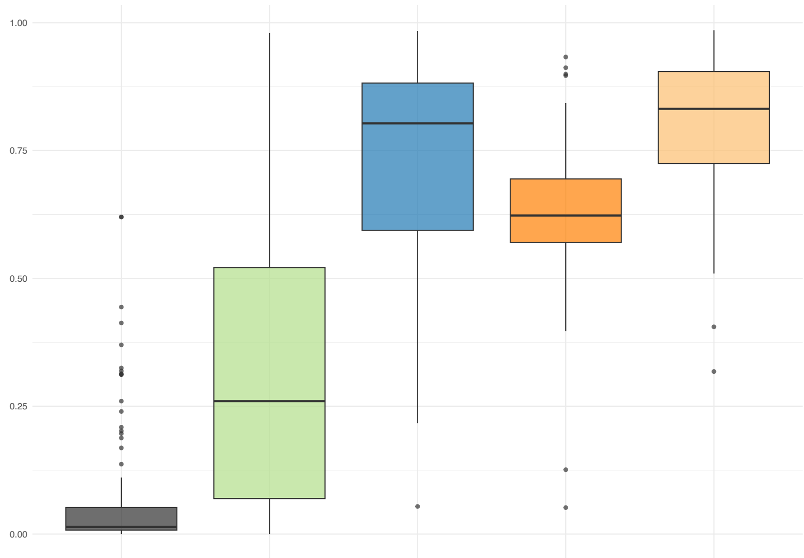


Fig. 31d, MXI distribution

Mixed-Use Index (MXI)

This variable captures the landuse diversity pattern. Interestingly, the urban core typology (Cluster 4) exhibits a lower degree of functional mix than Clusters 3 and 5. While Cluster 1 displays an exceptionally low level of land-use mixing, it also contains a substantial number of statistical outliers, indicating pronounced heterogeneity among individual segments within this cohort.

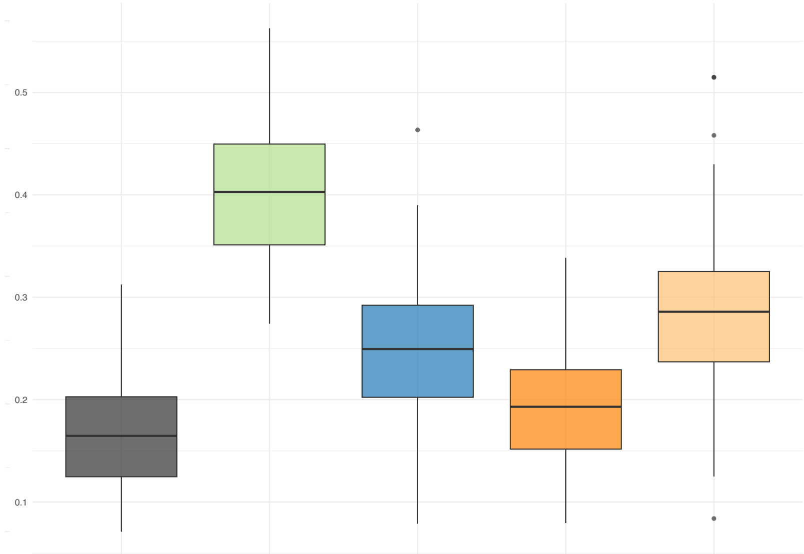


Fig. 31e, Average NDVI distribution

Average NDVI

This variable assesses green infrastructure capacity. Cluster 3 demonstrates a moderate level of green cover, whereas Cluster 1 exhibits low vegetation density. The urban core segments (Cluster 4) similarly display low NDVI values, which aligns consistently with typical urban morphological expectations.

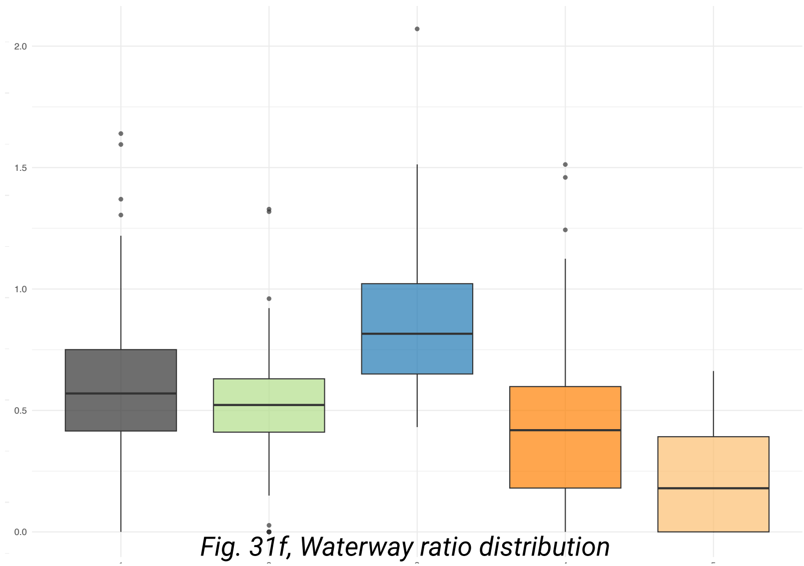


Fig. 31f, Waterway ratio distribution

Waterway Ratio

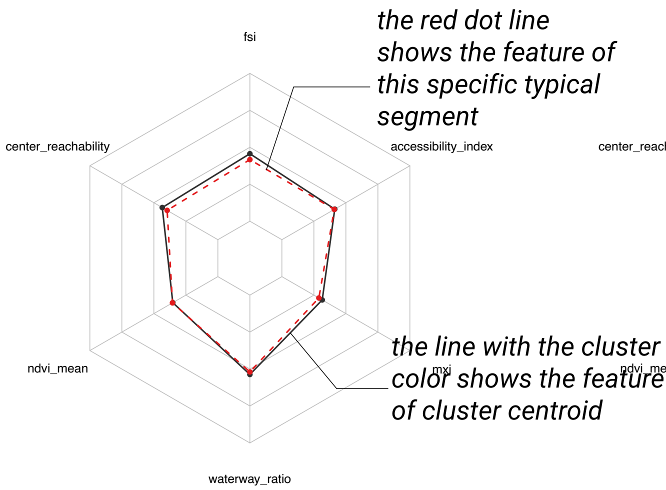
This metric evaluates blue infrastructure capacity, representing the waterfront spatial resources detailed previously. The data show that Cluster 3 scores significantly higher in this metric than all other cohorts, which underscores the profound analytical and strategic value attributed to this specific cluster within the framework of this study.

4.2.2 Typical Segment from Each Cluster

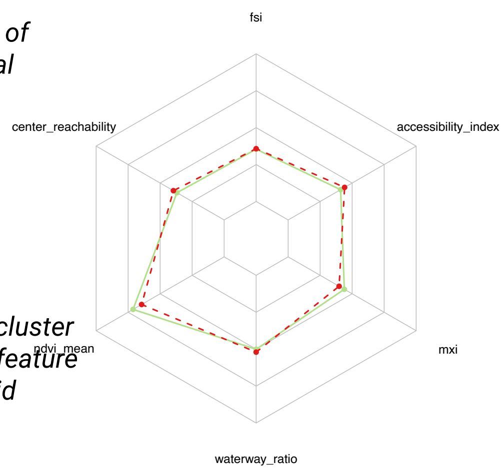
Alblasserdam

Venlo

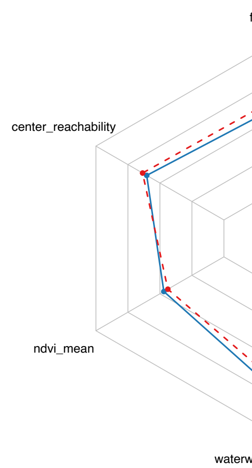
Vijfheere



Cluster 1 has a high correlation with industrial lands, while also containing residential areas with poor urban performance.



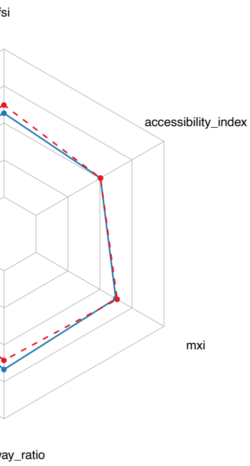
Cluster 2 contains mostly less urbanized segments at the periphery of the cities or suburban residential areas.



Cluster 3 contains relatively high urb resources of wate

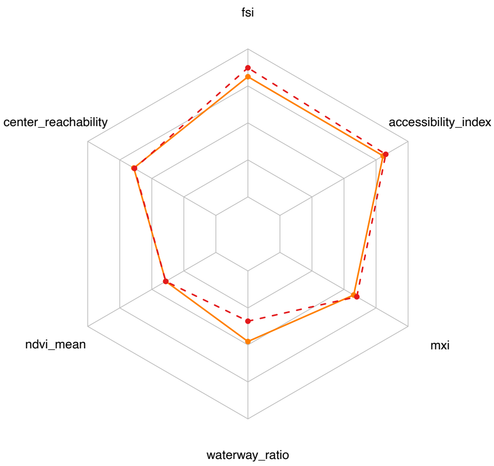
Fig. 32a-e, The most typical

enlanden



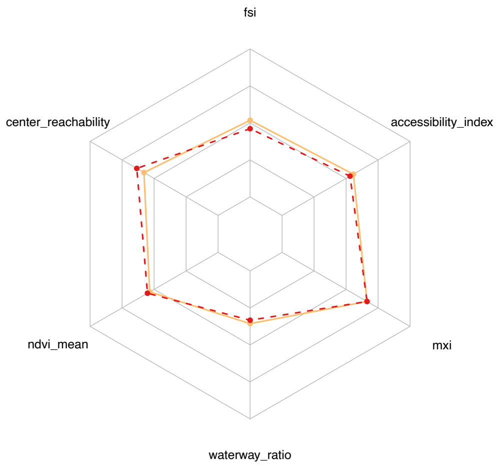
s segments with
anity with more
erfront spaces.

Breda



Cluster 4 contains the typical urban cores of dutch cities with high density and medium exposure to waterway.

Ridderkerk



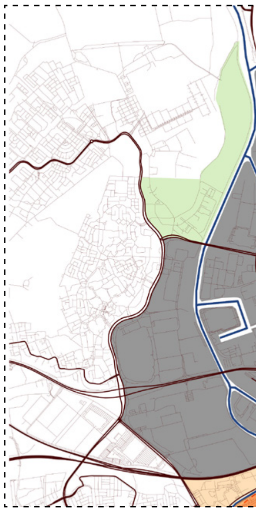
Cluster 5 is similar to cluster 3 but with less exposure to waterfront.

segment from each cluster

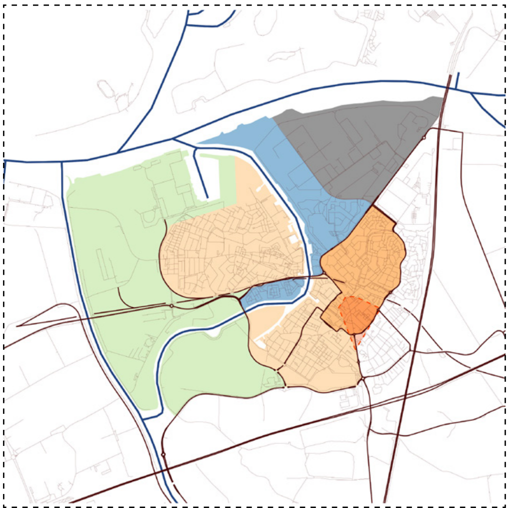
4.2.3 Atlas of the Clustering Result

Alblasserdam

Arnhem



Bre



Geertruidenberg

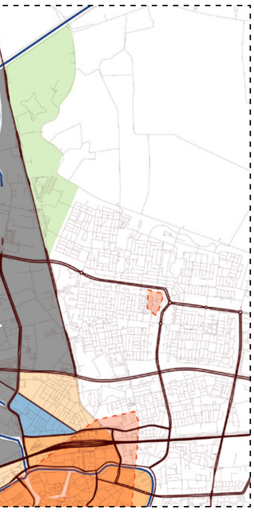
Gennep

Gorin

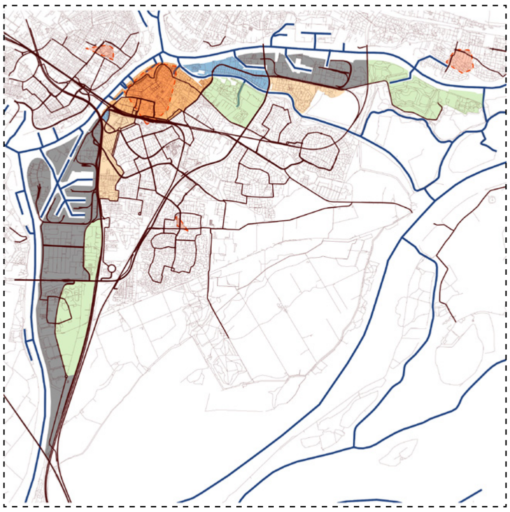
Legend

cluster 1
cluster 2
cluster 3
cluster 4
cluster 5
urban center calculated from DBSCAN using POI density

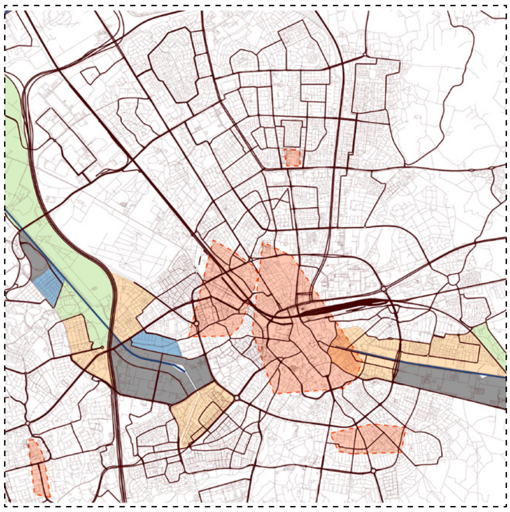
Fig. 33a-j, Atlas f



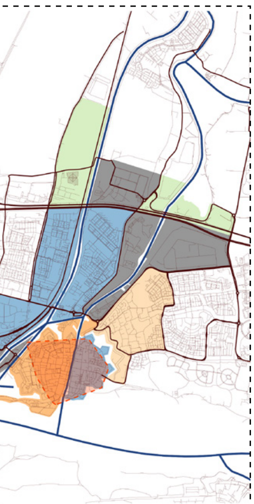
eda



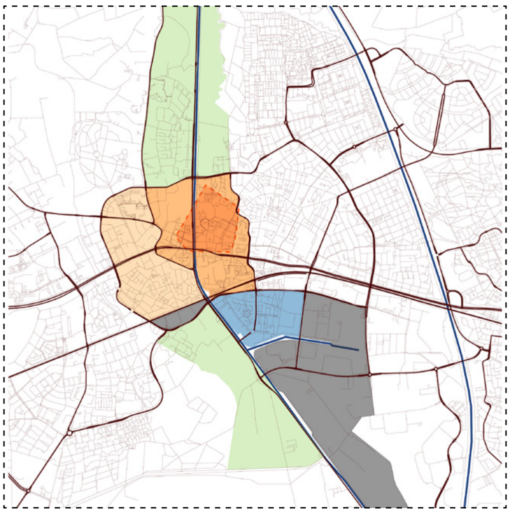
Dordrecht



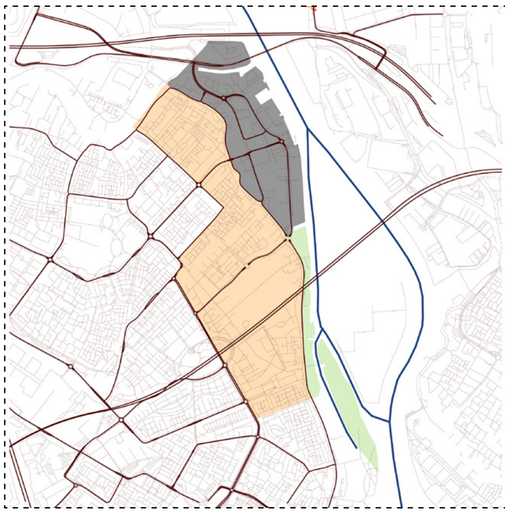
Eindhoven



chem



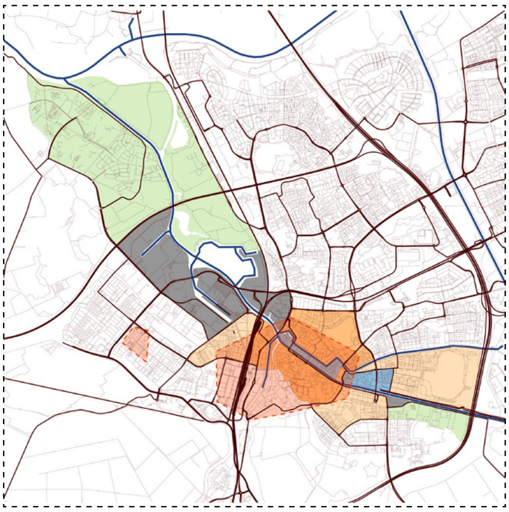
Helmond



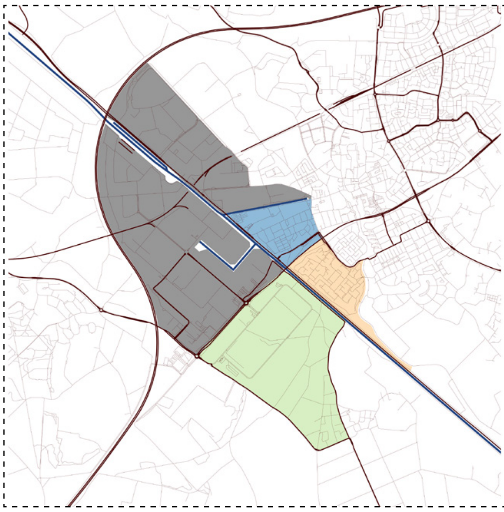
Hendrik-Ido-Ambacht

road network
major infrastructure
waterway

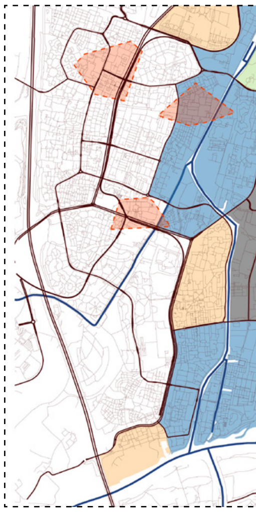
or selected IIPCs



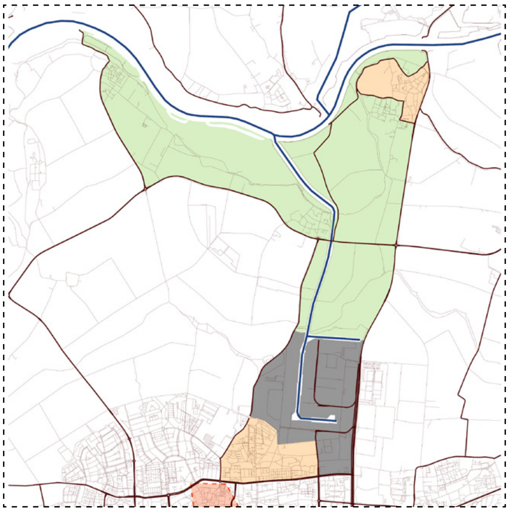
's-Hertogenbosch



Meierijstad



Nieuw



Oss

Papendrecht

Ridde

Legend

cluster 1

cluster 2

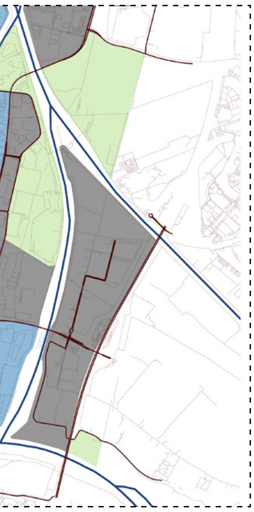
cluster 3

cluster 4

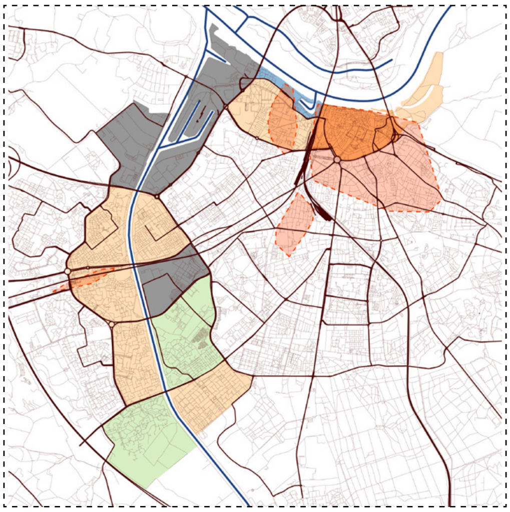
cluster 5

urban center calculated from DBSCAN using POI density

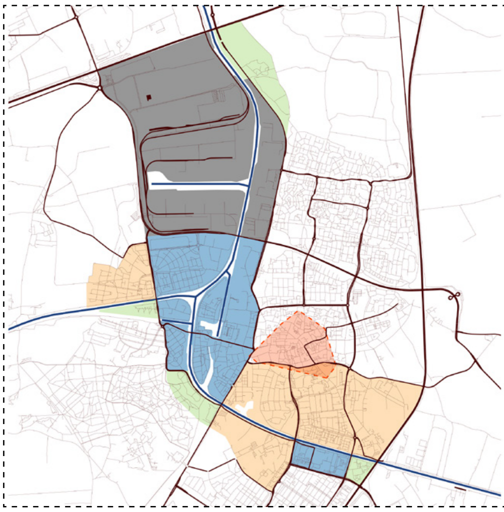
Fig. 34a-j, Atlas f



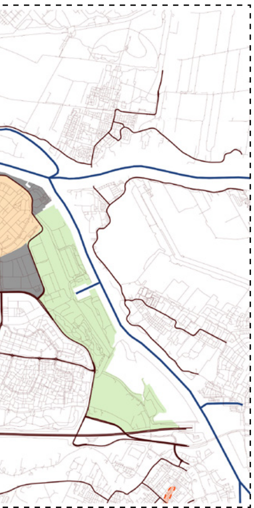
vegein



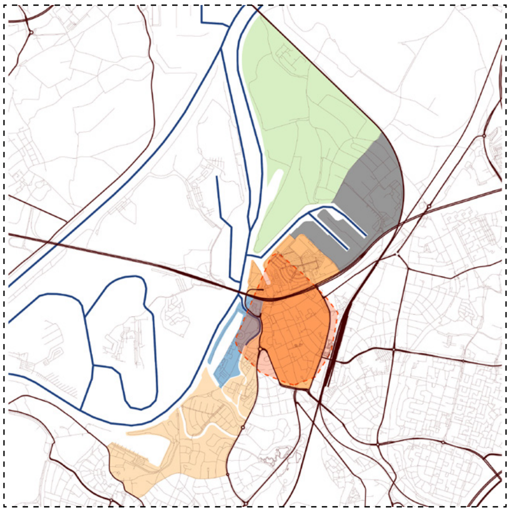
Nijmegen



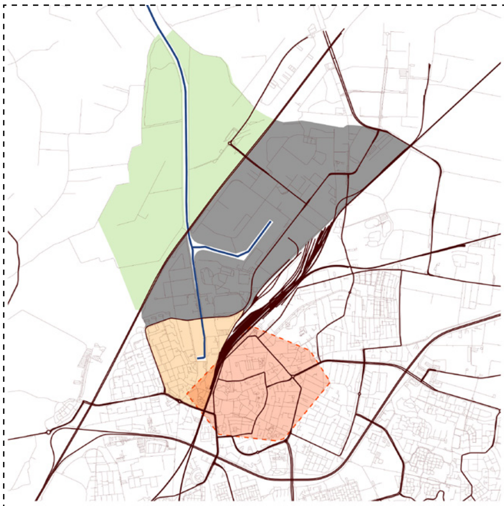
Oosterhout



rkerk



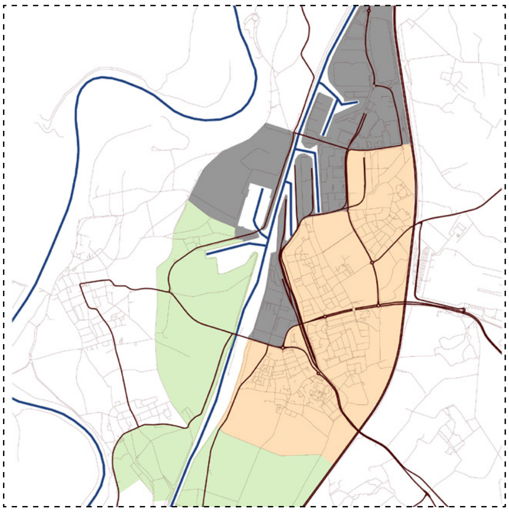
Roermond



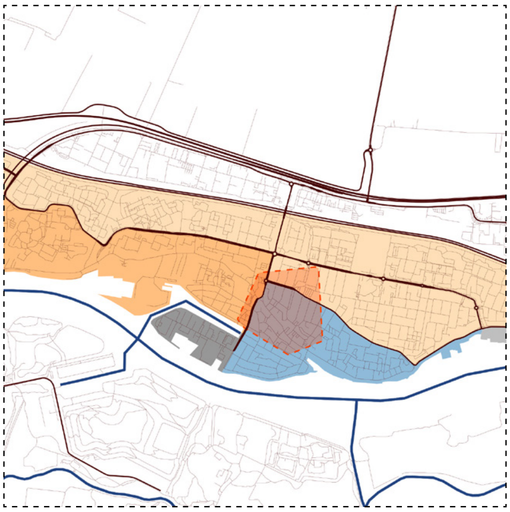
Roosendaal

road network
major infrastructure
waterway

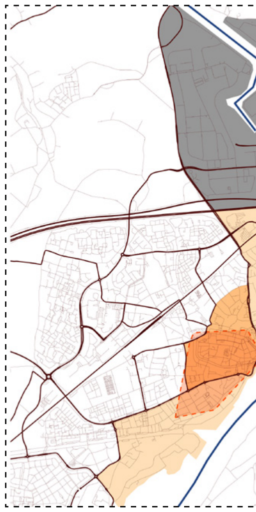
or selected IIPCs



Sittard-Geleen

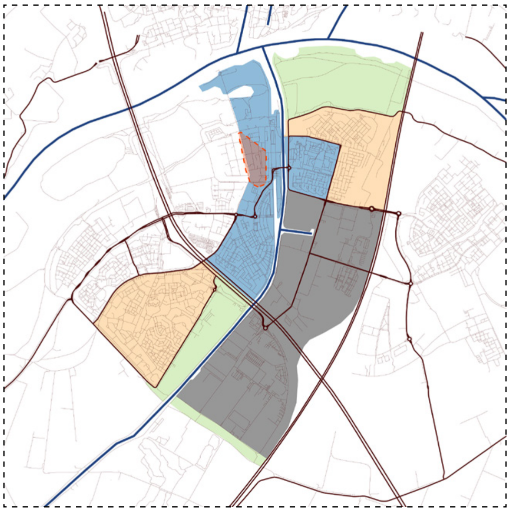


Sliedrecht



Ti

Venlo



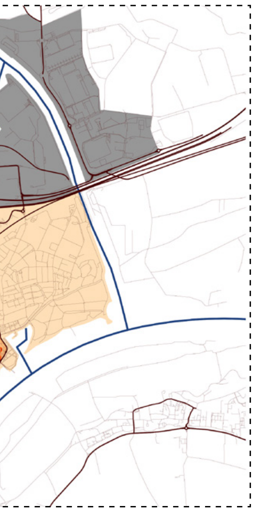
Vijfheerenlanden

Waa

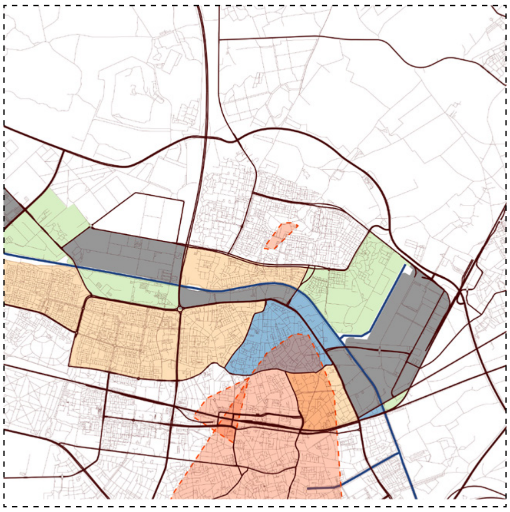
Legend

cluster 1
cluster 2
cluster 3
cluster 4
cluster 5
urban center calculated from DBSCAN using POI density

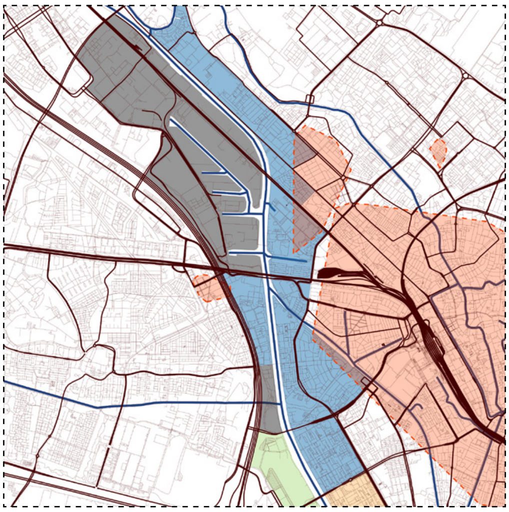
Fig. 35a-j, Atlas f



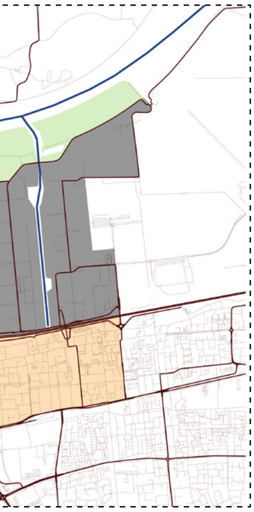
el



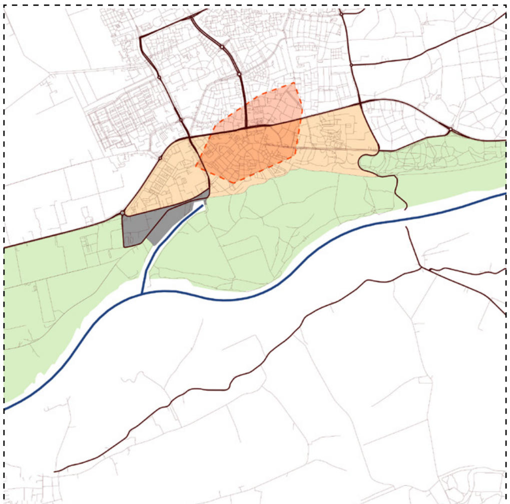
Tilburg



Utrecht



lwijk



Wageningen

Zwijndrecht

road network
major infrastructure
waterway

or selected IIPCs

4.2.4 Segment Scale Urban Performance Assessment

As previously noted, the second layer of transformation potential identified in this thesis stems from urban morphological imbalances. These imbalances are conceptualized as structural mismatches among the classified urban morphological identity, existing landuse regulations, and tangible urban performance indices. As illustrated in Fig. 14, urban morphological identity operates as an intermediary morphological state; it is fundamentally shaped by landuse regulations and simultaneously manifests as a set of urban performance indices. While this identity encapsulates the contemporary urban morphological characteristics of a given segment, it can be dynamically influenced from two distinct directions:

The Regulatory Direction (Landuse Regulation):
Modifications to landuse zoning directly catalyze shifts in the internal urban morphology of a segment over time.

The Performance Direction (Tangible Urban Performance):
Spatial interventions can directly alter specific, tangible attributes within a segment, such as densification, increasing localized civic amenities, or introducing pedestrian pathways leading to the waterfront. While these incremental interventions may not immediately shift the overarching urban morphological identity of the segment, they can tangibly elevate localized spatial quality.

Consequently, at the segment scale, the clustering of urban morphological identities reveals which specific clusters possess baseline transformation potential within the context of this thesis (namely, Clusters 1 and 3). To operationalize this potential, it is necessary to establish an assessment framework to evaluate whether an urban morphological imbalance exists, and to determine its precise typology. This diagnosis provides the empirical evidence required to formulate targeted design interventions. Incorporating the spatial insights from the corridor-scale landuse analysis and the segment-scale variable selection, the assessment framework developed in this study comprises six distinct dimensions categorized into two primary components:

Component A: Landuse Regulation
This component evaluates the regulatory framework through two key indices:

1. Industrial Landuse Ratio:
Used to evaluate whether a segment identified with high waterfront redevelopment value remains constrained by an excessive proportion of industrial land.

2. Residential Landuse Ratio:
Used to detect whether a segment with deficient urban performance has already transitioned into residential landuse.

Component B: Tangible Urban Performance
This component translates abstract morphological identities into actionable design parameters across four specific indices:

1. Longitudinal Connectivity Index:
Measures the density of pedestrian pathways running parallel to the waterfront within a designated buffer zone.

2. Lateral Connectivity Index:
Measures the density of pedestrian pathways running perpendicular to the waterfront.

3. Amenity Density Index:
Quantifies the spatial concentration of commercial and civic service facilities.

4.Built Density Index:
Evaluates the built environment through the FSI.

The defining attribute of these four indices is their tangible nature; each metric corresponds directly to a concrete spatial design strategy, thereby operationalizing abstract urban morphological identities into specific properties that can be enhanced and optimized. This thesis identifies six distinct types of urban morphological imbalances in total (Fig. 37). Fig. 36 shows the average profile of assessment score for cluster 1 and 3.

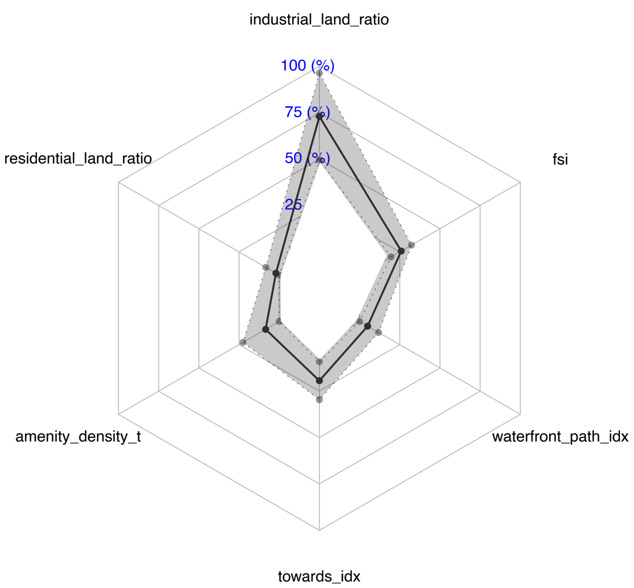


Fig. 36a, Assessment score of the profile of cluster 1: centroid & ±1SD corridor

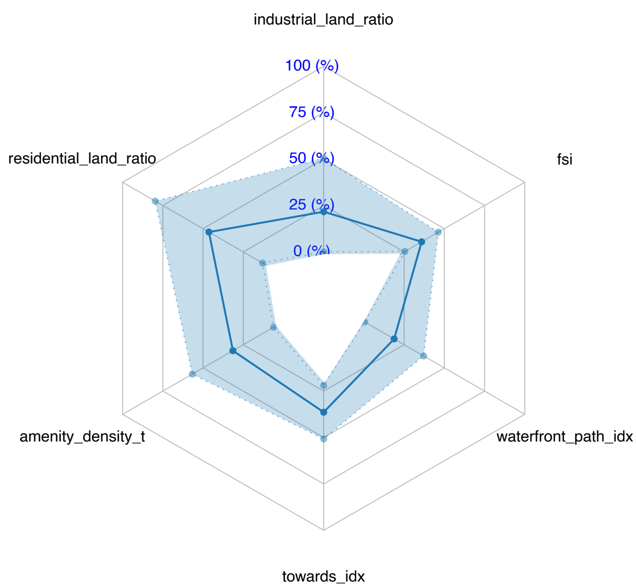
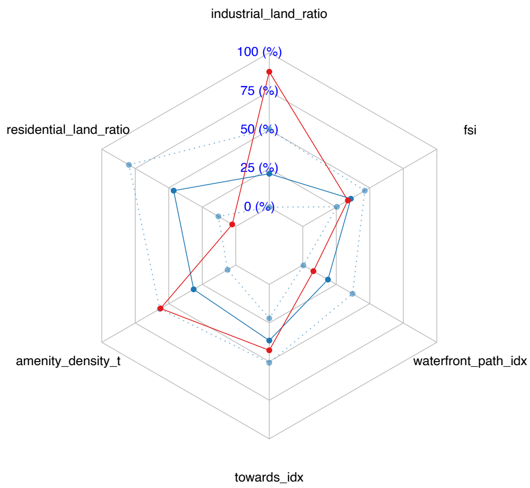


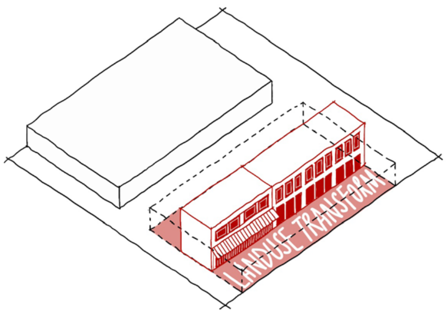
Fig. 36b, Assessment score of the profile of cluster 3: centroid & ±1SD corridor

4.2.5 Typical Segment from Each Imbalance Type

Industrial Landuse Imbalance

Condition:
A segment with high waterfront redevelopment potential still exhibits an exceptionally high proportion of industrial land.



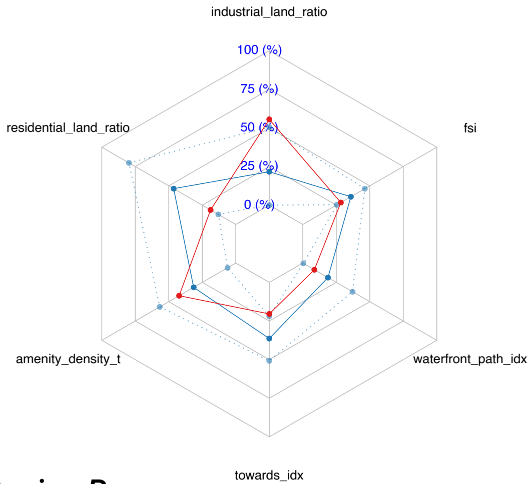


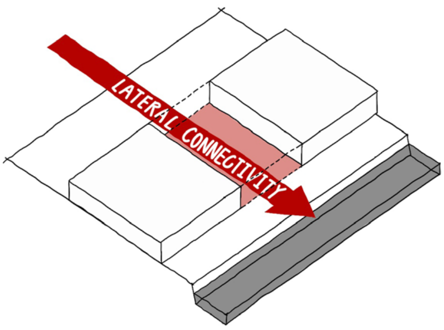
Design Response:
Requires adjustments to land-use regulations to incrementally introduce residential and public functions.

Fig. 37a, Assessment score of typical imbalance segment and strategy for the industrial landuse imbalance type

Lateral Connectivity Imbalance

Condition:
A segment with high waterfront development value scores significantly below the cluster average in lateral connectivity.

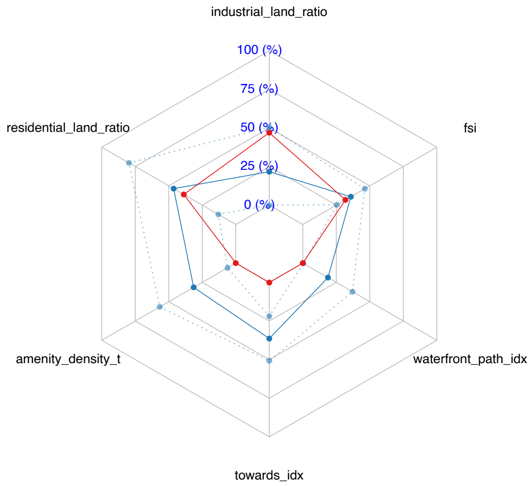




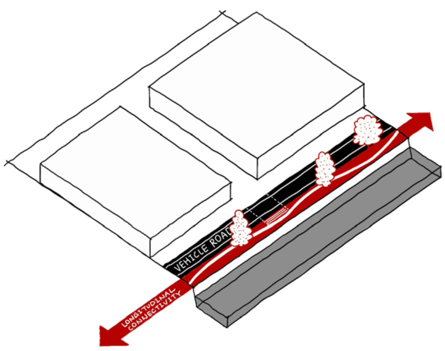
Design Response:
Recommends the introduction of perpendicular pedestrian pathways leading to the waterfront or the puncturing of existing blocks to establish new public rights-of-way.

Fig. 37b, Assessment score of typical imbalance segment and strategy for the lateral connectivity imbalance type

Longitudinal Connectivity Imbalance



Condition:
A segment with high waterfront development value scores significantly below the cluster average in longitudinal connectivity.

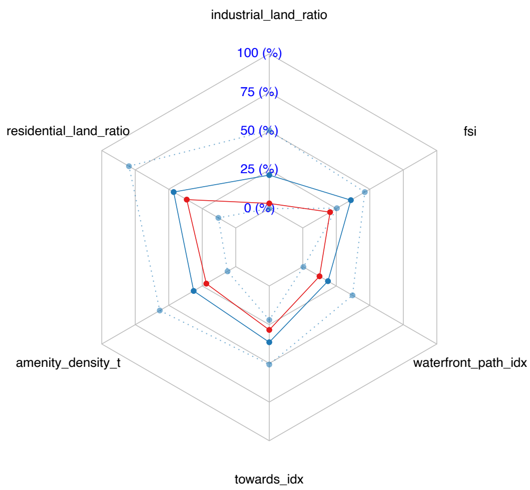


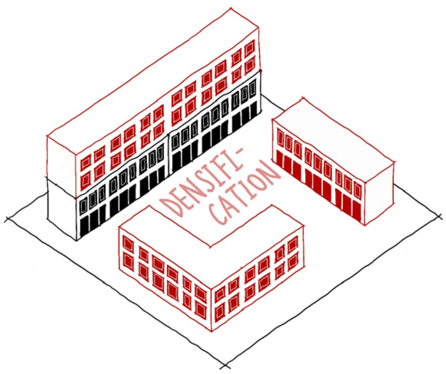
Design Response:
Suggests the strategic integration of continuous pedestrian promenades along the waterfront.

Fig. 37c, Assessment score of typical imbalance segment and strategy for the longitudinal connectivity imbalance type

Built Density Imbalance

Condition:
A segment with high waterfront development value scores significantly below the cluster average in built density.

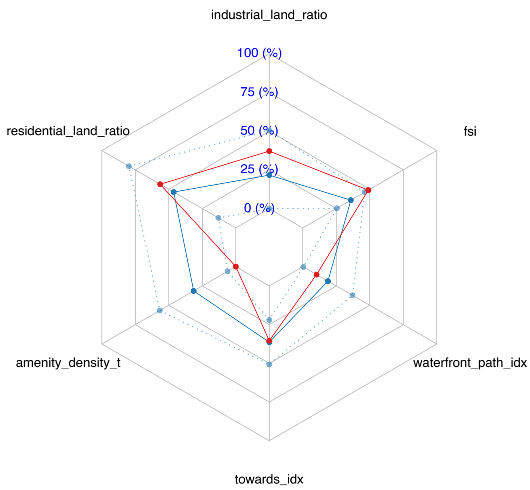




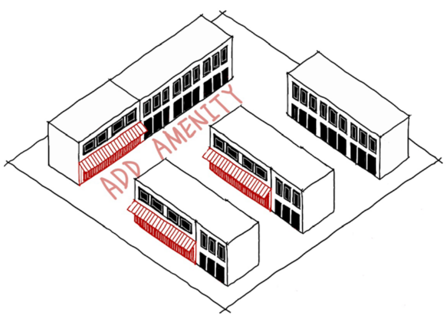
Design Response:
Justifies targeted urban densification strategies.

Fig. 37d, Assessment score of typical imbalance segment and strategy for the built density imbalance type

Amenity Density Imbalance



Condition:
A segment with high waterfront development value scores significantly below the cluster average in amenity density.

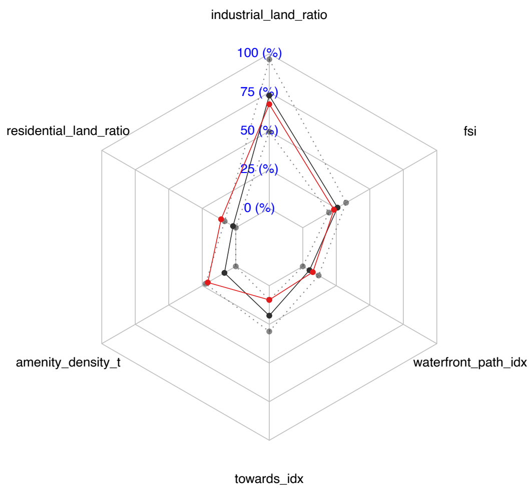


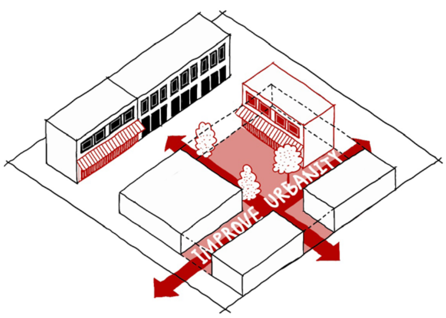
Design Response:
Indicates the need to incorporate active ground-floor commercial spaces, public furniture, and community infrastructure.

Fig. 37e, Assessment score of typical imbalance segment and strategy for the amenity density imbalance type

Poor Urban Performance for Residential Area

Condition:
A segment displaying poor urban performance metrics already contains a high proportion of residential land use.





Design Response:
Demands comprehensive improvements to tangible urban performance to elevate the overall residential experience and spatial quality.

Fig. 37f, Assessment score of typical imbalance segment and strategy for the poor urban performance imbalance type

4.3 Overlapping of Multi-Scalar Transformation Potential

As established in the preceding chapters, the waterfront transformation potential defined in this study is derived from three distinct scales across two analytical levels, ultimately synthesizing into two core layers of findings: identifying waterfront transformation potential from the IIPC development model (network and corridor scale) and identifying waterfront transformation potential from urban morphological imbalances (segment scale).

Upon transitioning to the detailed design phase (level of details), these two analytical layers are translated into two primary aspects of the spatial design strategy: ***connectivity*** and ***intensity***. Furthermore, when executing urban design interventions within a specific built environment, the localized context surrounding the site must be integrated. Consequently, this study introduces site specificity at the design stage, which is operationally translated within the design strategy as ***interface***.

4.3.1 Interface (Site Specificity)

The interface constitutes the foundational step in the spatial design workflow. Individual segments are structurally partitioned by urban infrastructure, which possesses distinct spatial and barrier characteristics; while certain infrastructure assets physically segregate the surrounding urban fabrics, others present strategic opportunities for spatial reconnection. Moreover, specific civic and public space assets, such as municipal parks or newly developed commercial areas, often exist immediately adjacent to the segment boundaries, offering potential for new spatial integration. Conducting a rigorous study and spatial mapping of a segment's interface is an absolute prerequisite for translating generalized analytical strategies into site-specific physical designs. In this thesis, the interface of the segments contains two major types: urban boundary and waterway bank.

Within this thesis, the segment boundaries identified can be classified into three primary categories:

Barriers:
These refer to highly impermeable infrastructure networks, such as major highways and railways, that present severe physical obstructions to pedestrian movement.

Divisions:
These comprise the secondary urban road network, which delineates urban sectors while maintaining a moderate level of permeability.

Soft Borders:
These consist of natural or semi-natural elements, such as secondary waterways or green buffers, that serve to demarcate segments without imposing a harsh physical segregation.

When synthesized with the analytical conclusions of the IIPC development model, two distinct spatial approaches emerge for addressing these boundaries: re-establishing connectivity or creating transitional buffers. These attitudes subsequently dictate localized spatial retrofitting strategies.

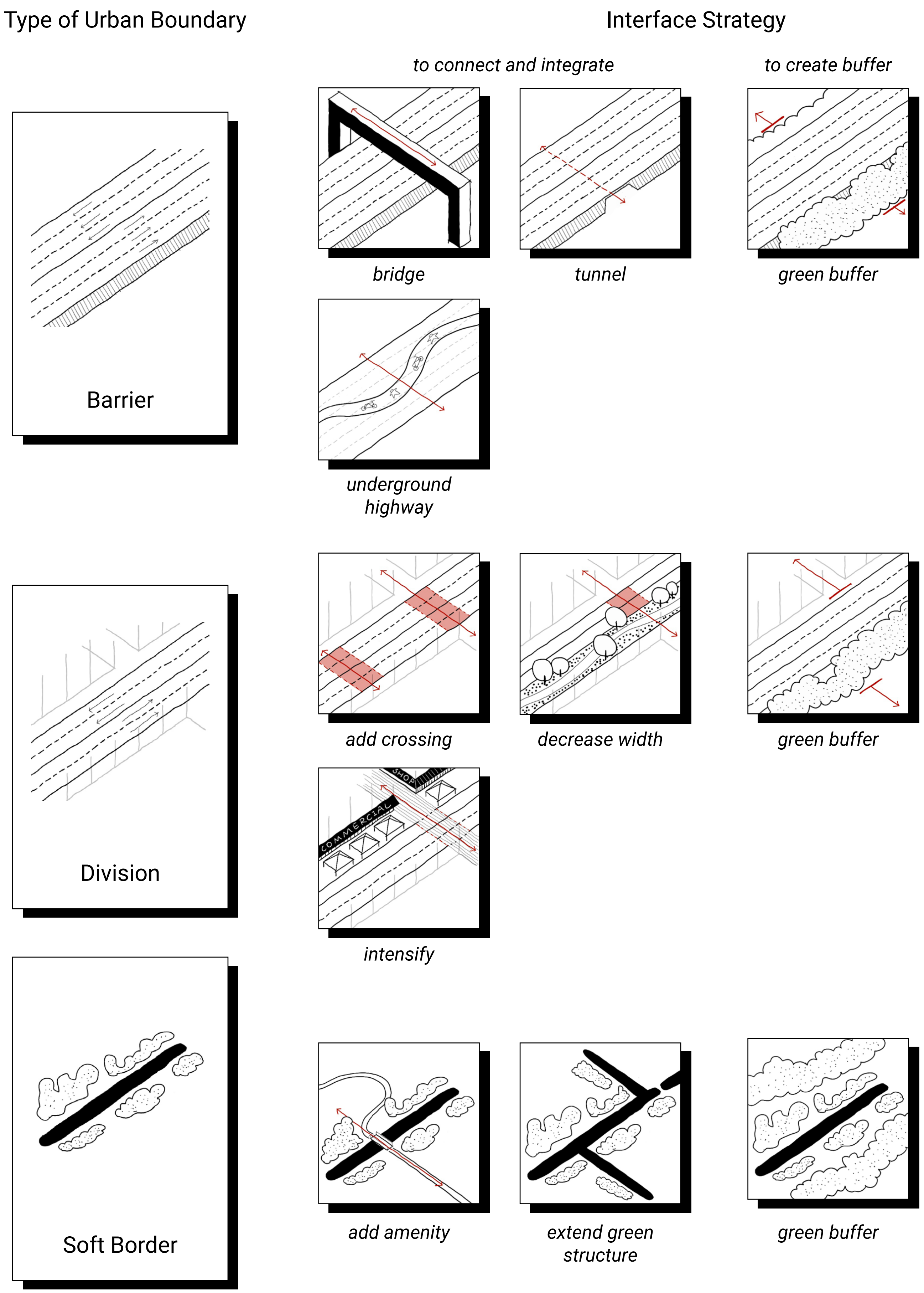


Fig. 38, Three types of urban boundary and interface strategies

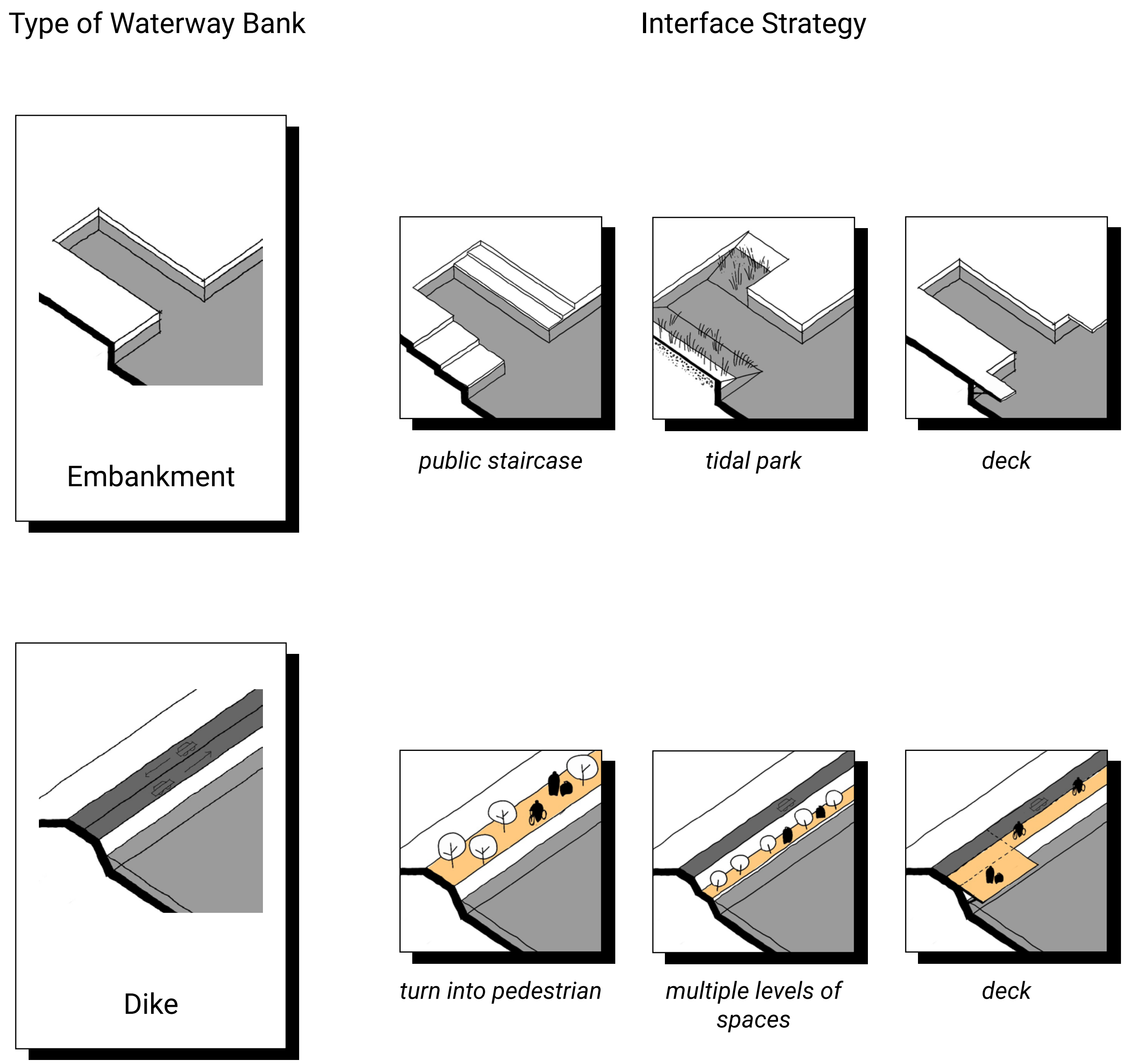


Fig. 39, Two types of waterfront interfaces and interface strategies

Regarding the waterfront interfaces, this thesis adopt the categorization of embankment by Prominski (2012). Based on the fact that the waterways discussed in this thesis are mostly canals, two prominent morphological variations of waterway banks can be observed across the study areas:

Embankment promenades:
Vertical, artificially formed embankments that serve both as flood protection and as riverbank reinforcement. In this thesis mostly appearing in old town centers or quays of industrial ports.

Dikes:
Flood protections that separate the urban context with the flood plain. In the dutch context, vehicular roads often sit on the dike, further strengthening this separation.

4.3.2 Connectivity (IIPC Development Model)

The connectivity strategies are firstly derived from the structural conclusions of the development model, with supplementary inputs from the urban morphological imbalance analysis (specifically the longitudinal and lateral connectivity indices). The spatial configuration patterns identified in the development model (next-to, in-between and blocking) each dictate a specific directionality for spatial connectivity. These directions establish the primary framework for the design brief, serving as the spatial axes along which subsequent intensity strategies are deployed to fortify localized spatial quality.

4.3.3 Intensity (Urban Morphological Imbalances)

The intensity strategy is firstly informed by the IIPC development trajectory (Fig. 26). Secondly, it from the diagnoses of the urban morphological imbalances, encompassing interventions such as the introduction of residential programming (residential landuse ratio), the densification of civic amenities (amenity density), and the elevation of volumetric built density (FSI). The precise spatial allocation and siting of these newly introduced residential and commercial programs must be dynamically synchronized with the newly established public passages developed during the connectivity phase. The objective is to leverage architectural massing, volumetric enclosure, and active ground-floor commercial frontages to comprehensively enhance the spatial and experiential quality of the public realm.

4.4 Design Cases

In this thesis, three design cases selected from three different IIPCs are presented to demonstrate the integration of multi-scalar design strategies and their ultimate impact on shaping urban space. Among these cases, two are situated in consolidation cities (Tilburg and Utrecht), while one is located in a shrinkage city (Roosendaal). At the corridor scale, the segments chosen as design sites represent three distinct patterns: next-to (Roosendaal), in-between (Utrecht), and blocking (Tilburg). At the segment scale, the case studies correspond to Cluster 3 (Utrecht and Tilburg) and Cluster 1 (Roosendaal).

The Utrecht case study is developed as a detailed design. Here, the central segment, along with its adjacent segments to the north and south, collectively form an in-between pattern. The spatial imbalance diagnosis reveals an industrial landuse imbalance in the central segment and an amenity imbalance in the northern segment, while the southern segment shares a waterway boundary with the center. Consequently, this design holistically considers these three segments constituting the in-between pattern throughout the design process. The implementation steps strictly follow the previously described methodology, progressing from interface, to connectivity, and finally to intensity. To validate the design outcomes, the post-intervention segments are re-evaluated within the initial assessment framework.

Conversely, the design cases for Tilburg and Roosendaal are presented as more schematic designs. Their primary objective is to illustrate how spatial strategies derived from different scales can be organically synthesized to ultimately generate human-scale urban design interventions. In those two cases, the urban segments which form the spatial configuration patterns together with the selected sites are recognized more as a context, rather than part of the design site.

4.4.1 Utrecht

Transformation Potential from IIPC Development Model

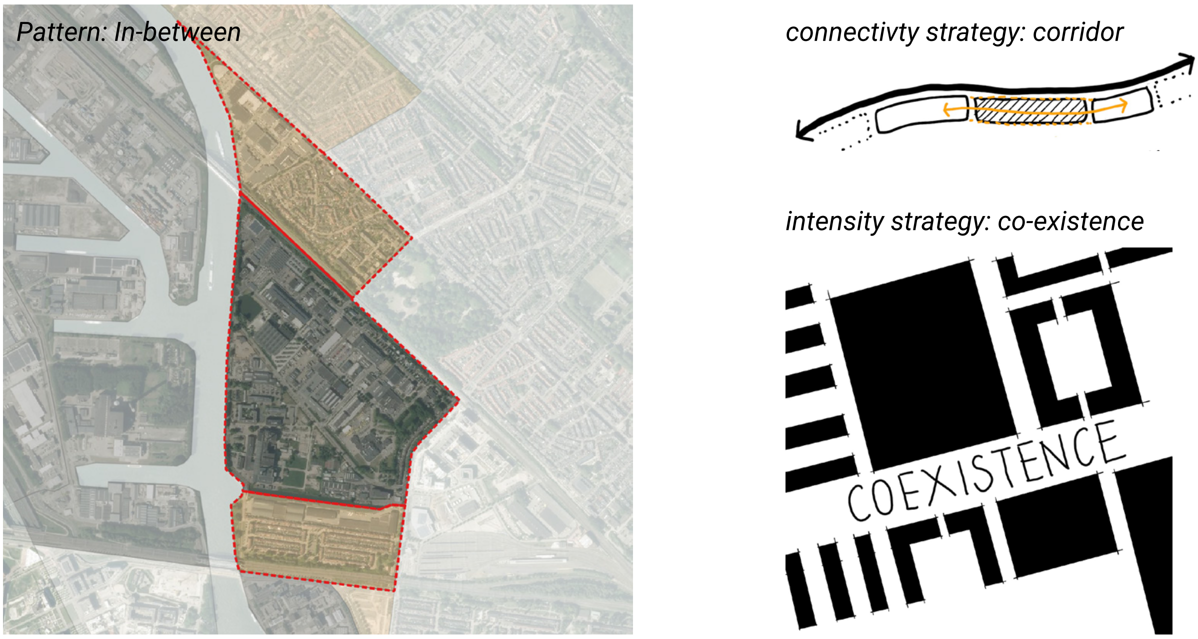


Fig. 40, Conclusions from IIPC development model for the case in Utrecht

Transformation Potential from Urban Morphological Imbalances

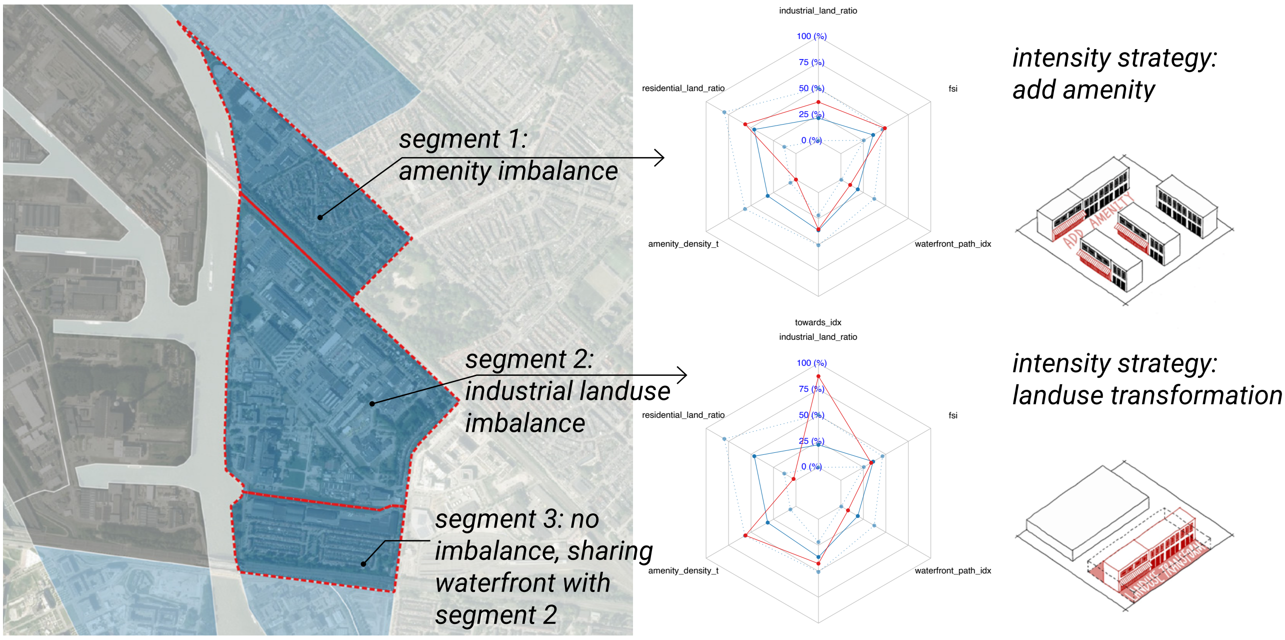


Fig. 41, Conclusions from urban morphological imbalances for the case in Utrecht

Within this specific design case, the in-between configuration pattern encompasses two flanking urban segments and a centrally positioned industrial segment. The outputs of the morphological imbalance assessment indicate a significant deficit in local amenities within the northern segment of the site.

Interface

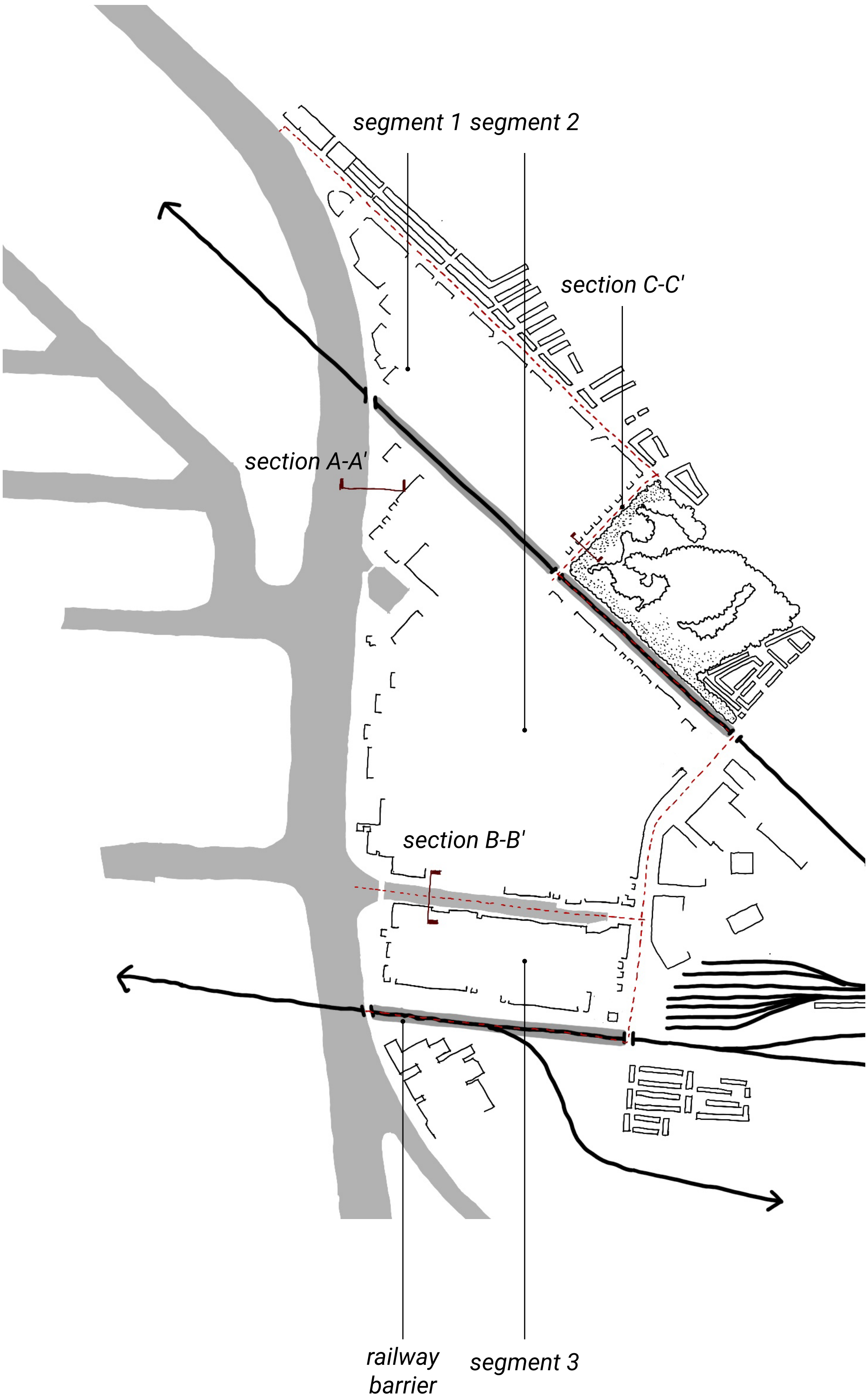
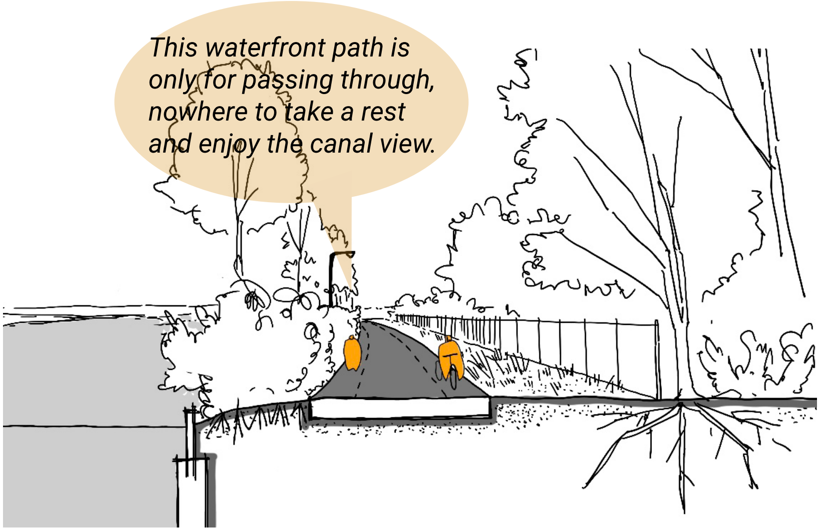
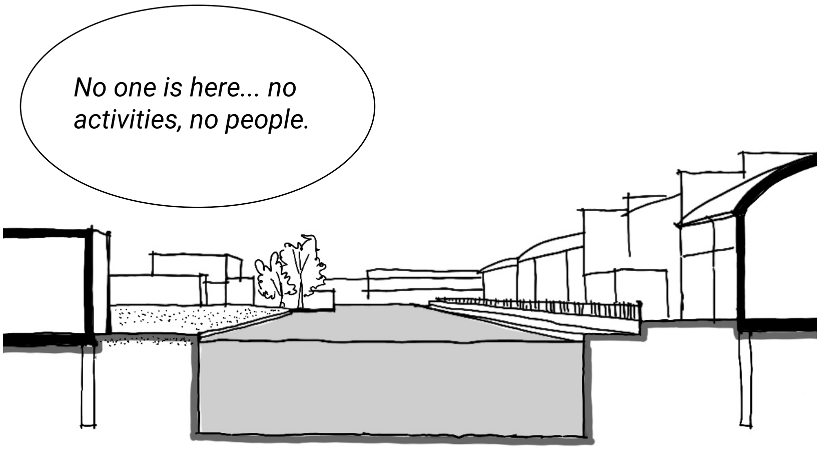


Fig. 42, Interface strategies in the case of Utrecht



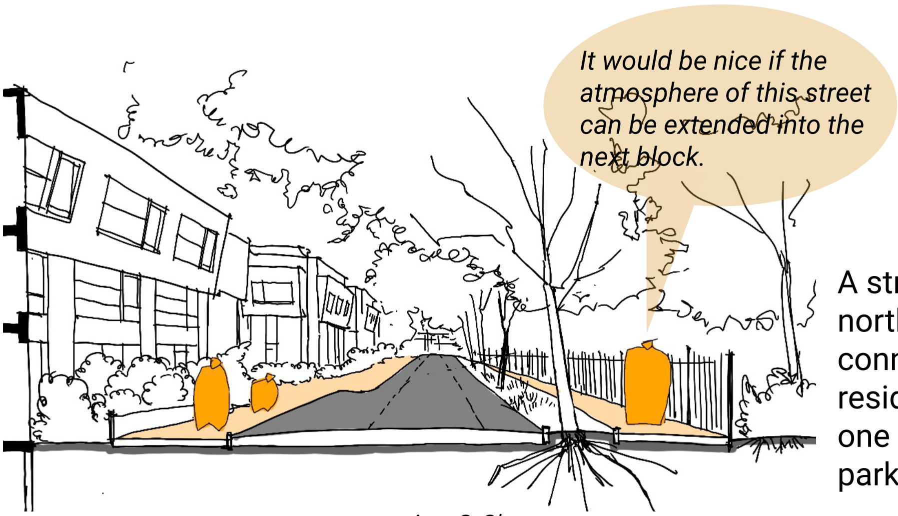
The vehicular road and adjacent cycling infrastructure running parallel to the canal on the western periphery of the site, a corridor primarily optimized for vehicular movement.

section A-A'



Within the design site, there is a port not in use anymore. The flanking waterfront zones continue to be dominated by logistical warehousing and industrial manufacturing plants.

section B-B'



A street situated on the northern boundary of the site connects directly to an adjacent residential quarter, flanked on one side by a municipal urban park.

section C-C'

Fig. 43a-c, Street cross sections of the interfaces of the site segments

Connectivity

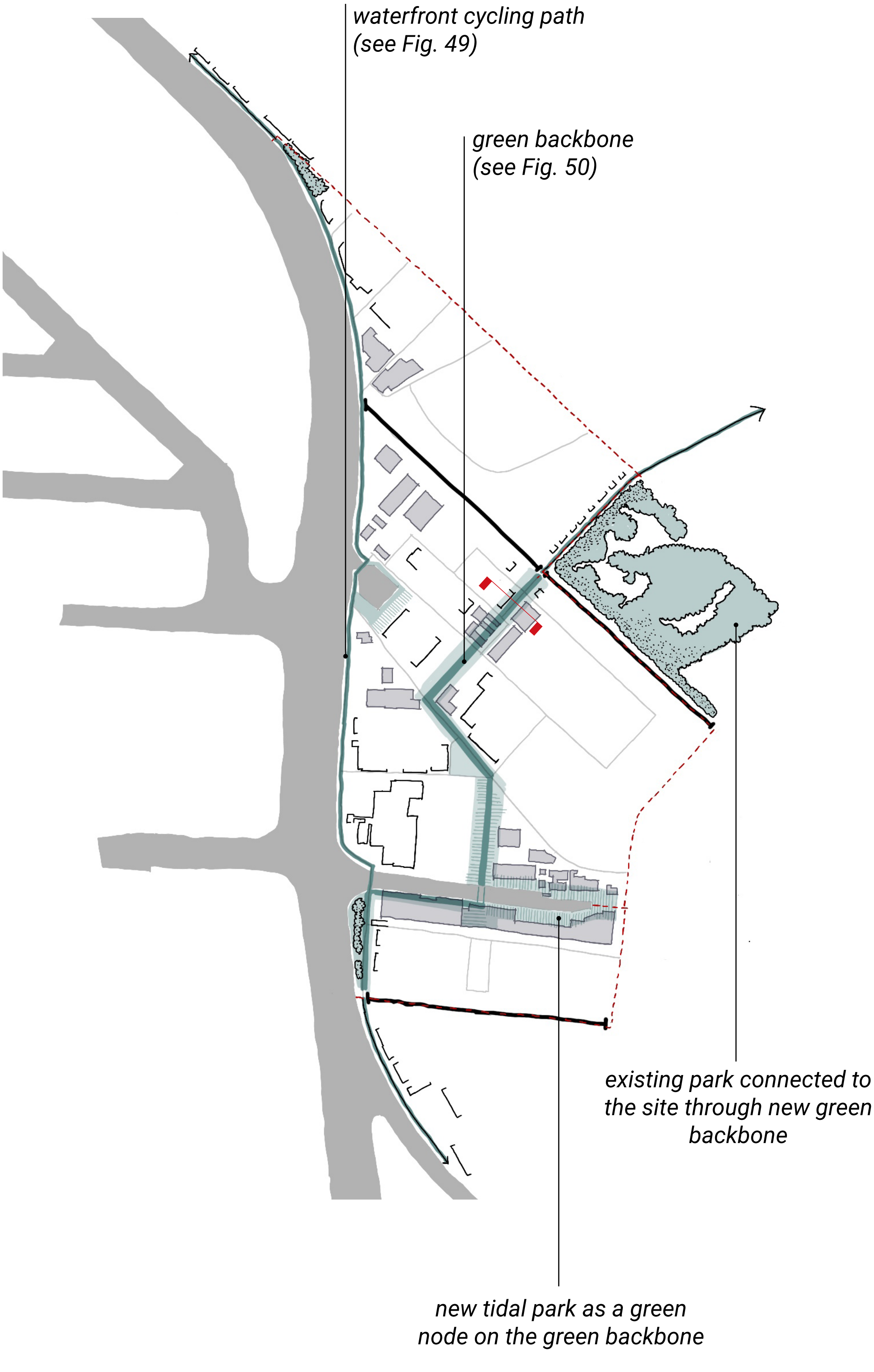


Fig. 44, Connectivity strategies in the case of Utrecht

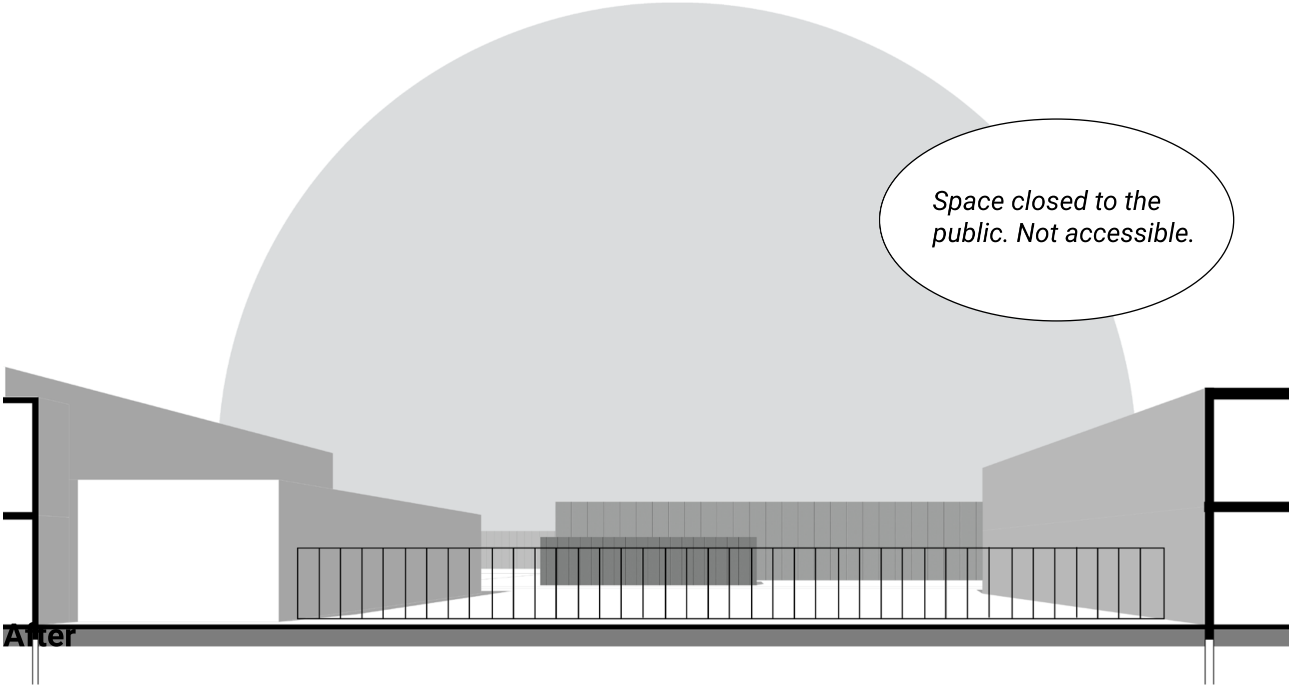


Fig. 45a, Cross section of the green backbone before intervention

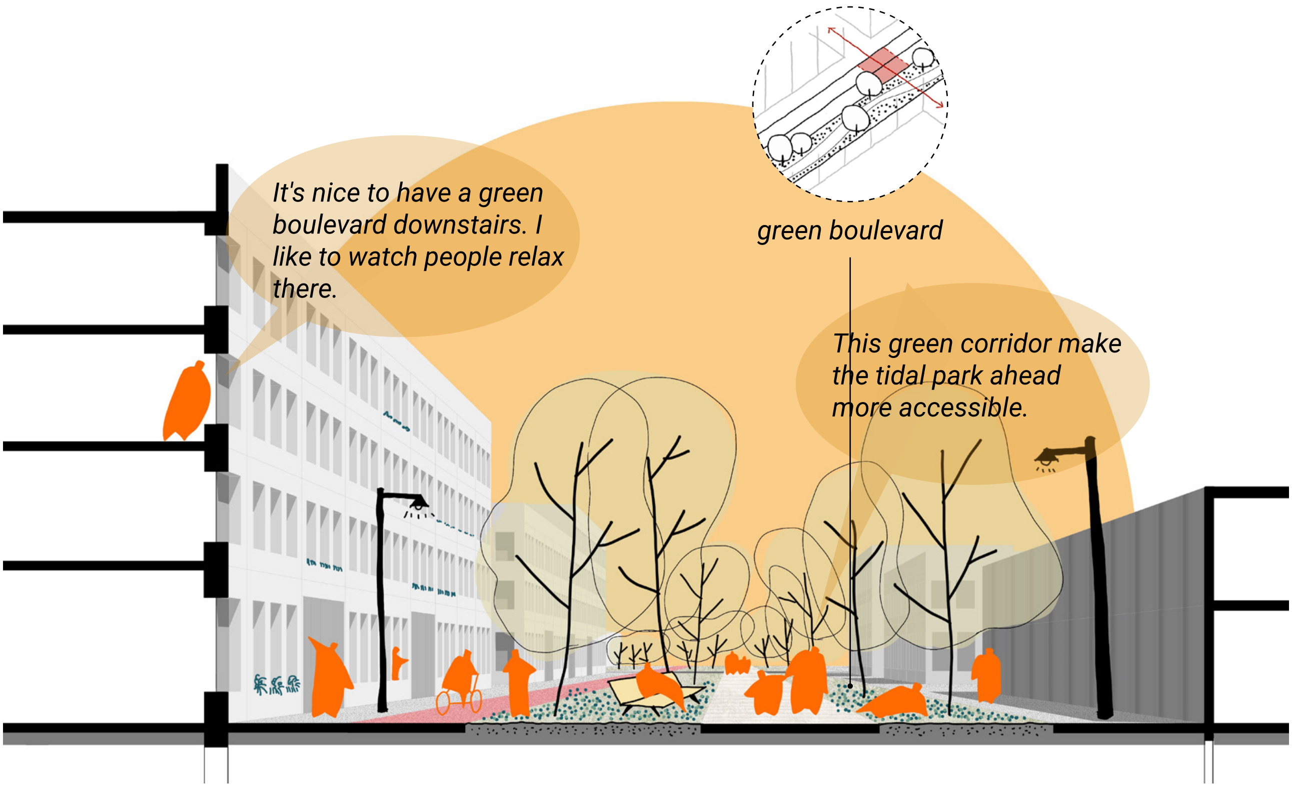
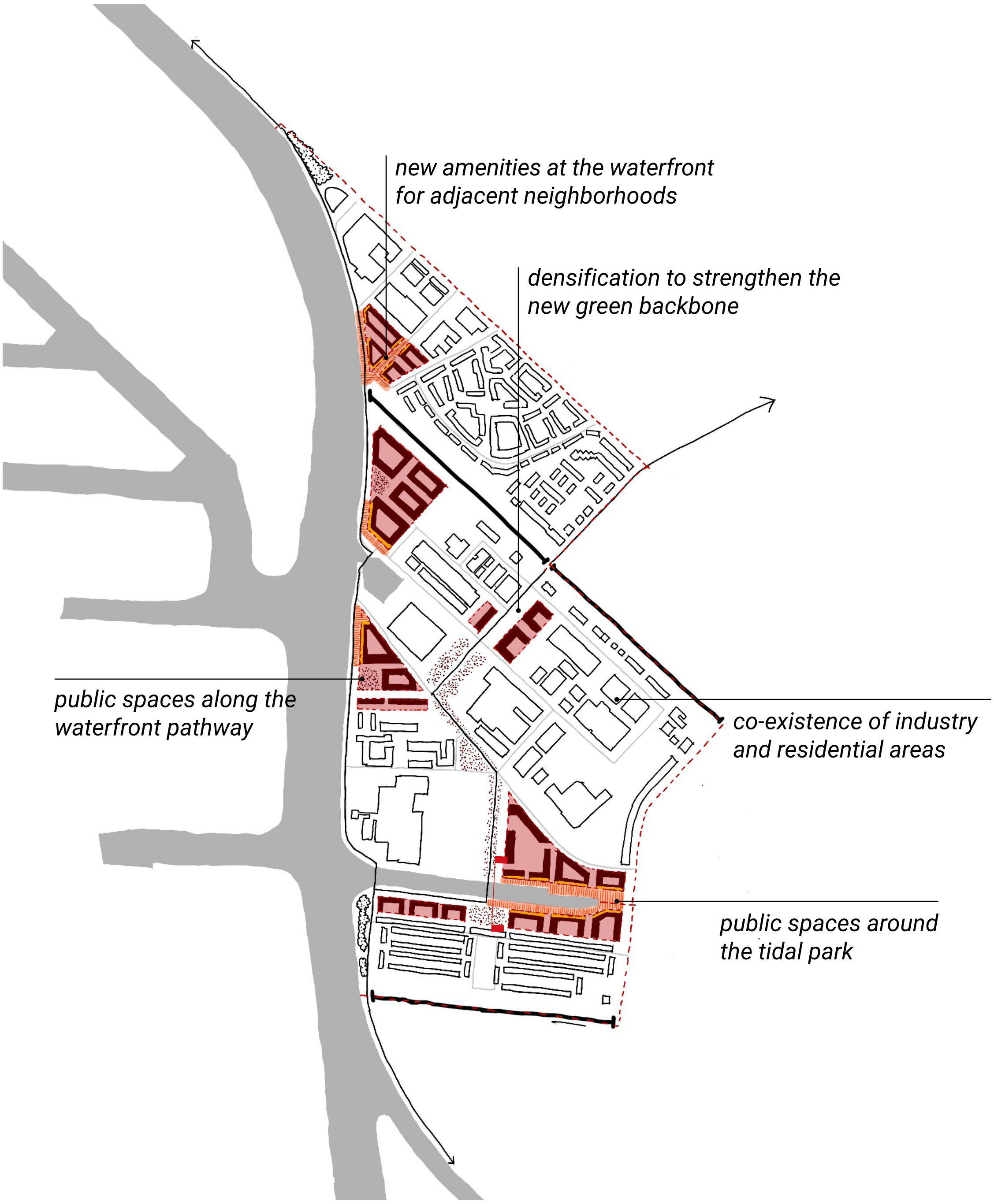


Fig. 45b, Cross section of the green backbone after intervention

Intensity



Synchronized with the newly punctuated public pedestrian pathways established during the preceding connectivity phase, residential densification and ground-floor commercial frontages are strategically deployed along both sides of the green backbone and the newly created tidal park.

Fig. 46, Intensity strategies in the case of Utrecht

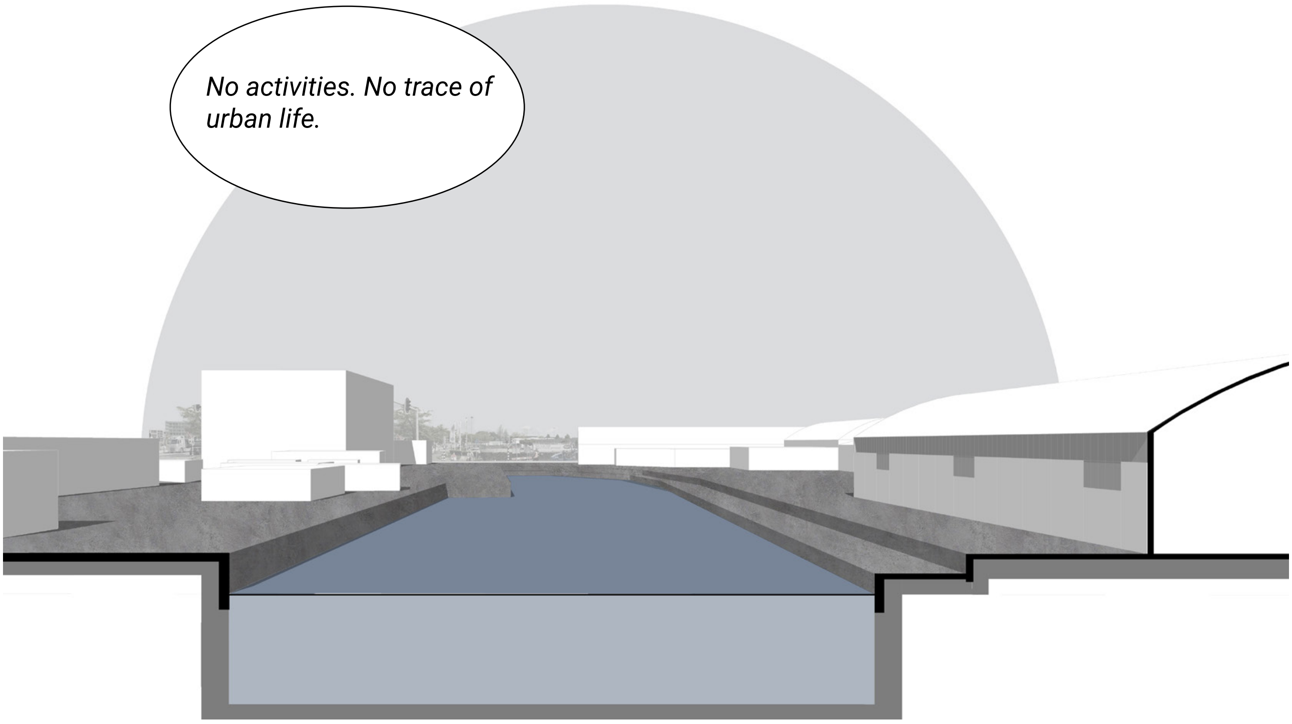


Fig. 45c, Cross section of the port waterfront before intervention

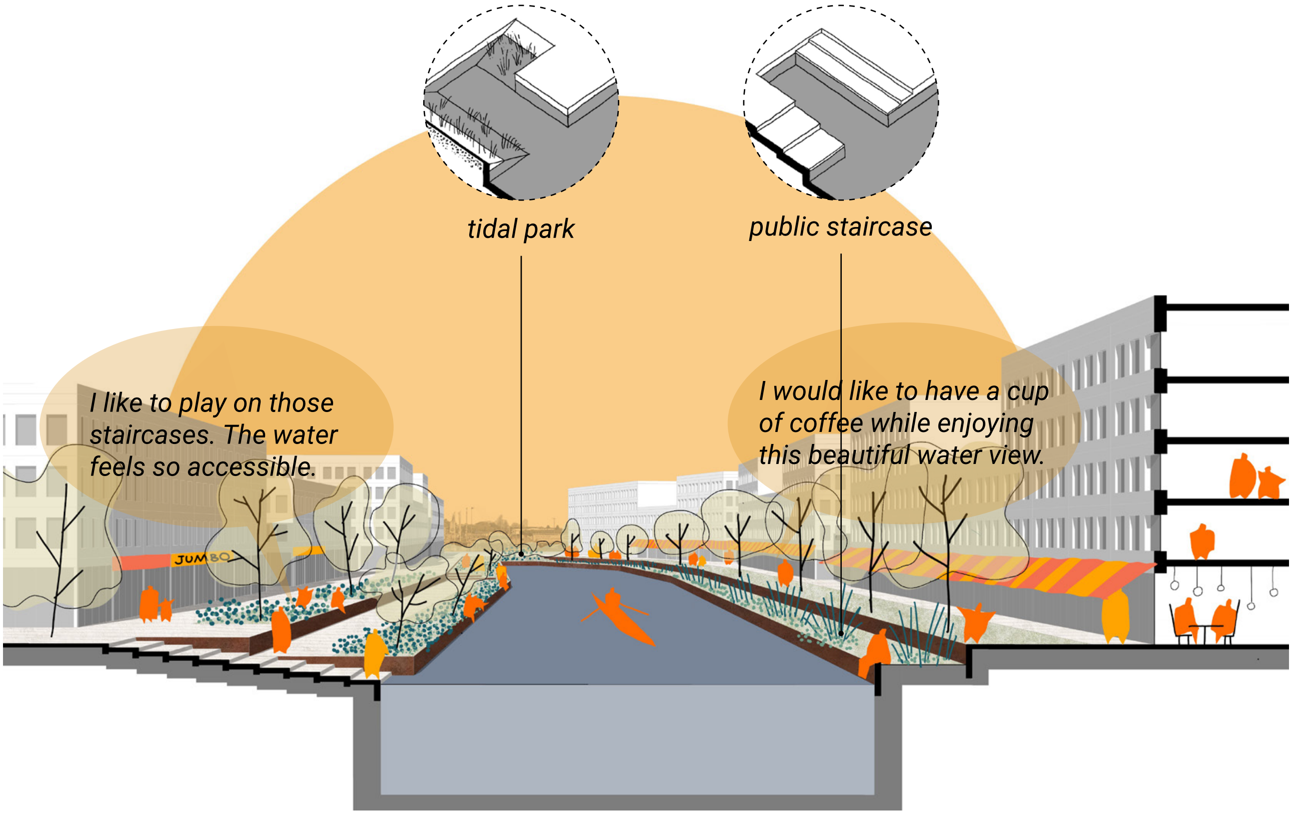


Fig. 45d, Cross section of the port waterfront after intervention

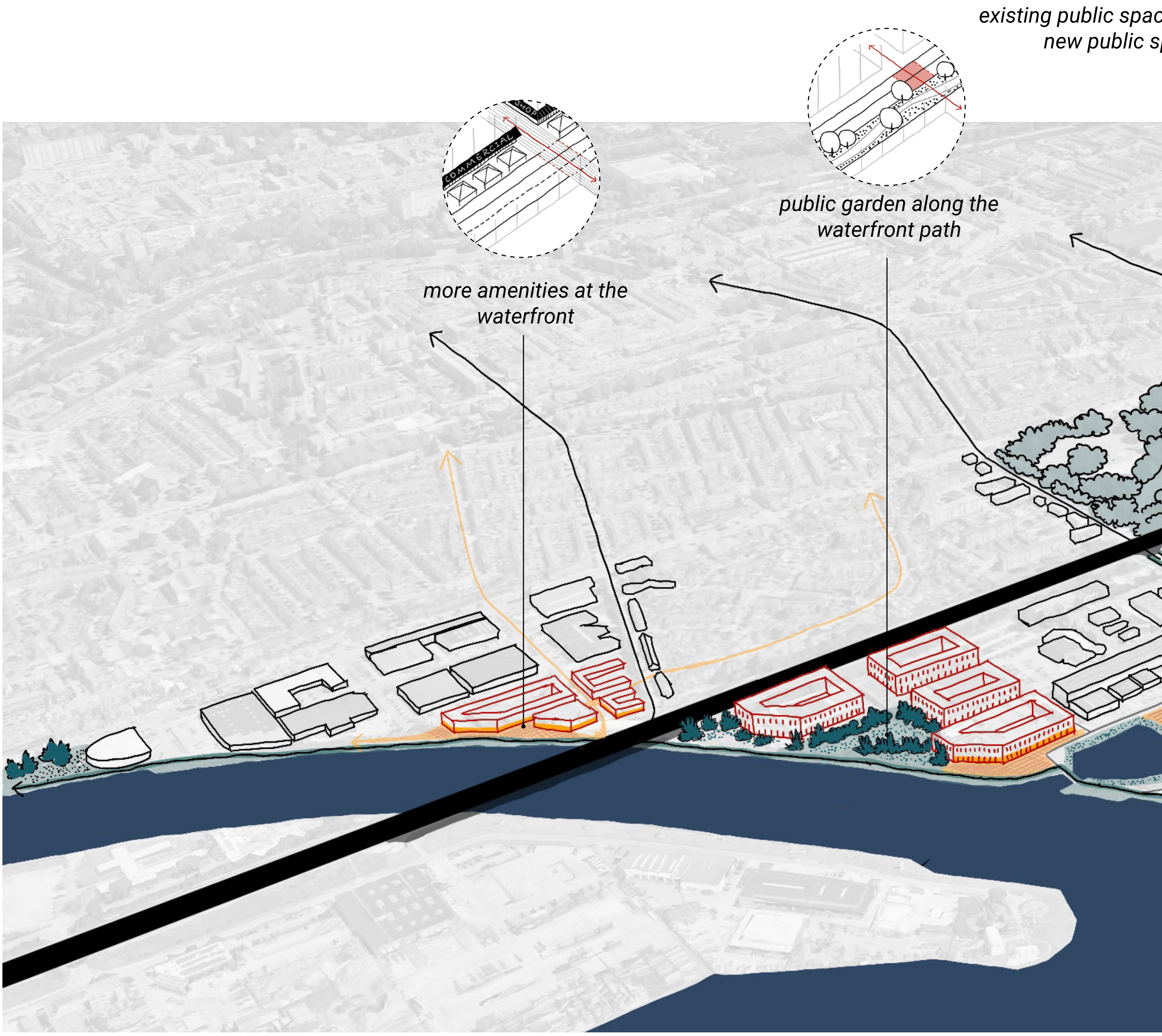


Fig. 47, Birdeye view of th

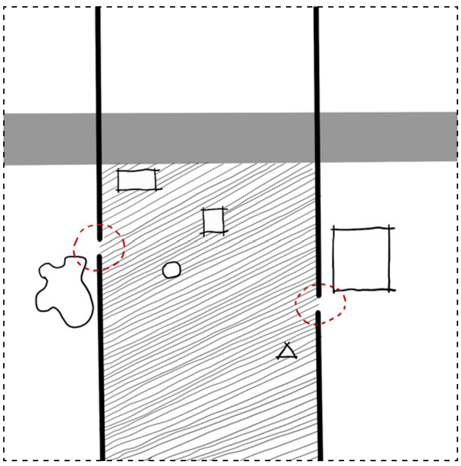


Fig. 48a, Generalized design step 1

Identify the possible nodes for connection and the urban resources that can be linked to the new connection

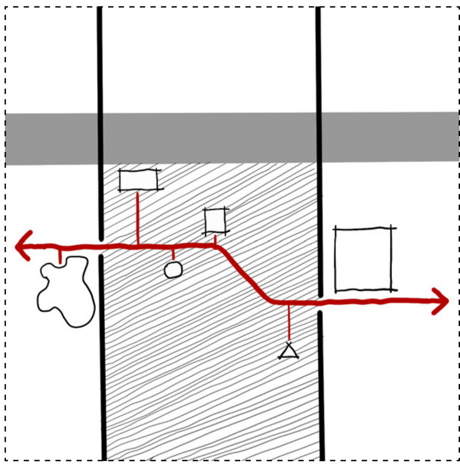
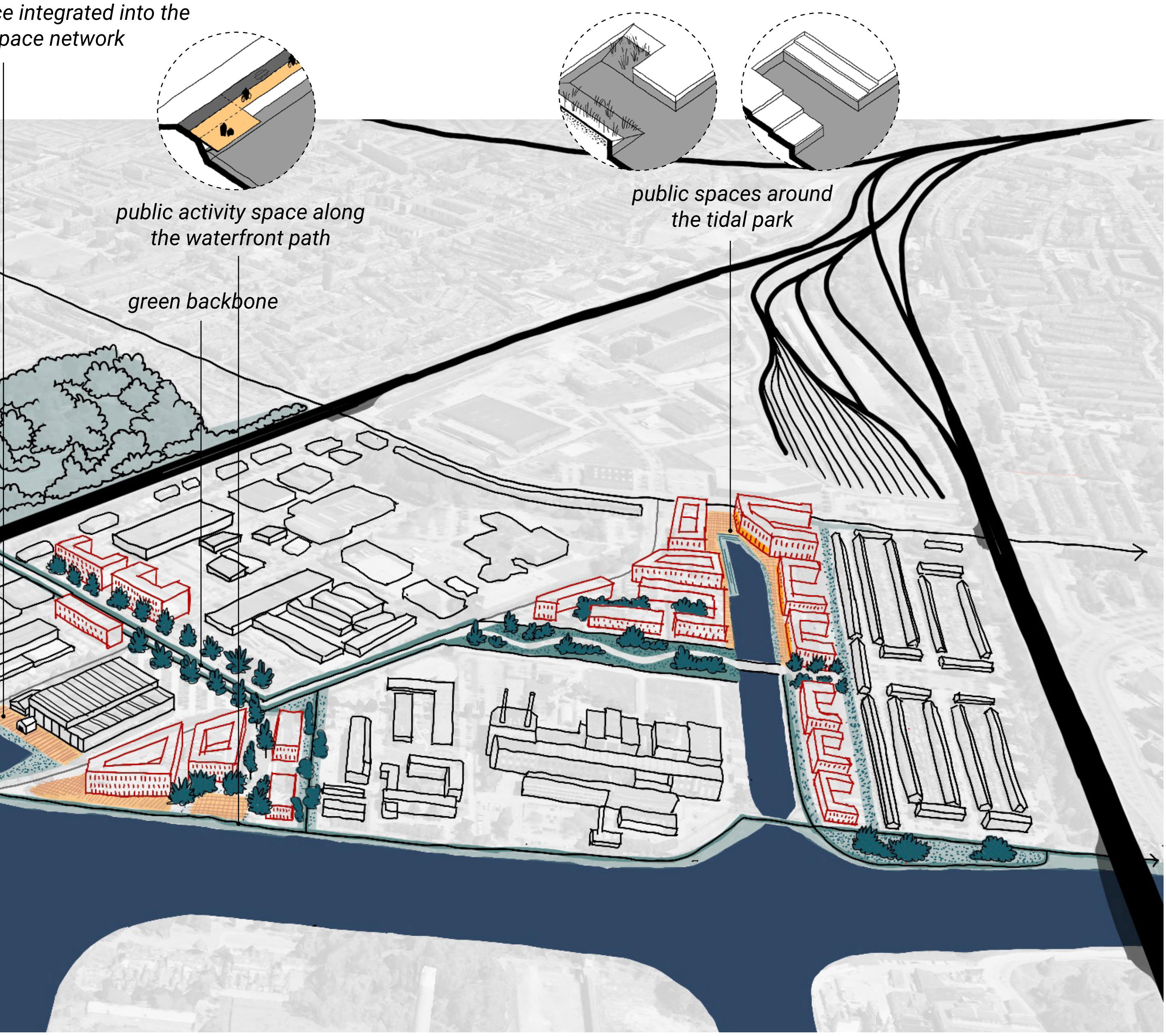


Fig. 48b, Generalized design step 2



e interventions in Utrecht

Make the connection and link the identified urban resources

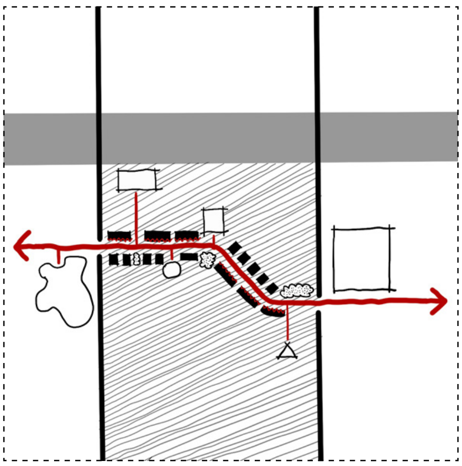


Fig. 48c, Generalized design step 3

Strengthen the connection by adding more public spaces or densifying to boost vibrant urban activities

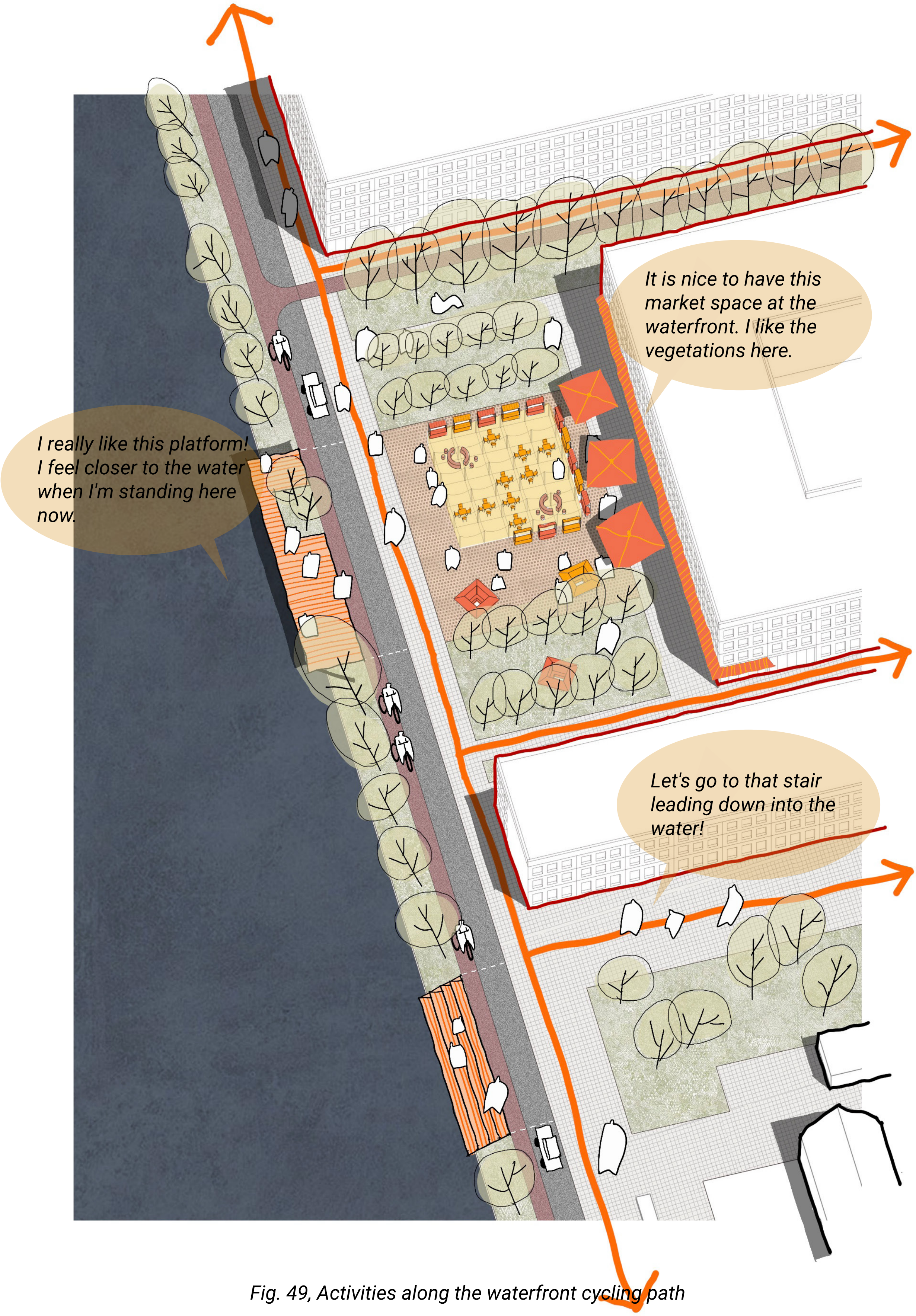


Fig. 49, Activities along the waterfront cycling path

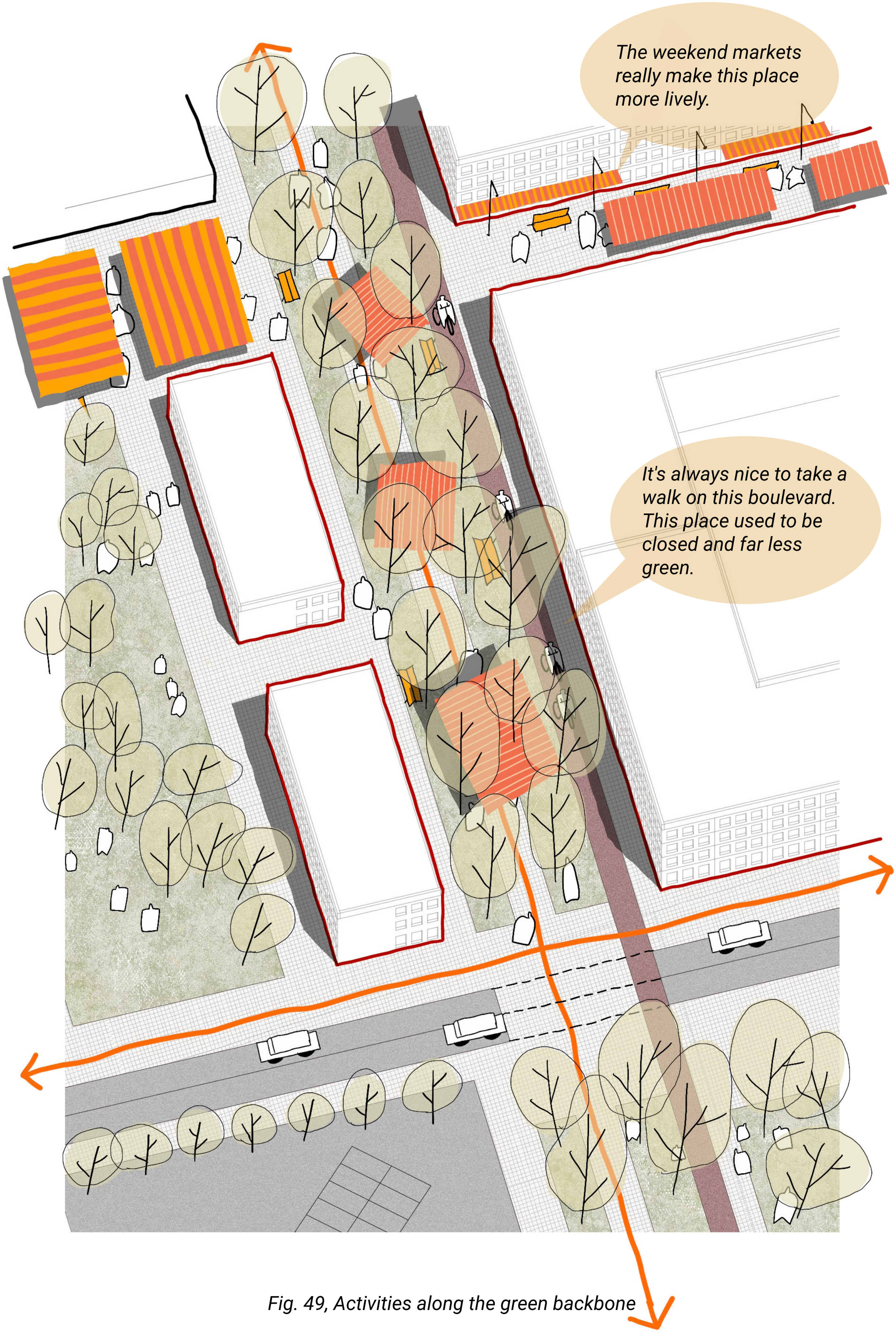


Fig. 49, Activities along the green backbone

Evaluation

Segment 1 Amenity density imbalance **Segment 2 industrial landuse imbalance**

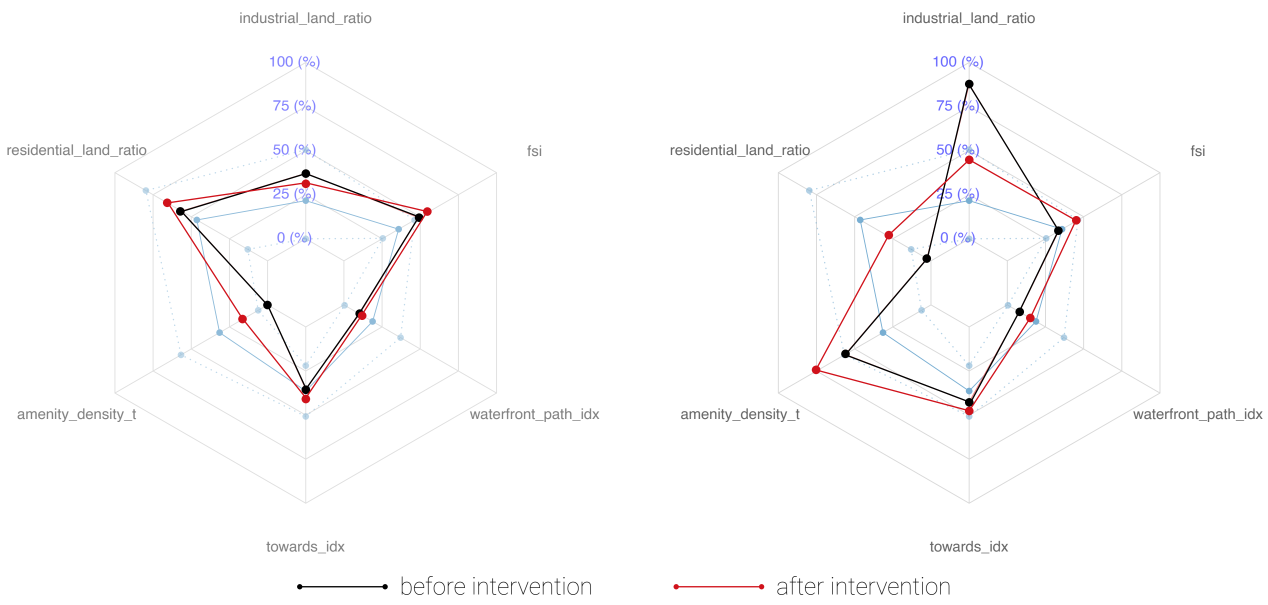


Fig. 51, Evaluation of the two segments with imbalances after intervention

As illustrated in the two radar charts above, the targeted, symptom-specific design interventions successfully mitigated the spatial imbalance issues regarding certain urban performance metrics within the segments. In Segment 1, amenity density was effectively enhanced, while Segment 2 exhibited a more balanced equilibrium between industrial and residential land uses compared to its baseline state.

Notably, this spatial transformation does not occur along a single isolated dimension; rather, it reflects a dynamic, multi-dimensional covariance among several urban parameters. However, it must be acknowledged that this assessment framework ultimately provides a purely quantitative evaluation. It cannot entirely substitute for the qualitative perception of the lived, sensory spatial experiences engendered by physical urban design.

4.4.2 Tilburg

Transformation Potential from IIPC Development Model

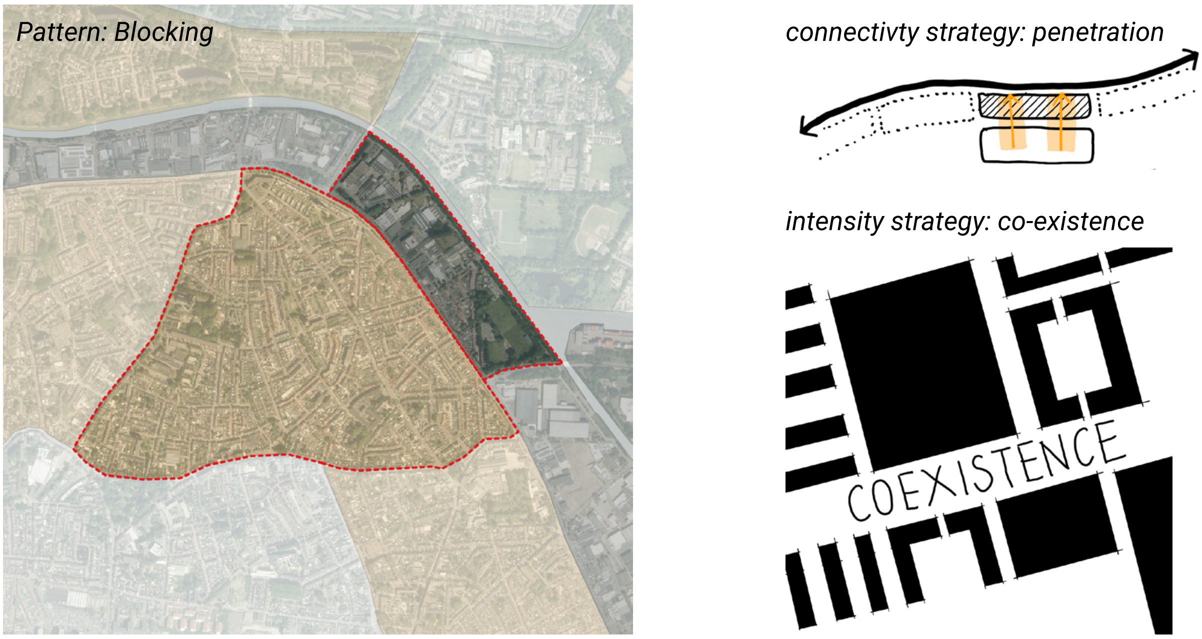


Fig. 52, Conclusions from IIPC development model for the case in Tilburg

Transformation Potential from Urban Morphological Imbalances

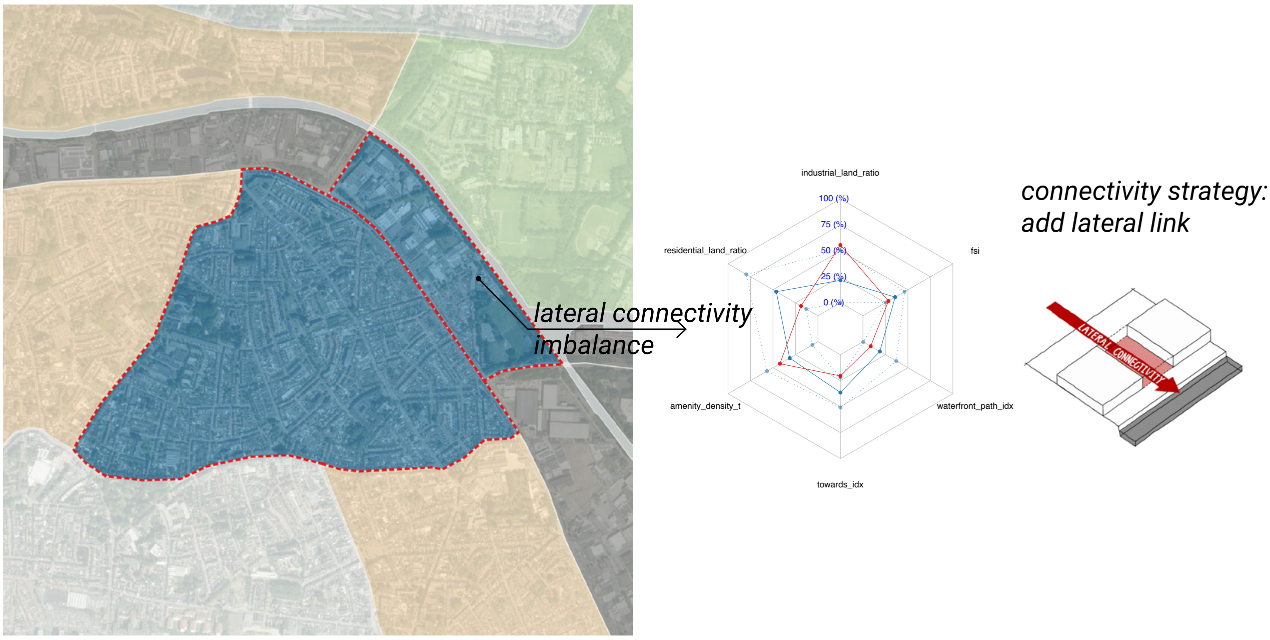


Fig. 53, Conclusions from urban morphological imbalances for the case in Tilburg

Within this particular design case, the analyzed segment is situated within a blocking configuration pattern. The primary objective of the design is to systematically identifying opportunities along the segment's external perimeter to implement new lateral connectivity and intensity the urban use to strengthen these lateral connectivities.

Interface

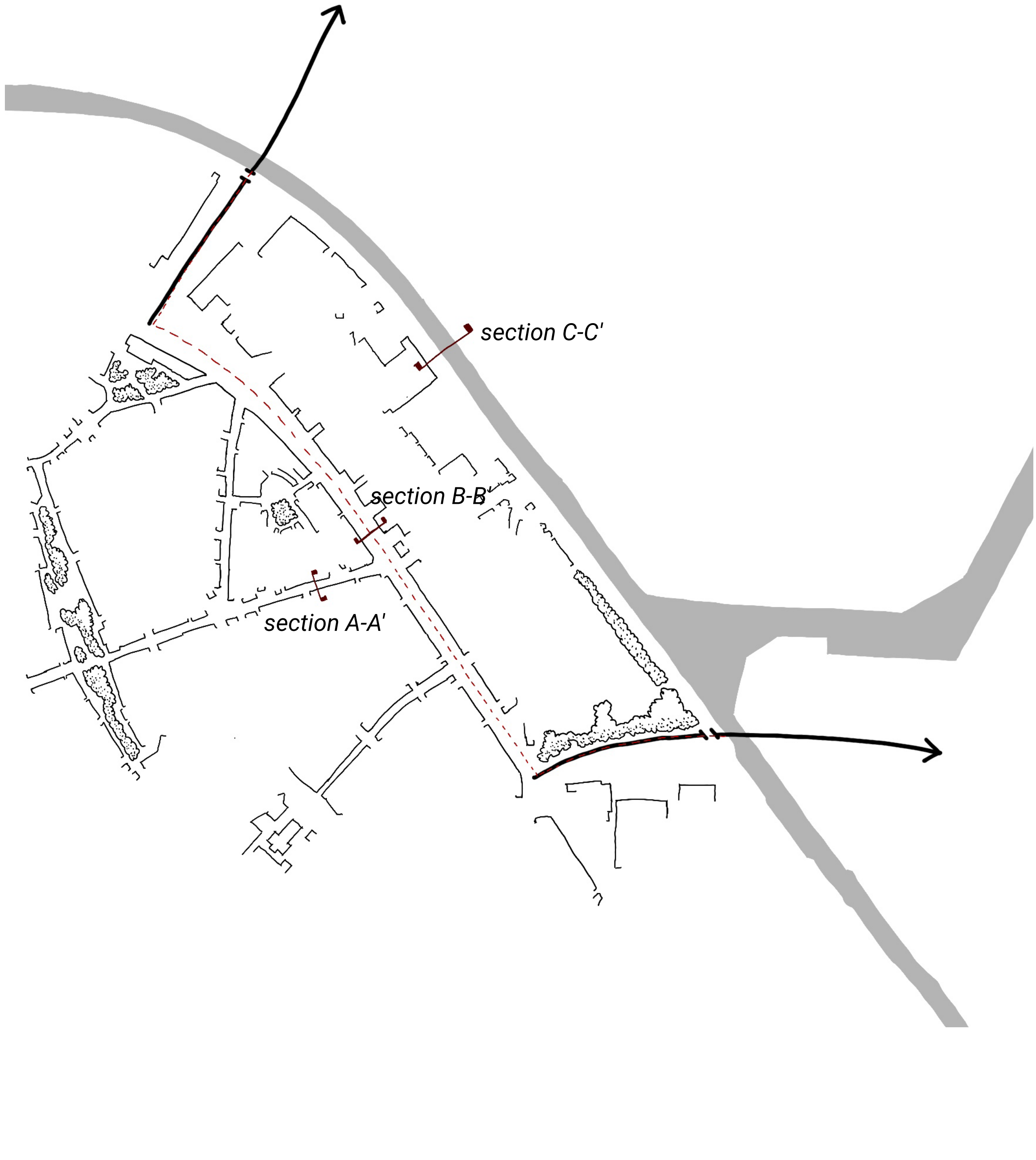
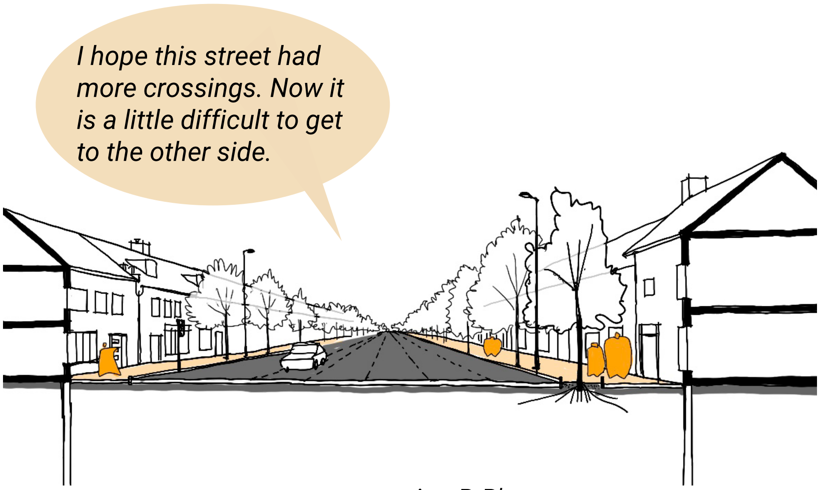


Fig. 54, Interface strategies in the case of Tilburg

section A-A'

The street cross-section of the surrounding residential quarter. The area is dominated by multi-story terraced housing typologies and exhibits a complete absence of commercial or civic service facilities.



section B-B'

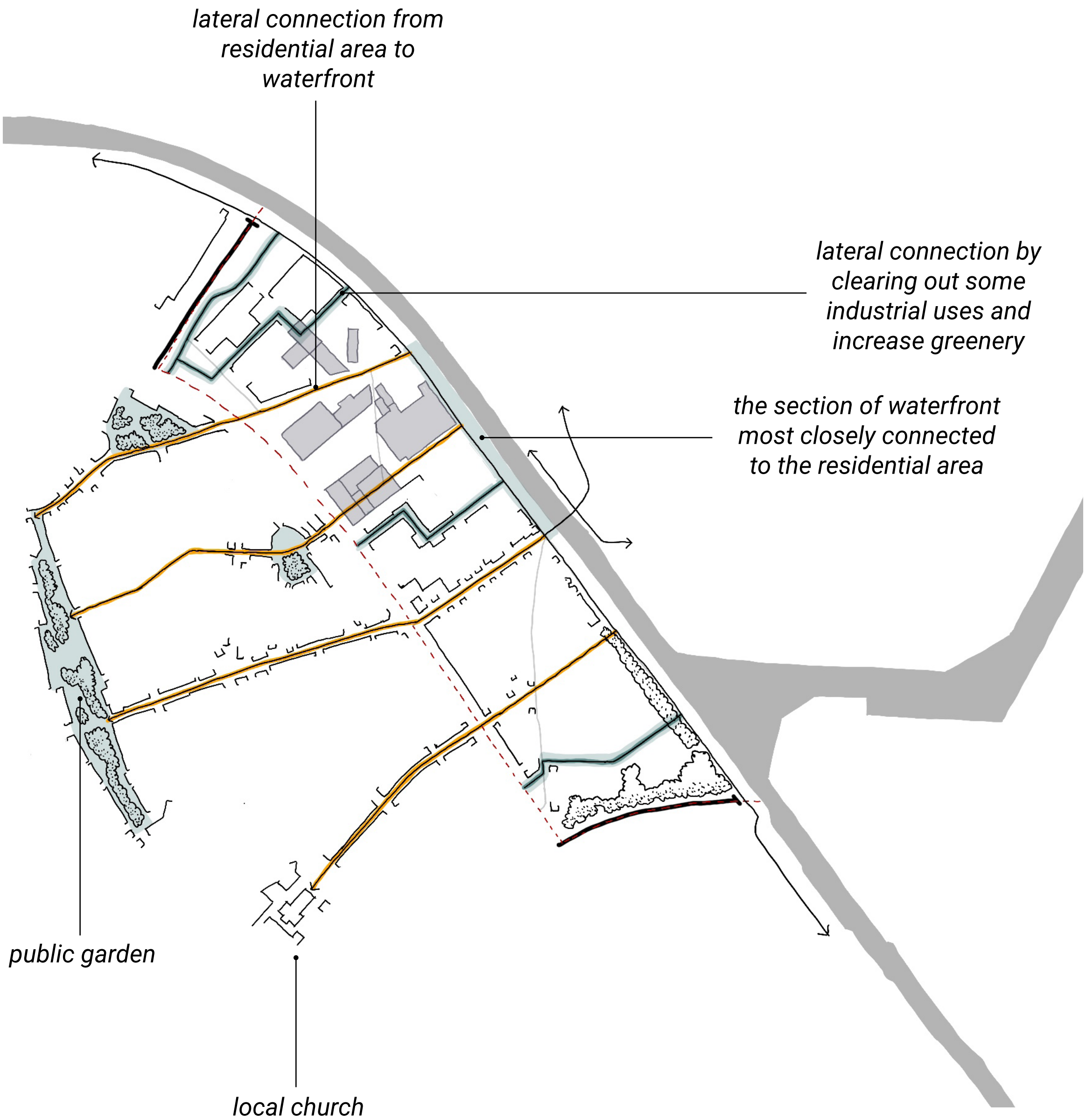
The urban boundary between the segment and the neighboring residential segment. Although the road is considerably wide, it contains no physical or infrastructural barriers.

section C-C'

The current waterfront is primarily for vehicular throughput; however, the soft green open space flanking the right hand side of the corridor presents a strategic opportunity for adaptation into a vibrant node for public programming and civic activities.

Fig. 55a-c, Street cross sections of the interfaces of the site segments

Connectivity



The Orange Axes designate strategic structural connections between the segment and the adjacent southern open public spaces or community landmarks (such as the local church).

The Green Axes delineate newly punctured public corridors established within the existing industrial fabric. This is achieved through selective structural demolition and the integration of intensive vegetation infrastructure, thereby enhancing the permeability of the waterfront.

Fig. 56, Connectivity strategies in the case of Tilburg

Intensity

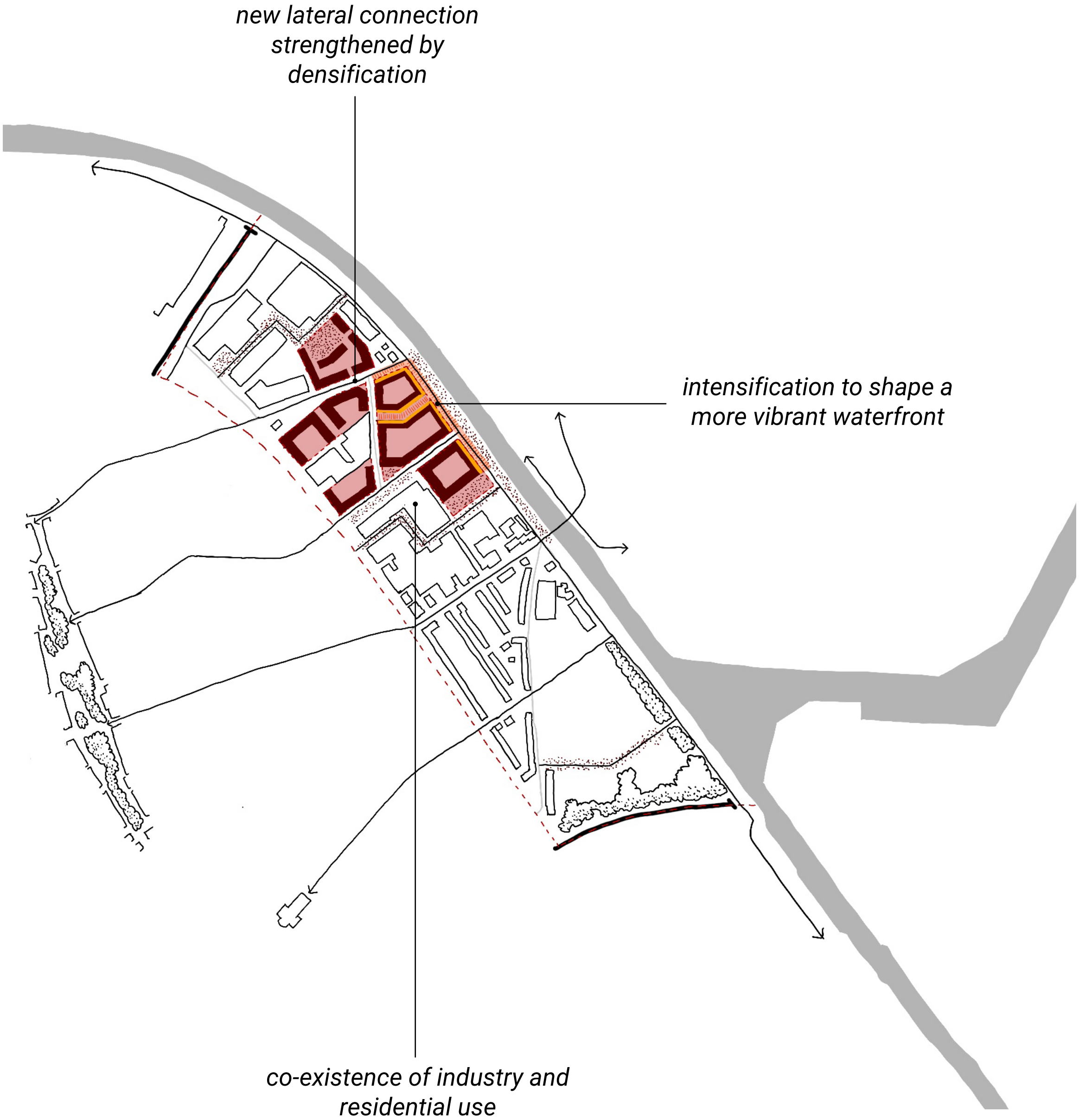


Fig. 57, Intensity strategies in the case of Tilburg

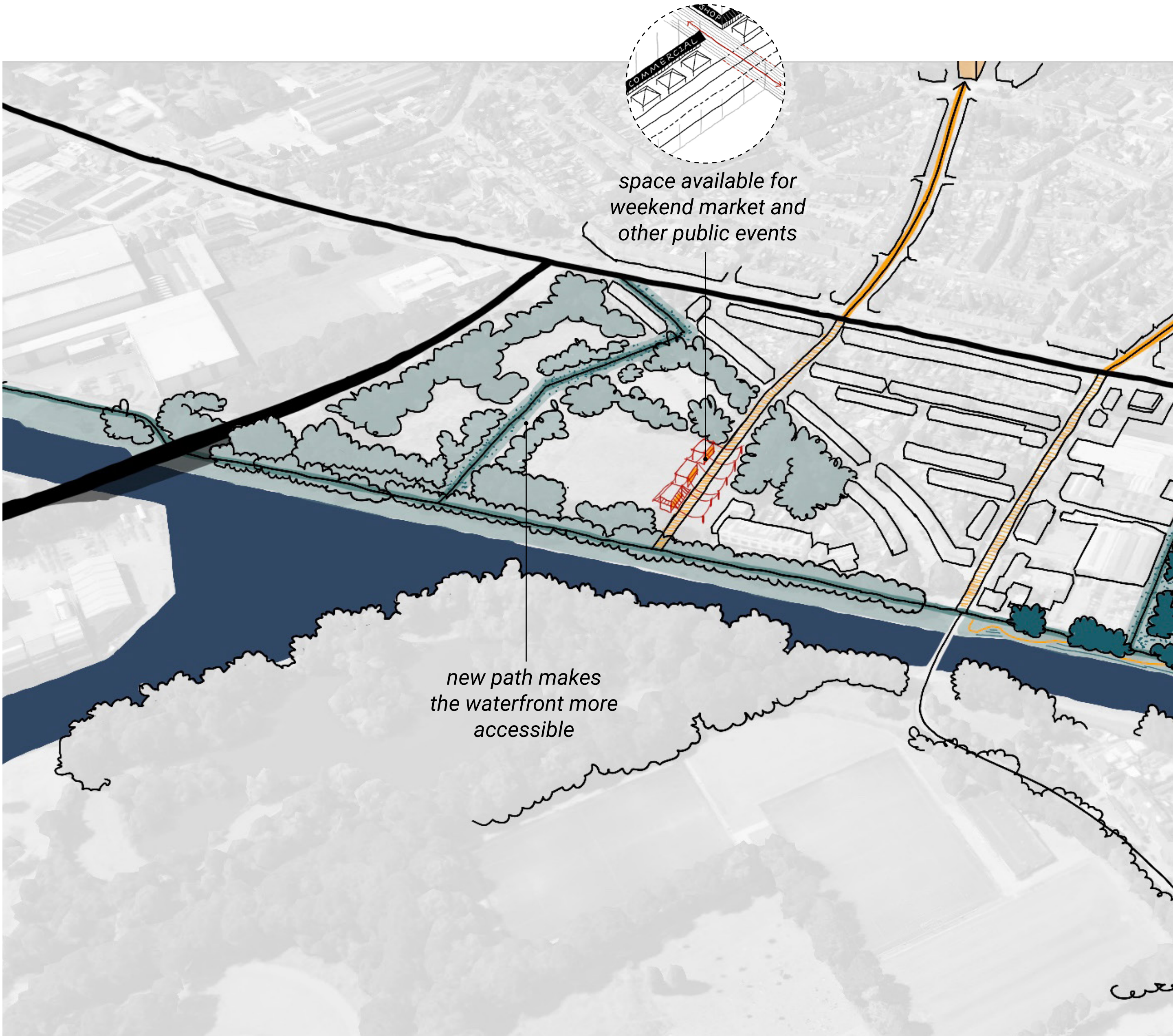


Fig. 58, Birdeye view of th

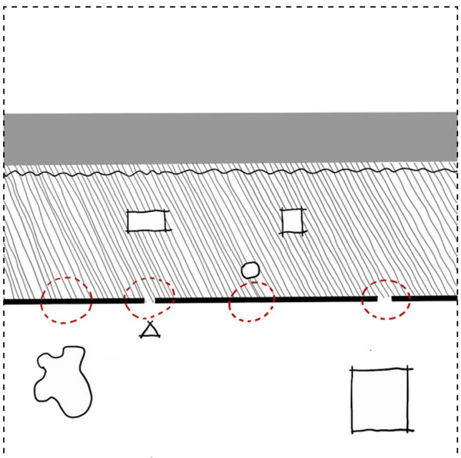


Fig. 59a, Generalized design step 1

Identify the possible nodes for connection and the urban resources that can be linked to the new connection

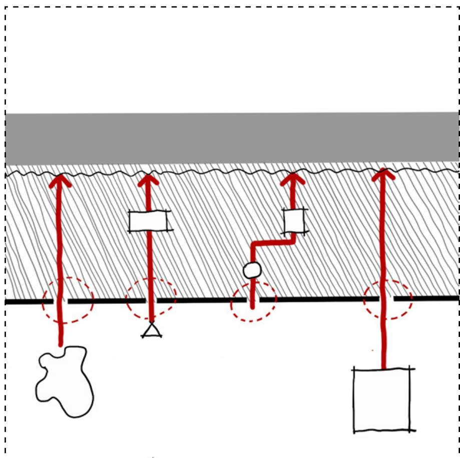
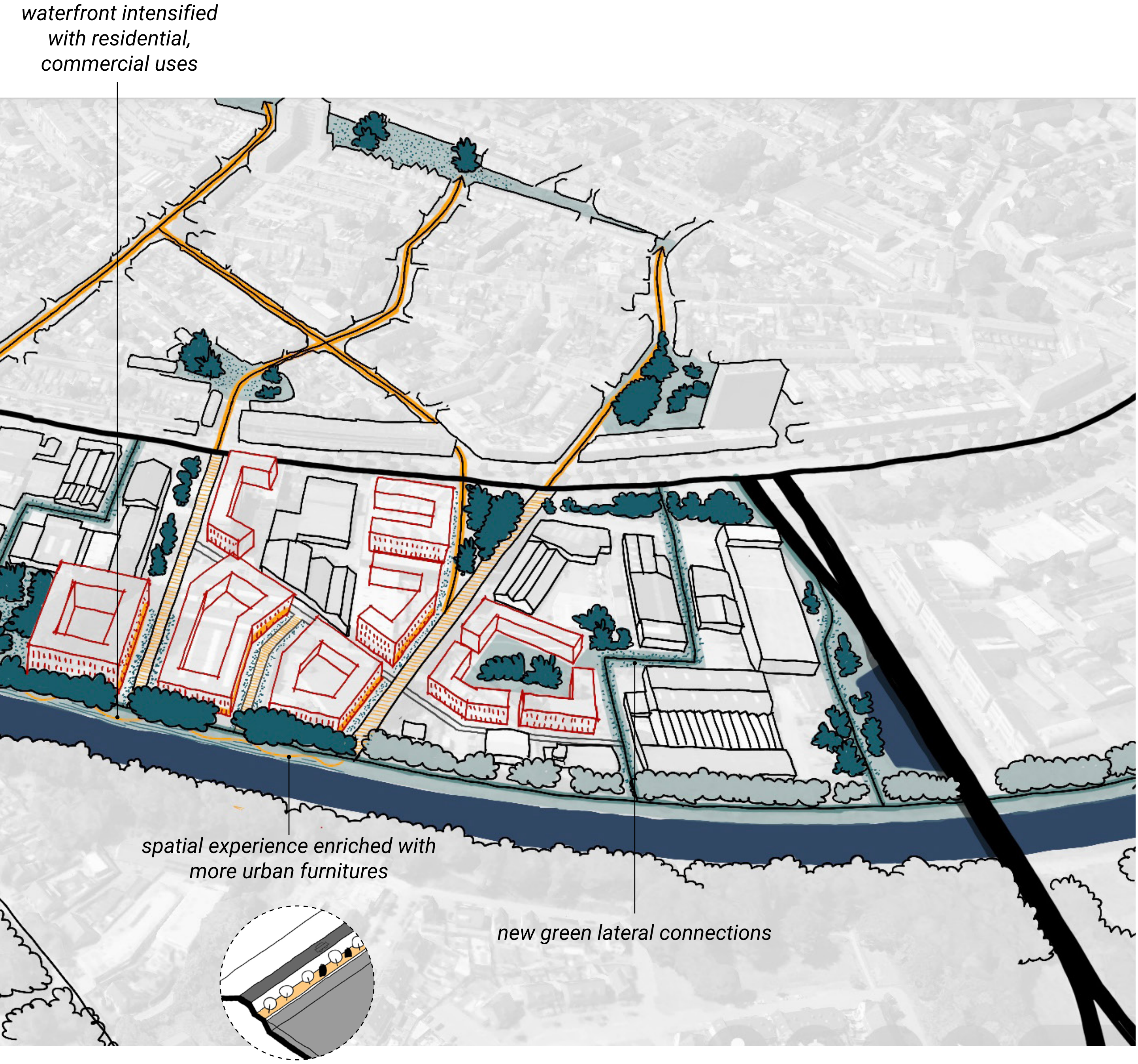


Fig. 59b, Generalized design step 2



e interventions in Tilburg

Make the connection and link the identified urban resources

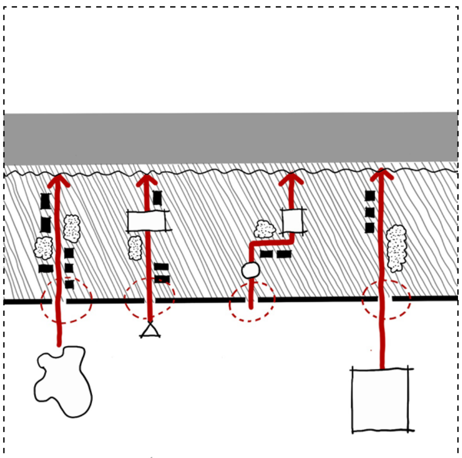


Fig. 59c, Generalized design step 3

Strengthen the connection by adding more public spaces or densifying to boost vibrant urban activities

4.4.3 Roosendaal

Transformation Potential from IIPC Development Model

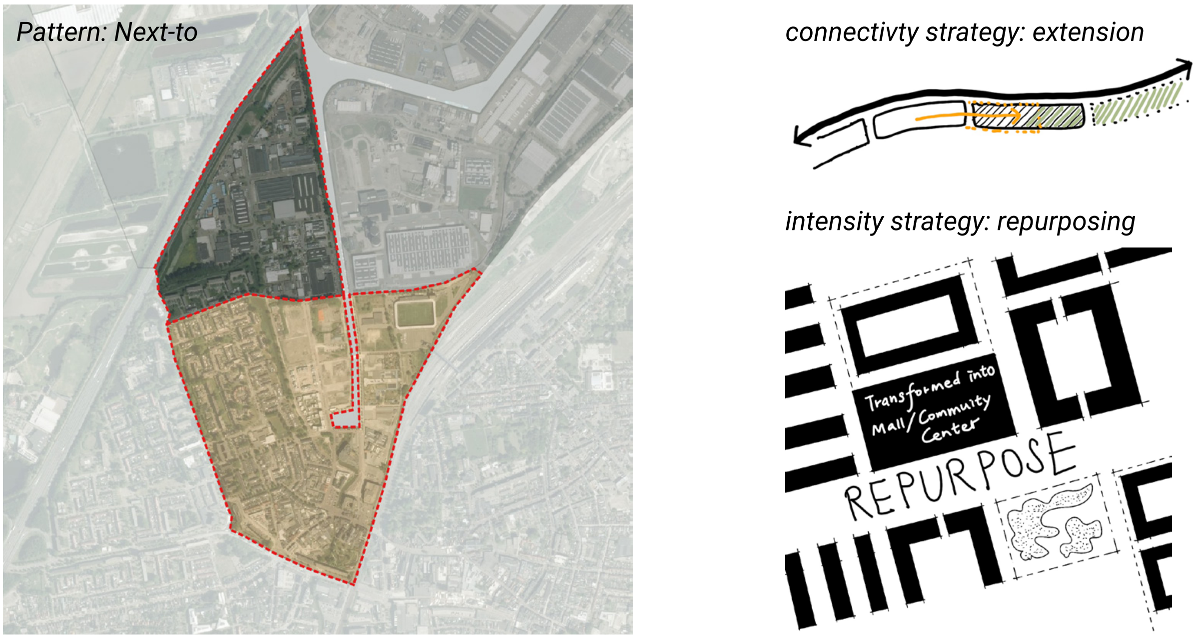


Fig. 60, Conclusions from IIPC development model for the case in Roosendaal

Transformation Potential from Urban Morphological Imbalances

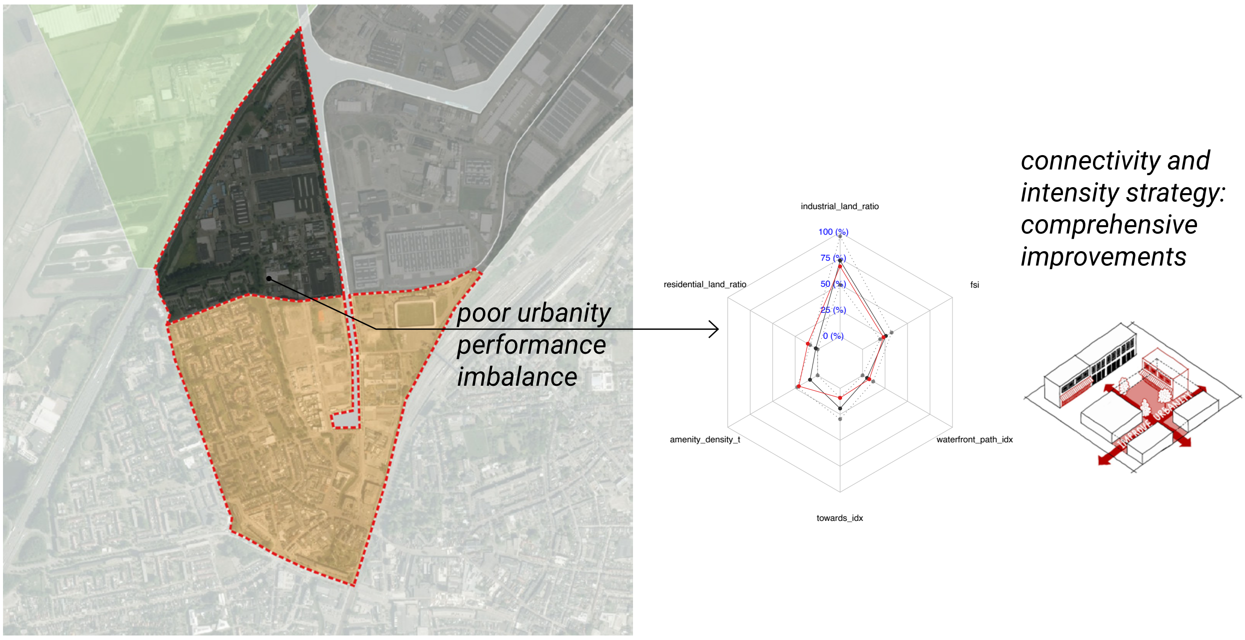


Fig. 61, Conclusions from urban morphological imbalances for the case in Roosendaal

This specific urban design case is situated under the shrinkage trajectory, exhibiting a next-to configuration pattern. The primary objective is to extend from the established urban fabric directly into this industrial segment.

Interface

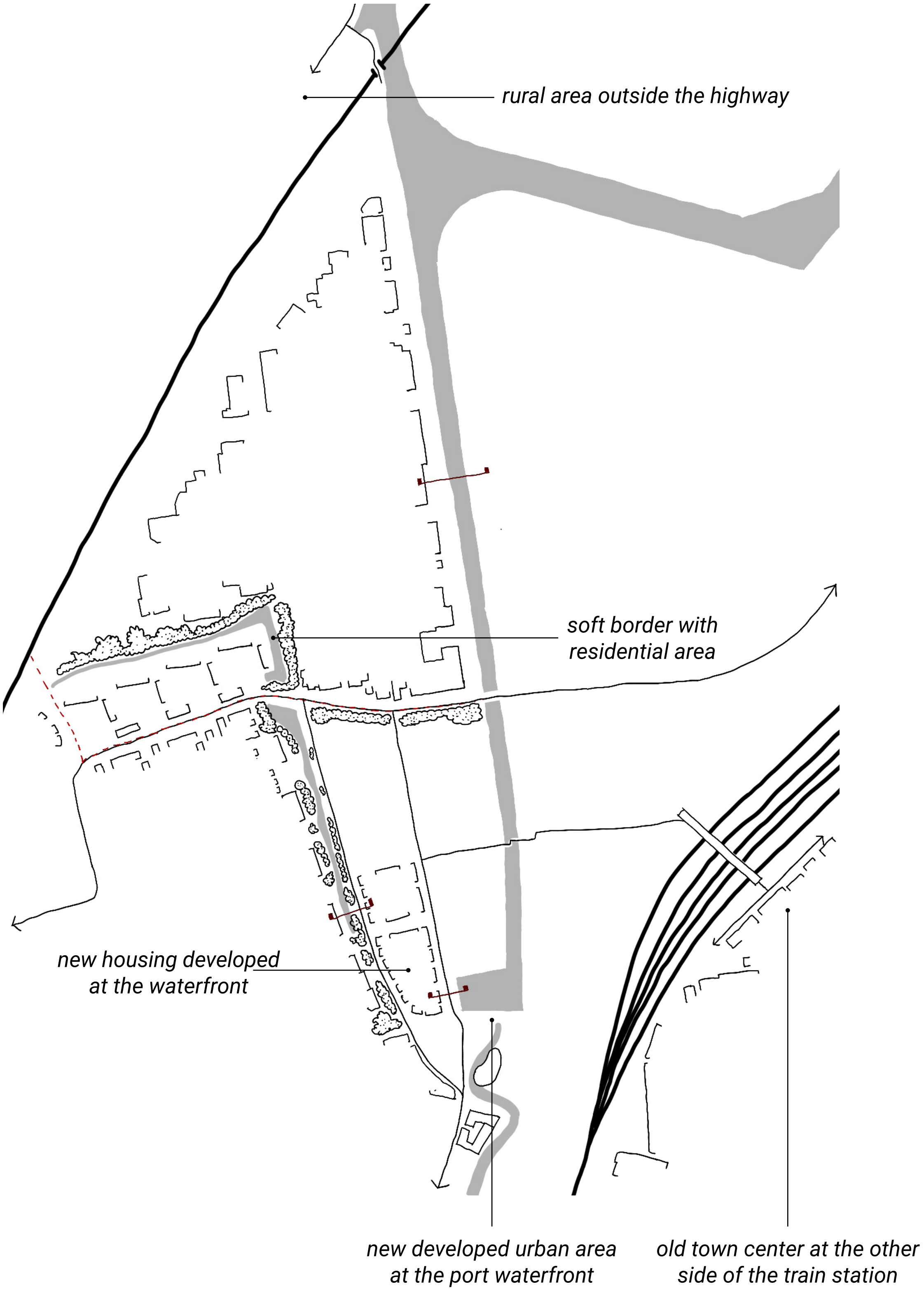


Fig. 62, Interface strategies in the case of Roosendaal

Connectivity

The core connectivity intervention manifests as the implementation of two continuous green corridors running parallel to the canal axis.

Fig. 63, Connectivity strategies in the case of Roosendaal

Intensity

The poor urbanity imbalance requires the improvement by increasing the street network density, introducing a higher concentration of civic and commercial amenities, executing contextual residential densification, and amplifying the green infrastructure canopy.

Fig. 64, Intensity strategies in the case of Roosendaal

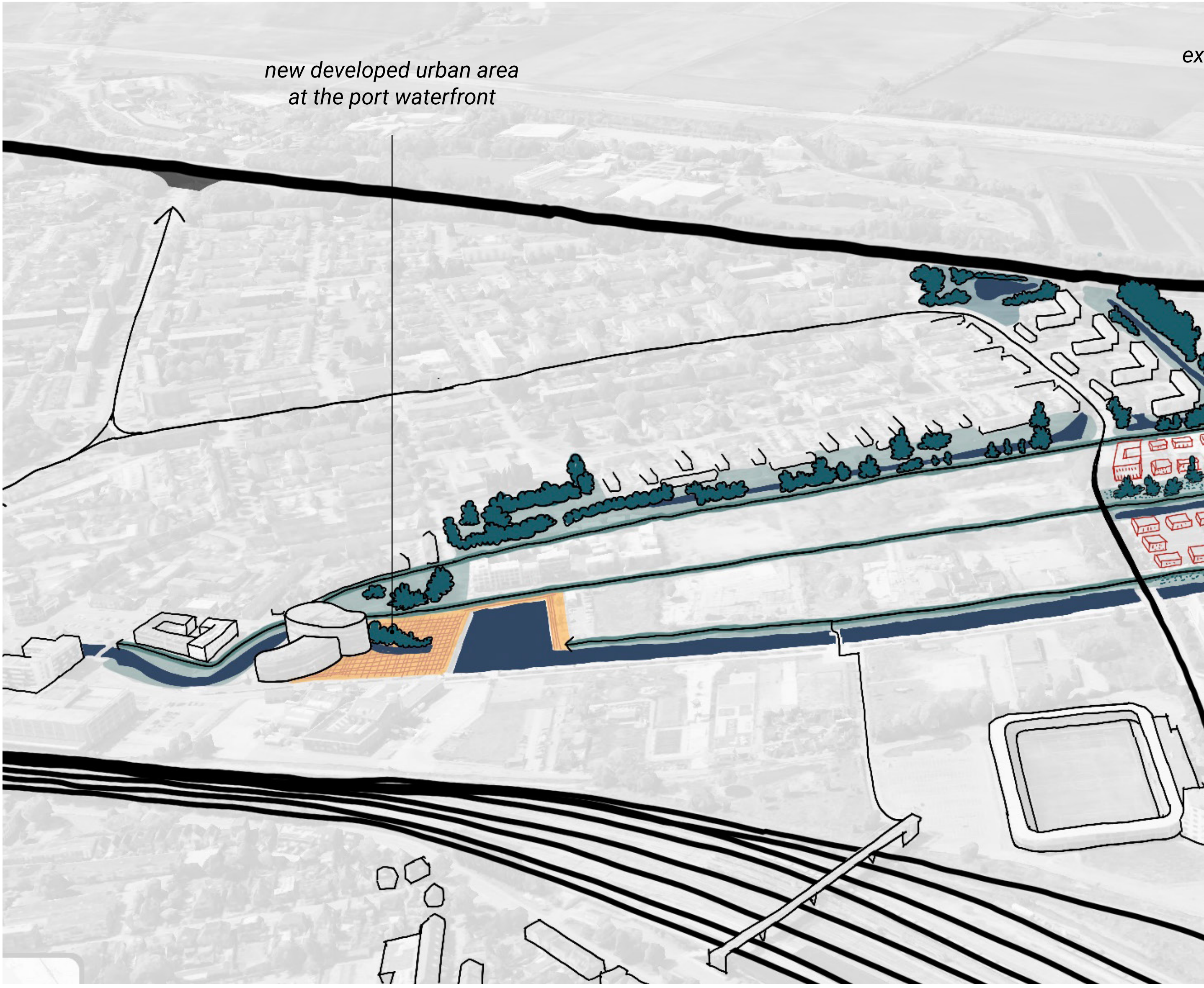


Fig. 65, Birdeye view of the

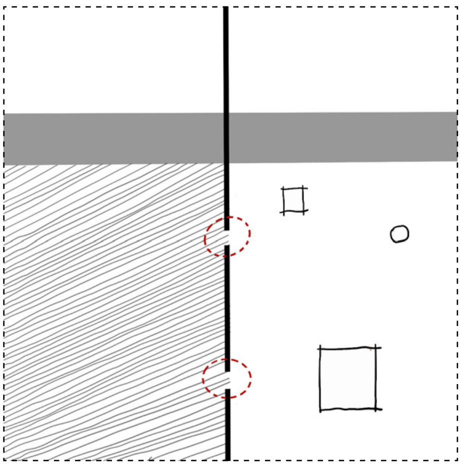


Fig. 66a, Generalized design step 1

Identify the possible nodes for connection and the urban resources that can be linked to the new connection

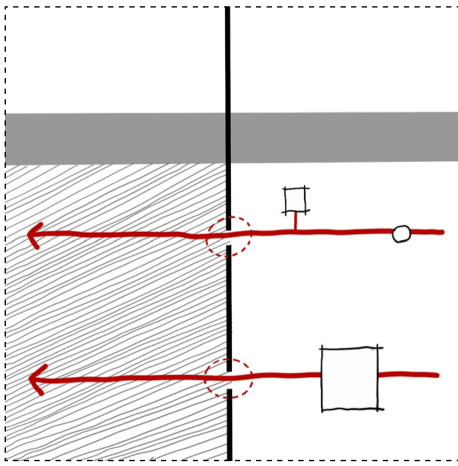
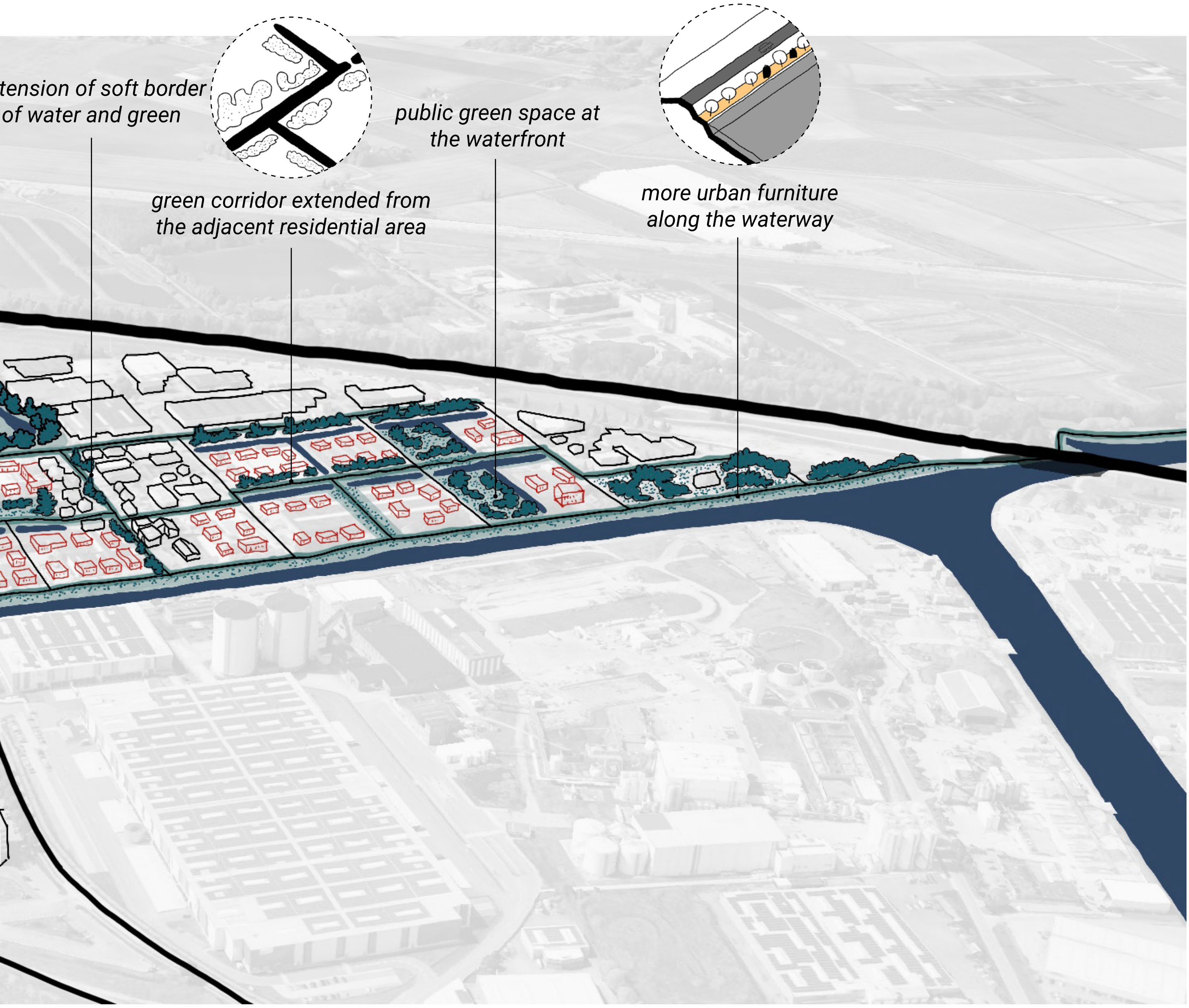


Fig. 66b, Generalized design step 2



interventions in Roosendaal

Make the connection and link the identified urban resources

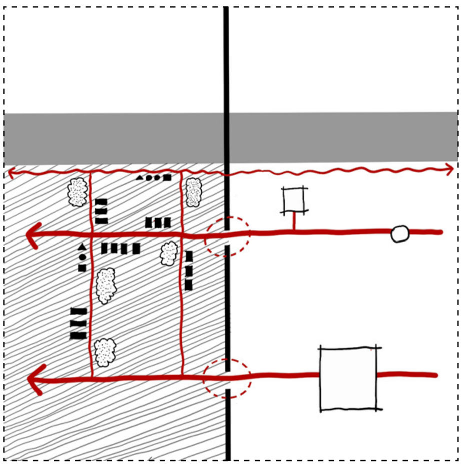


Fig. 66c, Generalized design step 3

Strengthen the connection by adding more public spaces or densifying to boost vibrant urban activities

5. Discussion

Throughout the development of this thesis, a series of experiments were carried out to establish a comprehensive typology rooted in an urban morphological perspective. Concurrently, critical reflections were directed towards the inherent limitations of this research methodology. In summary, the discussion chapter of this thesis is structured into two primary sections: the methodological limitations of the current framework and the potential refinement for future researches.

Limitations of the Research

This study primarily investigates the transformation and redevelopment potential of urban waterfronts through the lenses of urban morphology and port-city development models. In empirical urban renewal practices, however, identifying morphologically and spatially suitable sites is only one facet of a complex process; the most formidable challenge often lies in the realm of property rights and land ownership during implementation. Particularly in the contemporary era of mature urban environments and advanced urbanization, intricate and fragmented property rights frequently constitute the primary obstacle to urban regeneration. This dimension falls outside the scope of the current study, and the extent to which property rights resolution mechanisms can be integrated into quantitative analytical frameworks remains unexamined.

Furthermore, public policy and institutional governance represent critical components of urban renewal. Port-cities, for instance, routinely experience institutional fragmentation due to jurisdictional divides between municipal administrations and autonomous port authorities. The omission of these socio-political and administrative factors represents a significant limitation of this research, delineating a critical avenue that warrants rigorous attention in subsequent studies.

At the network scale, the clustering process was substantially constrained by data accessibility. A considerable volume of port-related economic data is proprietary or classified, remaining inaccessible to the public. Consequently, the generic datasets available for this study inevitably contain confounding "noise" generated by disparate urban sectors, leaving room for debate regarding how precisely these data mirror actual port development trajectories. Beyond the constraints of data accuracy, analysis at the network scale inherently simplifies the projections of future urban development trends. In empirical reality, this trajectory is governed by far more convoluted mechanisms, necessitating the incorporation of a broader matrix of variables in future predictive models.

In conducting the analysis of spatial configuration and pattern recognition at the corridor scale, this study primarily focuses on the patterns of direct contact between industrial and urban segments. This specific spatial relationship frequently signifies functional conflicts

between residential and industrial uses, as well as intensified landuse competition. Concurrently, however, it is observable that some "in-between" segments, which are positioned between the industrial and urban zones, likewise constitute a compelling subject for research. Investigating these intermediate spaces in conjunction with the inherent characteristics and design strategies of "in-between" and transitional zones in waterfront urban development, particularly within the expansion typology of IIPCs, represents a dimension that falls outside the scope of this current study. Nevertheless, this could emerge as a highly fruitful and engaging avenue for future scholarly inquiry.
Overall, this research aims to pioneer a cross-scalar methodological blueprint and conceptual framework wherein specific constituent variables can be optimized or substituted. Should subsequent scholarship further refine the analytical outputs at one or more of these individual scales, it would significantly enhance the capacity to guide the selection of strategic redevelopment segments and the formulation of precise spatial design interventions.

Methodological Refinements for Future Research
A core challenge in assessing urban waterfront redevelopment potential lies in the selection and delineation of appropriate spatial units of analysis. Because this study operates within a multi-scalar framework, the selected spatial units are inherently multi-tiered. Commencing with the network of port-cities interconnected by inland navigable waterways, the analysis utilizes the corridor scale as an intermediary port-city nexus, ultimately anchoring its empirical focus at the segment scale. Within this framework, segments are delineated using the RCRISP methodology, bounded by major municipal roadways, railways, and waterways. While this partitioning strategy is conceptually grounded in urban morphology, it exhibits a distinct lack of engagement with institutional governance and property boundaries, a limitation that must be carefully caveated.

The selection of clustering variables for this study involved multiple iterative rounds of investigation, during which numerous novel variables were systematically integrated and subsequently eliminated to determine the final matrix presented in this report. Depending on the specific research objectives, variable selection inherently necessitates an extensive process of trial and error. Furthermore, following the derivation of the clustering results, conducting a correlation analysis among the constituent variables represents a critical methodological step. This analytical procedure not only verifies the absence of multi-collinearity or redundant variables but also uncovers deeper spatial regularities and underlying patterns within these correlations. While existing literature has demonstrated established correlations between landuse patterns and morphological features, I think that this specific interrelation still constitutes a compelling direction for further academic research.

Furthermore, because an unsupervised clustering methodology is employed, the translation and interpretation of the clustering outputs remain inherently subjective. The selection of alternative variables typically yields divergent clustering patterns, and varying the value of k introduces subtle yet distinct shifts in the clustering result. Throughout this iterative process, two key methodological phenomena were observed:

1. Dominant Variables:
Certain variables exercise a disproportionate leverage over the final clustering outcomes. Once included, these dominant metrics inevitably force specific segments into predetermined categories, thereby obscuring more nuanced, latent spatial patterns. A prominent example is the *industrial landuse ratio*. The inclusion of this variable caused virtually all port-adjacent blocks to aggregate into a single homogeneous cluster, undermining the objective of identifying specific segments with high transformative value. Consequently, through iterative testing, such dominant variables were systematically omitted to facilitate the detection of more subtle and valuable morphological patterns.

2. The k-Value Dilemma:
Although data science offers standardized protocols for determining the optimal number of clusters, namely identifying the inflection points or peaks via elbow lines and silhouette scores, empirical urban data often subvert these ideals. In practice, the statistically optimal k value is frequently low, which oversimplifies the classification and compresses valuable morphological nuances out of the visible spectrum. This phenomenon likely stems from the inherently loose and dispersed spatial distribution characteristic of urban morphological datasets. The final k value selected for this study represents a localized statistical optimum that achieves a deliberate harmony between data-driven rigor and urban design legibility. However, reconciling the persistent contradictions between statistical ideals and spatial realities remains a critical frontier for quantitative urban analytics.

Finally, this study does not establish an external control sample or a benchmarking "paradigm collection" during clustering. Consequently, the attributes of all analyzed segments are evaluated strictly relative to one another within the specific context of Dutch IIPCs. In the domain of urban renewal research, this intra-contextual comparison can introduce methodological vulnerability, as it fails to explicitly define what constitutes an idealized urban fabric or optimal spatial quality.

During the subsequent assessment phase, individual segments are benchmarked exclusively against their respective cluster centroids to identify indices requiring amplification or reduction. This approach, however, does not imply that the centroid represents an urban ideal; certain indices may need to be substantially higher to foster a truly vibrant and habitable urban environment. The absence of an external, normative spatial paradigm is a recognized limitation that future research should seek to rectify.

3. Scalability, Reproducibility, and Automation
Scalability and reproducibility constitute core methodological objectives of this research. To ensure that the findings can be replicated and successfully applied to analogous urban waterfront contexts globally, the study prioritizes standardized, algorithmic workflows for data processing.

In practice, however, heterogeneous data quality necessitated manual interventions to ensure analytical fidelity, particularly during the segment delineation phase. Due to inconsistencies in the precision of underlying geospatial datasets (e.g., roads, railways, and waterways), certain segment boundaries required manual adjustments. This human intervention inevitably introduces a degree of subjectivity; specific segments would be assigned to entirely different typologies if partitioned using alternative configurations. While a subset of segments in the final classification reflects these subjectively adjusted delineations, the vast majority were processed via automated workflows, thereby preserving a high degree of systemic reproducibility.

Lastly, because the empirical scope of this study is restricted to Dutch IIPCs, the case cities possess an inherent baseline similarity in their historical and spatial morphology. When clustered collectively, they successfully reveal subtle variations within a shared typological framework, providing a comparative foundation upon which transformation potential can be theorized. Should this methodology be exported to geographically diverse regions, or applied to highly heterogeneous cities simultaneously, the morphological variances would be substantially more pronounced. Consequently, the analytical matrix of variables would need to be re-evaluated and adapted to accommodate greater cross-regional spatial diversity.

6. Conclusion

This study establishes a cross-scale methodological framework to bridge the gap between data-informed research approaches and traditional urban design. From the perspective of urban morphology, both qualitative and quantitative analyses are conducted across three hierarchical scales. The primary objective is to derive actionable strategies capable of guiding specific urban design interventions, thereby providing systematic recommendations for the waterfront spatial regeneration of IIPCs in the post-expansion era.

At the level of context, this research focuses on the network scale, examining thirty major IIPCs situated along the inland waterway network that connects the Port of Rotterdam with key industrial hinterlands in Northwest Europe. Spatial expansion capacity, alongside economic and social datasets for these cities, was compiled and processed using the K-prototypes unsupervised clustering algorithm. Consequently, the cities were categorized into three distinct trajectories: expansion, consolidation, and shrinkage. Integrating these typologies with the Anyport model offers distinct projections for the future developmental paths of these cities. By mapping these cluster results onto the regional network, this study examines the long-term impacts of these anticipated trends on industrial clusters, ensuring that such projections contribute to the formation of a decentralized and resilient IIPC network.

The level of focus is bifurcated into the corridor scale and the segment scale; the former investigates the developmental possibilities exhibited by IIPCs within the broader urban structure, while the latter scrutinizes how the urban morphological identity of individual segments influences the potential for waterfront regeneration. At the corridor scale, landuse analysis reveals three distinct spatial configuration patterns with substantial transformation potential. By synthesizing these three patterns with the developmental projections derived from the network scale, the initial layer of transformation potential is established: potential based on development model.

At the segment scale, grounded in the quantitative urban morphology of the Conzenian school, six morphological variables were selected. The K-means clustering algorithm was then deployed to classify 500 spatial segments across the thirty cities, yielding five distinct urban morphological identities. Two of these clusters demonstrate a high degree of relevance to this study, exhibiting pronounced potential for waterfront development. Subsequently, the segments belonging to these two clusters were evaluated through an assessment framework comprising a landuse assessment and an urban performance index. This step aims to identify critical “imbalances”, areas where specific metrics fall significantly below the baseline average, thereby generating targeted design strategies and successfully operationalizing the transition from data-informed analysis to concrete urban design guidance.

Finally, at the level of details, the aforementioned transformation potentials, derived from both the development models and urban morphological imbalances, are translated into specific design strategies centering on connectivity and intensity. Incorporating site specificity which is translated into interface, these strategies are empirically validated through the urban design of three specific sites.

The principal contribution of this research lies in its pioneering attempt to construct a cross-scale framework that harmonizes quantitative analysis with traditional design methodologies. Looking forward, the variables and numerical thresholds utilized within this framework remain open to further optimization. Furthermore, the specific algorithms and variable selections can be flexibly adapted or substituted to address diverse design agendas and research questions.

7. Reflection

The most compelling aspect of this research lies in the endeavor to deploy quantitative methodologies to investigate urban phenomena and guide spatial design, culminating in the formulation of a comprehensive methodological framework, a paradigm I had not previously attempted. This kind of passion comes from my thinking on the reality that more and more computational tools and new technologies are entering this field. It is high time that we started to positively embrace them in the researches and studies in urbanism.

This thesis is anchored in a multi-scalar framework, fulfilling a long-standing academic ambition. Throughout the preceding quarters of my curriculum, I frequently observed that urban planning and spatial design operate as interconnected processes across multiple scales. Consequently, I aspired to materialize these cross-scalar dynamics within my final graduation project. Admittedly, upon transitioning into the detailed design phase, I began to scrutinize the rigidity of this hierarchy. One might reasonably question whether a definitive, causal link truly exists between the cross-section of a waterfront pathway and the macro-structural industrial shifts within the Province of North Brabant. Nonetheless, the research trajectory has yielded a meaningful framework. The strength of this multi-scalar blueprint rests in its modularity; while individual parameters and variables can be optimized or substituted, the overarching framework provides a robust reference for formulating analogous urban design strategies. Furthermore, conducting quantitative research at the regional scale initially felt like venturing into an entirely foreign academic discipline. Consequently, this macro-level analysis was intentionally simplified in this study, though I think that it remains a critical dimension for holistic urban planning.

The selection of variables for the k-means clustering algorithm undoubtedly proved to be the most protracted and experimental phase of this research. At times, the iterative process felt akin to an alchemist brewing potions, introducing an array of seemingly relevant variables into the chaotic crucible of the algorithm, while hoping the final clustering output would yield a meaningful narrative. My proficiency in this "Potions" felt as clumsy as Neville Longbottom's, a reality evidenced by a hard drive populated with countless abortive clustering results. Segments subjectively identified as possessing immense transformation potential would stubbornly coalesce with unremarkable, homogeneous clusters. Anticipated combinations of variables rarely manifested in the outputs; instead, a dominant few would heavy-handedly dictate the clustering result, while other variables, introduced to infuse nuance into the analysis, consistently emerged as statistically insignificant with negligible contributions in the Principal Component Analysis. Ultimately, I learned to navigate these constraints through strategic compromises, largely dictated by the temporal limitations of the thesis timeline. While the final clustering result may not represent a perfectly sharp or intuitively elegant outcome, it was through the systematic calibration of the methodological framework that actionable design guidelines were eventually derived.

Furthermore, the variable selection process was deeply intertwined with the iterative loop between research and design. Initially, more generic variables were selected based on a broad, fundamental understanding of urban morphology. However, as the clustering results and typologies were applied to concrete design scenarios, more specific and detailed variables were introduced. The intention was to generate typologies directly reflecting these specific spatial performances through clustering, thereby directly informing the design strategies. Nevertheless, it soon became evident that mixing these hyper-specific performance variables with more generic morphological parameters yielded sub-optimal clustering outcomes. Consequently, a balanced compromise was adopted: variables summarizing the core morphological identity were selected for the clustering phase, whereas the more detailed indicators of spatial performance were integrated into the subsequent assessment framework.

Throughout this process, I found myself in a state of continuous critical reflection regarding how “potential”, which I intuitively recognized as a designer, could be rigorously quantified and defined. This remains an open inquiry requiring further intellectual maturity. In an era where new computational technologies and data-driven methods increasingly permeate the discipline, I contend that the designer’s intuition and spatial judgment remain indispensable. Indeed, it is precisely this creative intuition that steers advanced technologies towards generating meaningful and context-sensitive design interventions.

Ultimately, unsupervised clustering represents merely the tip of the data analytics iceberg. The intersection of quantitative methodologies and urban studies offers vast, uncharted territory for exploration, though the synthesis will rarely be seamless or straightforward. Moving forward, I aspire to continually learn, experiment, and refine the methodologies required to render this disciplinary hybridization truly organic and valuable.

8. Reference

Aouissi, K., Madani, S., Hein, C., & Benacer, H. (2023). Morphological approach for the typological classification of waterfront revitalization. Journal of the Geographical Institute Jovan Cvijic, SASA, 73(1), 109–122. https://doi.org/10.2298/IJGI2301109A

Bird, J. H. (1963). The major seaports of the United Kingdom. Hutchinson.

Centraal Bureau voor de Statistiek. (2025, November). Binnenhavengemeentes in Nederland naar type haven, 2023-2024. https://www.cbs.nl/nl-nl/maatwerk/2025/46/binnenhavengemeentes-in-nederland-naar-type-haven-2023-2024

Chalmers University of Technology, Sweden, Berghauser Pont, M., Haupt, P., & Delft University of Technology. (2023). Spacematrix: Space, Density and Urban Form (revised). TU Delft OPEN Publishing. https://doi.org/10.59490/mg.38

De Koning, R. E., Van Nes, A., Ye, Y., & Roald, H. J. (2017). Strategies for integrated densification with urban qualities: Combining Space Syntax with building density, land usage, public transport and property rights in Bergen city. In Proceedings of the 11th International Space Syntax Symposium (SSS2017) (pp. 56.1-56.17). Instituto Superior Técnico.

De Martino, P., Hein, C., Harteveld, M., & Forgaci, C. (2023). Designing Public Spaces for Maritime Mindsets: Rotterdam as Case Study. PORTUSplus, 16. https://portusplus.org/index.php/pp/article/view/295

European Commission. (2021). NAIADES III action plan on inland waterway transport: Boosting future-proof European inland waterway transport. Directorate-General for Mobility and Transport. https://transport.ec.europa.eu/transport-modes/inland-waterways/promotion-inland-waterway-transport/naiades-iii-action-plan_en

Fleischmann, M., Romice, O., & Porta, S. (2021). Measuring urban form: Overcoming terminological inconsistencies for a quantitative and comprehensive morphologic analysis of cities. Environment and Planning B: Urban Analytics and City Science, 48(8), 2133–2150. https://doi.org/10.1177/2399808320910444

Forgaci, C. (2018). A+BE | Architecture and the Built Environment, No. 31 (2018): Integrated Urban River Corridors [Delft University of Technology]. https://doi.org/10.7480/ABE.2018.31

Forgaci, C., & Nattino, F. (2025). rcrisp: Automate the Delineation of Urban River Spaces [Computer software]. Zenodo. https://doi.org/10.5281/zenodo.15793526

Gallagher, R., Sigler, T., & Liu, Y. (2023). How path dependent urban morphology restricts the effectiveness of rezoning for urban consolidation: Lessons from Brisbane, Australia. Journal of Urban Affairs, 1–21. https://doi.org/10.1080/07352166.2023.2211770

Gehl, J. (2001). Life between buildings: Using public space. The Danish Architectural Press.

Government of the Netherlands. (n.d.). Inland shipping. https://www.government.nl/topics/freight-transportation/inland-shipping

Harteveld, M. G. A. D. (2021a). The Port-City Portrayed in its Public Spaces: Introducing Micro Biographies of

Places. PORTUSplus, 11(11). https://portusplus.org/index.php/pp/article/view/235

Harteveld, M. G. A. D. (2021b). In the Minds of People: Port-City Perspectives, The Case of Rotterdam. European Journal of Creative Practices in Cities and Landscapes (CPCL), 4(2), 60-81. https://doi.org/10.6092/issn.2612-0496/12380

Hein, C. (2019). The Port Cityscape: Spatial and institutional approaches to port city relationships. PORTUSplus, 8(Special Issue). https://portusplus.org/index.php/pp/article/view/190

Hein, C. (2021). Port City Porosity: Boundaries, Flows, and Territories. Urban Planning, 6(3), 1–9. https://doi.org/10.17645/up.v6i3.4663

Hein, C. (2023). Re-centering the Port in the Port City Territory. PORTUSplus, 16. https://portusplus.org/index.php/pp/article/view/289

Huang, L. S., Han, Y., & Ye, Y. (2022). Coastal Waterfront Vibrancy: An Exploration from the Perspective of Quantitative Urban Morphology. Buildings, 12(10), 1585. https://doi.org/10.3390/buildings12101585

Huang, S., & Zheng, H. (2022). Morphological Regeneration of the Industrial Waterfront Based on Machine Learning. 475–484. https://doi.org/10.52842/conf.caadria.2022.1.475

Jacobs, J. (1961). The death and life of great American cities. Random House.

Jansen, M., & Hein, C. (2023). Port city symbiosis: introduction to the special issue. Maritime Economics and Logistics, 25(2), 211-229. https://doi.org/10.1057/s41278-023-00257-x

Kadaster. (2024). Basisregistratie Adressen en Gebouwen (BAG) [Data set]. Publieke Dienstverlening Op de Kaart (PDOK). https://www.pdok.nl/introductie/-/article/basisregistratie-adressen-en-gebouwen-bag-

Kadaster. (2025). Bodemgebruik - Land Cover (INSPIRE geharmoniseerd) [Data set]. PDOK. https://www.pdok.nl/introductie/-/article/bodemgebruik-inspire-geharmoniseerd-

Ministry of Infrastructure and Water Management (IenW). (2024). Begroting Infrastructuur en Waterstaat – Scheepvaart en havens [Parliamentary document]. Tweede Kamer der Staten-Generaal. https://zoek.officielebekendmakingen.nl

Ministry of the Environment, Nature Conservation and Transport of North Rhine-Westphalia, Ministry of Infrastructure and Water Management (Netherlands), & French partner authorities. (2023). Joint declaration: Perspective for sustainable Rhine navigation 2030 (Gemeinsame Absichtserklärung Perspektive nachhaltige Rheinschifffahrt 2030). https://www.umwelt.nrw.de/system/files/media/document/file/absichtserklarung-perspektive-nachhaltige-rheinschifffahrt-2030-de-nl-fr-ohne-unterschriften.pdf

Notteboom, T. (2026). Chapter 2.1 – Port hinterlands, regionalization and corridors. Port Economics, Management and Policy. https://porteconomicsmanagement.org/pemp/contents/part2/port-hinterlands-regionalization/

Oliveira, V. (2016). Urban morphology: An introduction to the study of the physical form of cities. Springer. https://doi.org/10.1007/978-3-319-32039-7

PBL Netherlands Environmental Assessment Agency, & TNO. (2025). Klimaatneutrale binnenvaart in 2050: Technologie, beleid en infrastructuur. https://www.pbl.nl/publicaties/klimaatneutrale-binnenvaart-in-2050

Pinto, P. J., & Kondolf, G. M. (2020). The Fit of Urban Waterfront Interventions: Matters of Size, Money and Function. Sustainability, 12(10), 4079. https://doi.org/10.3390/su12104079

Port of Rotterdam Authority. (2022). Port Vision 2050: Together towards a competitive, sustainable and resilient port. https://www.portofrotterdam.com/en/port-future/port-vision-2050

Port of Rotterdam Authority. (2023). Port of Rotterdam annual report 2023: Highlights. https://reporting.portofrotterdam.com

Port of Rotterdam Authority. (2024). Testing digital sea and inland port networking has commenced [Press release]. https://www.portofrotterdam.com/en/news-and-press-releases/testing-digital-sea-and-inland-port-networking-has-commenced

Prominski, M. (2012). River, space, design : planning strategies, methods and projects for urban rivers. Birkhäuser. https://doi.org/10.1515/9783034611732

Rijksdienst voor Ondernemend Nederland (RVO). (2024). Informatiesysteem Bedrijventerreinen (IBIS) [Data set]. Rijksdienst voor Ondernemend Nederland. https://www.rvo.nl/onderwerpen/ruimte-en-infrastructuur/bedrijventerreinen/ibis

Schirmer, P. M., & Axhausen, K. W. (2019). A Multiscale Clustering of the Urban Morphology for Use in Quantitative Models. In L. D'Acci (Ed.), The Mathematics of Urban Morphology (pp. 355–382). Springer International Publishing. https://doi.org/10.1007/978-3-030-12381-9_16

Turner, M.G., & Gardner, R.H. (2015). Landscape Ecology in Theory and Practice: Pattern and Process. New York: Springer.

Van Den Berghe, K., Louw, E., Pliakis, F., & Daamen, T. (2023). When "port-out – city-in" becomes a strategy: Is the port–city interface conflict in Amsterdam an observation or a self-fulfilling prophecy? Maritime Economics & Logistics, 25(2), 330–350. https://doi.org/10.1057/s41278-022-00236-8

van Nes, A. (2018). The explanatory power of Space Syntax and Urban Morphology. 181-181. Abstract from ISUF 2018: 25th International Conference on Urban Form , Krasnoyarsk, Serbia.

Witte, P., Wiegmans, B., & Louw, E. (2025). More claims than land: Multi-facetted land use challenges in the port-city interface. Journal of Transport Geography, 124, Article 104181. https://doi.org/10.1016/j.jtrangeo.2025.104181

Whitehand, J. W. R. (2001). British urban morphology: The Conzenian tradition. Urban Morphology, 5(2), 103–109. https://doi.org/10.51347/jum.v5i2.3896

Wu, X., & Li, X. (2025). Multi-Source Data-Driven Quality Assessment of Waterfront Public Spaces in Urban Contexts. Land, 14(2), 231. https://doi.org/10.3390/land14020231

Ye, Y., & Nes, A. V. N. (2014). Quantitative tools in urban morphology: Combining space syntax, spacematrix and mixed-use index in a GIS framework. Urban Morphology, 18(2), 97–118. https://doi.org/10.51347/jum.v18i2.3997

Ye, Y., Yeh, A., Zhuang, Y., Van Nes, A., & Liu, J. (2017). "Form Syntax" as a contribution to geodesign: A morphological tool for urbanity-making in urban design. URBAN DESIGN International, 22(1), 73–90. https://doi.org/10.1057/s41289-016-0035-3

9. Appendices

Fig. 67, Satellite image of dutch IIPCs

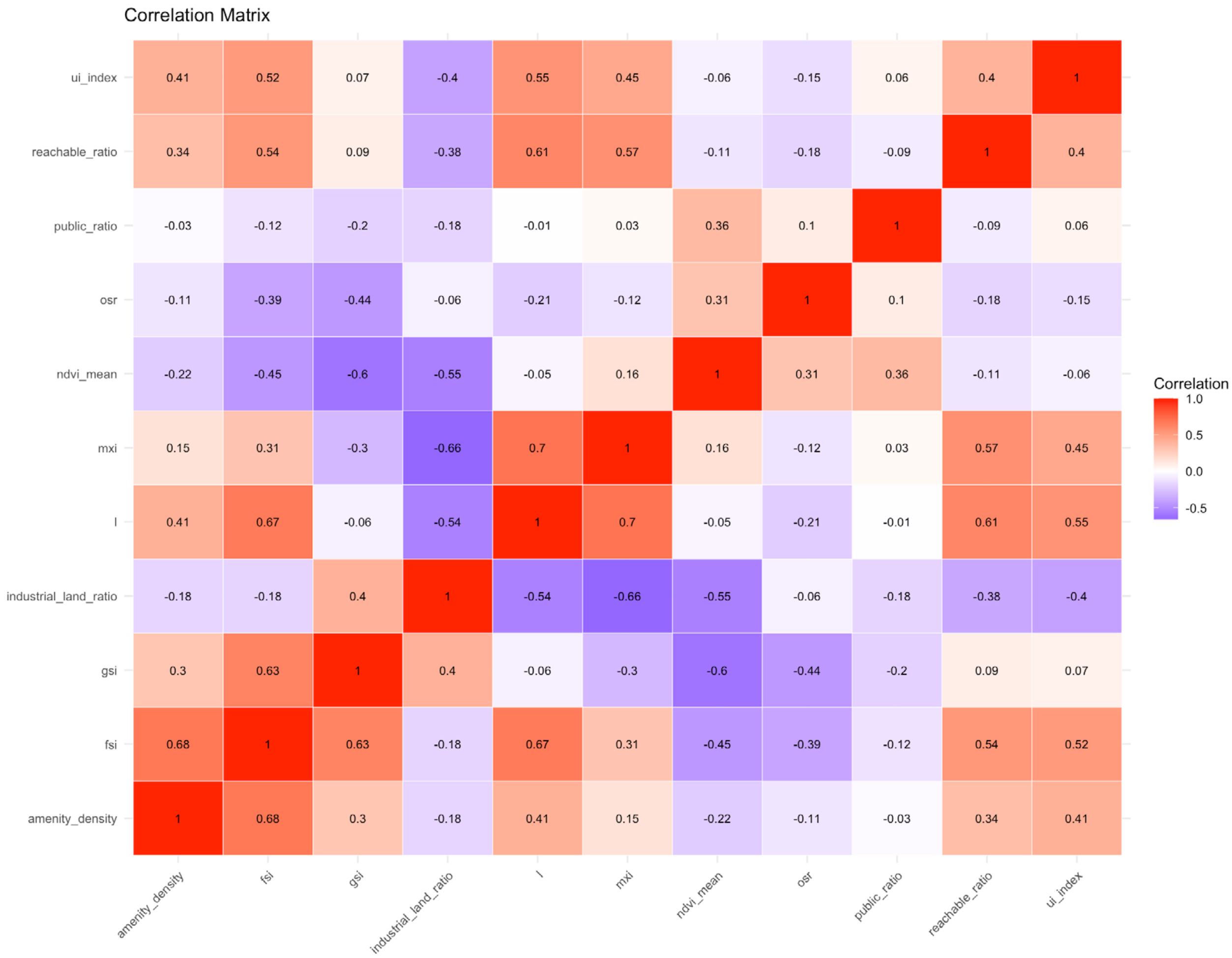


Fig. 68, Correlation matrix of variables

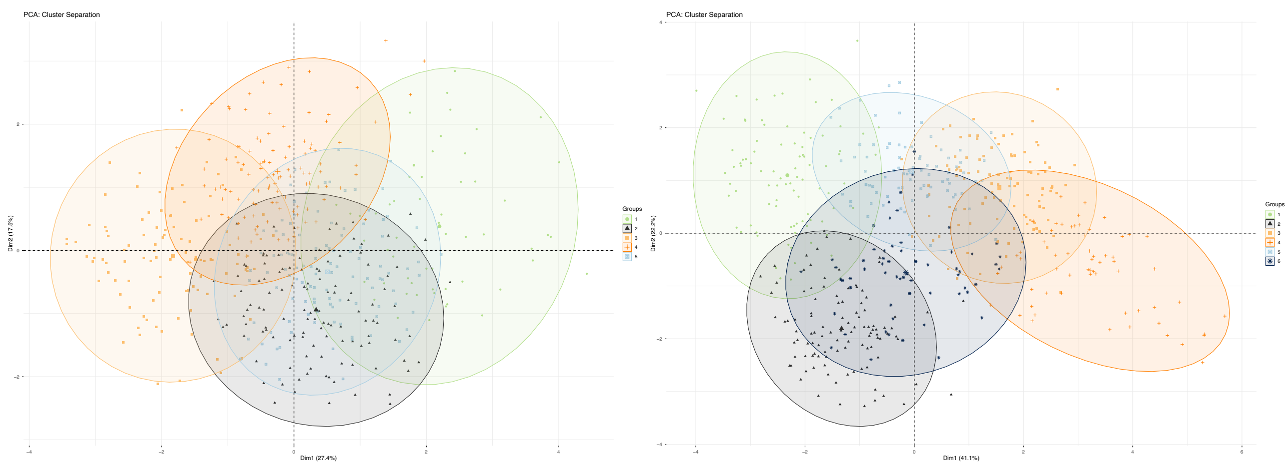


Fig. 69, Clustering results of past experiments