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Veröffentlichungsversion / Published Version

Zeitschriftenartikel / journal article

Empfohlene Zitierung / Suggested Citation:

Alsavada, M. O., & Karimi, K. (2023). The Spatio-Functional Role of Navigable Urban Canals in the City: Cases From London and Amsterdam. *Urban Planning*, 8(3), 438-454. <https://doi.org/10.17645/up.v8i3.6740>

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Article

The Spatio-Functional Role of Navigable Urban Canals in the City: Cases From London and Amsterdam

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Submitted: 29 January 2023 | Accepted: 22 May 2023 | Published: 26 September 2023

Abstract

Cities incorporating navigable canals have played a crucial role in global trade and provided a platform for a range of activities for people from various locations. This research aims to comprehend the role of inner-city canals, formed as branches of shipping canals, in the spatial accessibility and functional structure of two contemporary urban systems: London and Amsterdam. Both cities are major post-industrial hubs in Europe and their spatial development and socioeconomic conditions have been greatly influenced by waterways. While the canal network in Amsterdam was planned alongside street layout planning in the early 17th century, serving commercial purposes, canals were integrated into London's pre-existing urban form mainly for transportation in the 19th century. The current situation in these cities is impacted by this disparity in three ways: (a) the potential use of canals in the urban transportation system; (b) the spatial accessibility of street networks; and (c) the correlations between street accessibility and land use patterns in canal neighbourhoods. The research employs analytical methods of space syntax, geographic information systems, and statistical techniques to create and apply integrated urban models, incorporating spatial network measures, retail density, and functional diversity for street segments, to compare various urban conditions. The research reveals the crucial finding that the incorporation of canals into the street system leads to a substantial increase in the mean values of street network accessibility in Amsterdam. Additionally, the study highlights the vital contribution of diagonal streets linked with canal networks towards retail density in this city. In contrast, the accessibility measures and spatial patterns of urban functions in London are predominantly influenced by proximity to canals.

Keywords

data-driven urbanism; navigable canals; space syntax; urban functions; waterways

Issue

This article is part of the issue “Shipping Canals in Transition: Rethinking Spatial, Economic, and Environmental Dimensions From Sea to Hinterland” edited by Carola Hein (Delft University of Technology), Sabine Luning (Leiden University), Han Meyer (Delft University of Technology), Stephen J. Ramos (University of Georgia), and Paul van de Laar (Erasmus University Rotterdam).

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1. Introduction

Urbanisation processes, occurring in cities worldwide, highlight the spatial culture and lifestyle patterns of residents. This necessitates data analysis in urban research and academia to support decision-making in design processes. The physical form and structure of cities have various impacts, including environmental consequences like greenhouse gas emissions and thermal comfort, economic effects such as high taxes, public service expendi-

tures, and property values, as well as social and political issues like inequality and segregation. Therefore, urban morphology—the field of urban studies concerned with the physical characteristics, temporal dynamics, and their interactions with non-spatial factors—provides a reliable foundation for quantitative analysis of the urban environment. Cities are the epicentre of political, economic, and social activities, intricate entities woven together by people, activities, and spaces. They also reflect geography, commerce, culture, and society.

Shipping canals and their branches, as navigable urban canals, have played a significant role in shaping street layouts, activity patterns, and the creation of sedentary settlements. Water influences the functionality and aesthetic quality of cities, giving rise to distinct patterns of urban structures. While there is considerable research utilising quantitative methods to assess urban performance from the perspective of street layout (Hillier, 2007; Hillier & Iida, 2005; Omer & Kaplan, 2019), density patterns (Berghauer Pont & Haupt, 2021; van Nes et al., 2012), sustainability and resilience (Felicetti et al., 2016; Lai et al., 2018), urban sprawl (Gielen et al., 2018; Thomas et al., 2010), and urban growth patterns (Al-Sayed et al., 2009; Dhanani, 2016; Griffiths, 2009, 2012), there is a limited focus on issues specifically related to canals and their role in urban planning and design decisions.

The narrative surrounding waterways often portrays them as victims of urbanisation, their natural cycles disrupted to the point where their existence is threatened (Biscaya & Elkadi, 2021; Palanisamy & Chui, 2015). However, recent studies have challenged this perspective, highlighting the coevolutionary relationship between cities and waterways, characterised by reciprocal interactions throughout history (Knoll et al., 2017). While numerous studies have explored this relationship in the context of rivers (Everard & Moggridge, 2012; Knoll et al., 2017), there is a lack of research on canals and their impact on the surrounding built environment.

This research aims to investigate the reciprocal dependency between canal phenomena and urban morphology by examining how canal structures impact the relationship between the built form and socioeconomic activity patterns in Amsterdam and London, two cities with distinct canal structure–city relationship paradigms. The primary research question is how the spatial function varies between these cases. Our literature review focuses on studies related to waterways and canals, as well as quantitative techniques for investigating the spatial configuration of cities in relation to canal neighbourhoods or canal-side settlements. Given the complexity of canal phenomena, this research views canals as systems of city networks. The third section of the article describes the main methods and tools used to address the problems discussed in the previous section.

The study utilises an analytical framework to assess the performance of urban forms in terms of their potential to shape the movement of inhabitants and distribution of functions. Amsterdam and London have different waterway–street layout relationships: Amsterdam has a compact grid city form designed around its canal structure, while London can be considered a naturally grown city. Various historical and practical factors have influenced the growth and development of these cities. In the predominantly water-dominated mainland, Read (1999) defines the design of Amsterdam as a necessary product of water engineering and top-down planning. Water engineering has, therefore, artificially influenced how

Amsterdam appears today in terms of the arrangement of its parts, the edges, and the clarity of the whole (Read, 1999). Due to this circumstance, urban growth has not generally been as organic as London's progressive infilling of areas on the margins of its villages/towns caused by linear movement (Hillier & Vaughan, 2007).

This research aims to demonstrate how the spatial structures of these two post-industrial cities can affect the integration of canals, spatial accessibility, and socioeconomic activities of canal-side neighbourhoods. The study focuses on the neighbourhoods of Grachtengordel in Amsterdam and Regent's Canalside arm from Camden Lock to York Way in London. These two canal districts are notable examples of enduring urban development in Europe during the early modern period, with a unique combination of street and canal layout and functionality of the canal-side. What makes them particularly compelling as case studies in enduring urban development is the fact that they have been preserved for well over 250 years in cities that have experienced highly dense urban development processes as post-industrial cities. Unlike other historic canal districts, such as Venice or Bruges, which function as open-air museums and are extensively studied, Grachtengordel and Regent's Canalside arm have demonstrated remarkable adaptability and resilience over time, even in the face of new challenges. During their construction, both areas were in close proximity to the economic functions of their respective city cores, with the Regent's Canal and Grachtengordel designed to serve the needs of residential and industrial activities. Today, they serve as excellent examples of long-term urban architecture and resilience. Therefore, this article aims to conduct a data-driven advanced analysis of the spatial characteristics, including accessibility, density, and diversity of functions, affected by inner-urban canals and how these patterns are influenced by the relationship between canal-city structures.

While the focus of this study is on London and Amsterdam, the analytical approach used to assess urban performance can have a significant impact on the future development of cities worldwide, particularly when it comes to analysing cities with canals. Geographic information systems (GIS) are increasingly used to merge socioeconomic data and facilitate urban studies. This research applies a network-based accessibility analysis of space syntax, using GIS to create an integrated urban model that incorporates space syntax measures, retail density, and functional diversity on each street segment. Statistical analyses are then performed to compare the results of the analysis in London and Amsterdam and to investigate the correlations between street accessibility, density, and diversity of functions in each city.

The results demonstrate that canals play a crucial role in urban functionality, as evidenced by the analysis of street accessibility, retail density, and functional diversity. In Amsterdam, the geometric interaction between the street and canal networks has a clear influence on

the distribution of activities. In contrast, London's functional distribution varies depending on the distance from the Regent's Canal. This study's methodology can effectively enhance urban planning and design processes and can be applied at specific stages of a design process. As Karimi (2012, 2018) explained, these advanced spatial analysis tools, space syntax methods, and configurational approaches can provide improved design solutions at specific stages of project implementation by investigating a selected number of projects.

2. Theoretical Background

2.1. Canals in Urban Studies

Numerous intra-city canals and canal-side areas have been extensively studied in the fields of ecology (Biscaya & Elkadi, 2021), landscape and restoration (Button & Pearce, 1989; Palanisamy & Chui, 2015), health and well-being (Vaeztavakoli et al., 2018), as well as the regeneration and transformation of canal-side areas (Buckman, 2016), to create sustainable urban spaces that seamlessly connect the city environment with its waterways. To mitigate the adverse effects of urbanisation on canal systems, there has been a growing body of literature focusing on the restoration and revitalisation of lost waterways (canals, rivers, etc.). These efforts seek to restore the ecological balance, conserve regional biodiversity, enhance cultural value, and ensure the proper functioning of canal ecosystems as blue corridors (Biscaya & Elkadi, 2021).

Also, the decline of canal-side areas and the loss of the global economic fortune of the canals in post-industrial cities and towns have created new opportunities for regeneration, and numerous studies have examined the effects of waterside regeneration initiatives on urban landscape development (Cabau et al., 2021; Fageir et al., 2021; Ponzini & Akhavan, 2020). Studies of various waterfront initiatives have all reached a similar conclusion that they have transformed the character of cities and increased pedestrian activity, cultural facilities, and functional diversity (Ponzini & Akhavan, 2020). On the other hand, gentrification has impacted some of these regeneration initiatives. For instance, Edwards (2009) evaluates the King's Cross Regent's Canalside regeneration project as a corporate activity aimed at expansion and competitiveness and susceptible to gentrification, which has led to increased rent levels in its borough.

Finally, studies on physical activity, well-being, and health have also explored the role of canals. Research investigating the impact of natural settings on human health has found that being near water promotes a variety of physical activities, positively affects overall annual health, and reduces the risk of developing illnesses such as diabetes, particularly in communities with an ample presence of blue spaces (Vaeztavakoli et al., 2018; Vert et al., 2019).

2.2. Quantitative Approaches in Urban Studies and Space Syntax

Studies on the quantitative analysis of urban form can be categorised into three primary research goals: measuring urban performance, enabling comparisons between different case areas, and analysing urban growth using analytical tools (Fleischmann et al., 2021). Studies measuring urban performance focus on specific aspects of urban form, including network-based accessibility (Hillier, 2007; Hillier & Iida, 2005; Krizek, 2003; Omer & Kaplan, 2019), density (Berghauer Pont & Haupt, 2021; van Nes et al., 2012), economy (Shen & Karimi, 2017; Solis et al., 2022), sustainability (Haggag & Ayad, 2002; Lai et al., 2018), and resilience (Feliciotti et al., 2016; Marcus & Colding, 2014). In network-based accessibility studies, space syntax theory asserts that the configuration of the street network significantly influences movement patterns (Hillier et al., 1987; Hillier & Hanson, 1984). Hillier and Hanson (1984) introduced the concept of axial lines, representing the longest straight lines that denote the maximum extension of a point in space. Another method derived from the road centreline transport network is segment analysis, which involves topological, angular, and metric analyses (Hillier, 2007; Hillier & Iida, 2005). The metric integration measure determines the proximity of one segment to all others based on the metric distance, which is the distance between the mid-points of two adjacent segments along the lines. The metric choice measure counts the frequency of each segment appearing on the shortest path between all pairs of segment analyses within a given metric distance (Hillier, 2009). On the other hand, the angular choice measure considers the straightest route as the one with the least angular variation. Angular integration analysis calculates the proximity of each segment to others based on the total number of angular changes made along each route. The reciprocal of the normalised angular total depth represents the measure of normalised angular integration, allowing for comparisons between different systems (Hillier & Iida, 2005).

In terms of space syntax studies focusing on cities dominated by canals, Read (1999) examines the spatial configuration of Dutch cities, including Amsterdam, Den Haag, Haarlem, Alkmaar, and Zaanstad. The studies explore the nature of spatial-functional relationships in these cities. The main finding is that urban development often involves the transformation of unused or abandoned industrial or agricultural land into liveable settings through water engineering. This process entails creating a spatial pattern from scratch rather than inserting a pattern into an existing urban spatial structure (Read, 1999). Furthermore, Psarra (2018) investigates the island communities of Venice and their pedestrian and combined system of routes using space syntax methods. The main analysis suggests that navigation on a large scale is easier through canals than streets within these island communities. Psarra (2018) evaluates the structure of Venice

within the concept of a generic city. In theory, a generic city consists of a foreground network of interconnected centres at various scales, embedded in a background network of residential areas (Hillier, 2001, 2007). Comparing the space syntax analysis of the street network and the combined network of streets and canals in Venice, it becomes evident that the canal system is stronger in terms of the background network than the foreground network (Psarra, 2018).

To conclude, the main theoretical framework of this study aims to provide insights into the relationship between canal structure, the morphological characteristics of cities, and the analytical tools used to measure these attributes. While canal structures have been studied in various contexts, including landscape, ecology, health and well-being, restoration, urban transformation, and regeneration, the intersection of canal structures with urban form, spatial configuration, and land use has not been extensively explored using analytical methods and tools. This research aims to fill this gap by focusing on canal phenomena at the neighbourhood scale. With advancements in computational power and the availability of comprehensive spatial and socioeconomic datasets, it is now feasible to conduct configurational analyses that can address multiple issues, such as built form, street and canal arrangements, and land use types. In this research, we situate ourselves within this context and employ an analytical approach for morpho-

logical and socioeconomic analyses. The following section introduces the primary methods and tools used in this research to accomplish these objectives.

3. Methodology and Datasets

The areas of study are Regent’s Canalside arm from Camden Lock to York Way in London and Grachtengordel in Amsterdam (see Figure 1). The main reason for selecting these areas is that both have historical significance in Europe in terms of scale, mixed-use development, ecological principles, and architectural aesthetics, with their well-preserved historic buildings. The importance of preserving both areas has been recognised by the heritage departments of both countries. The preservation and transformation projects in these areas address similar fundamental issues in strategies and policies for the future, which emphasise the historical origins and contemporary challenges of urban canals (King’s Cross, 2020; Nijman, 2020).

The study consists of two main stages. The first stage focuses on examining the movement potential of Grachtengordel and Regent’s Canalside. The second stage involves analysing building and socioeconomic data to assess the impact of the canal and canal-side spatial characteristics on land use distribution and economic activity. This stage considers three key aspects: land use distribution, retail density, and land use diversity.



Figure 1. Case study areas.

To analyse the spatial configuration, a space syntax approach is employed, and an integrated urban model is developed by combining various datasets, including building form and land use types, with the street network. Space syntax involves measuring distance using three different metrics: metrical, topological, and geometrical distance (Hillier & Iida, 2005). The research utilises readily available data from the Netherlands and the UK, allowing for the layering of these different datasets. The network's spatial configurations are represented as segment line models, derived from the road centreline Ordnance Survey MasterMap Integrated Transport Network for London and Nationaal Wegenbestand for Amsterdam. Building footprint data is obtained from the OpenStreetMap source, while land use type data are sourced from Colouring London and the Data Amsterdam Website as of July 2020 (see Table 1).

In the second stage, the study examines land use distribution to investigate the economic activities surrounding the canals. The results of the syntactic analysis are then subjected to statistical analysis in conjunction with retail density to determine whether network accessibility correlates with economic activities. Finally, the study explores the influence of canals on land use diversity to determine if canal structures contribute to creating a mixed-use environment in contemporary cities.

For the analysis of spatial configuration, the primary measures of street network accessibility are the segment angular integration (Equation 1) and choice (Equation 2) values in space syntax. The case study areas encompass a city-wide scale and consist of a 5 km round circular spatial model centred on a focal point within each city's canal networks. This model includes a 2.5 km contextual area and a 2.5 km buffer area to avoid edge effects. As mentioned earlier, the street segment models for London and Amsterdam (Berghauser Pont et al., 2017) are derived from the road centreline maps, specifically the Ordnance Survey MasterMap Integrated Transport Network for London and the Nationaal Wegenbestand

for Amsterdam. The Space Syntax Toolkit for GIS (Gil et al., 2015) is utilised to calculate the segment angular integration and choice measures (Hillier & Iida, 2005; Hillier et al., 2012; Turner, 2001).

$$INT_{(i,r)} = \frac{(N_i - 1)}{\sum_{j=1}^j Dep_{(i,j)}}, \{dis_{(i,j)} \leq r\} \quad (1)$$

In this equation, $INT_{(i,r)}$ is the segment angular integration value at the radius r is demonstrated as the reciprocal of the mean angular depth from segment i to all reachable street segments j within a zone defined by a radius r .

$$CHO_{(i,r)} = \sum_{k=1}^K n_{jk}, \{dis_{(i,j)} \leq r; dis_{(i,k)} \leq r\} \quad (2)$$

In this equation, $CHO_{(i,r)}$ represents the segment angular choice value, which is similar to the concept of betweenness in graph analysis. It measures the number of times the targeted segment i has been traversed in the angular shortest paths from segment j to segment k within a reachable area defined by a radius r .

Hillier et al. (2012) propose a normalisation procedure for the angular weighted graph distance, taking into account the balance between the urban system's tendency to optimise travel distance between all origins and destinations and the potential cost of segregation due to system size. This normalisation procedure facilitates comparisons across different scales within a city or between cities.

According to Hillier et al. (2012), normalised angular integration $NAIN_{(\theta)}$ for a graph G' of size n is defined as follows:

$$NAIN_{(\theta)} = \frac{(n + 2)^{1.2}}{\left(\sum_{i=1}^j d_{(\theta)}(x, i)\right)} \quad (3)$$

Where d_{θ} is the length of a geodesic (shortest path) between vertex x and i .

Table 1. Datasets of the research taken.

Datasets	London	Amsterdam
Street segments	Road centerline map from Ordnance Survey MasterMap ITN Source: https://www.ordnancesurvey.co.uk	Road centerline map from Nationaal Wegenbestand Source: Berghauser Pont et al. (2017)
Waterway segments	Waterway centreline map from OpenStreetMap Source: http://download.geofabrik.de	Waterway centreline map from OpenStreetMap Source: http://download.geofabrik.de
Building form	Building footprint data from OpenStreetMap Source: http://download.geofabrik.de	Building footprint data from OpenStreetMap Source: http://download.geofabrik.de
Land use	Colouring London Source: https://colouringlondon.org	Land use type Point of Interest (POI) data from Data.Amsterdam Website Source: https://data.amsterdam.nl

Normalised angular Choice $NACH_{(B)}$ is defined as follows:

$$NACH_{(B)}(x) = \frac{\log\left(\sum_{i=1}^n \sum_{j=1}^n \sigma(i, x, j) + 1\right)}{\log\left(\sum_{i=1}^n d_{\theta}(x, i) + 3\right)} \quad (i \neq x \neq j) \quad (4)$$

Where $(i, x, j) = 1$ if the shortest path from i to j passes through x and 0 otherwise.

POI data refers to precise point locations representing retail stores, schools, stations, businesses, and other relevant establishments. The following formula is employed to calculate the retail density (Equation 3):

$$\text{retail } p_i = \frac{\text{SUM Retail POI}}{\text{LEN}_i} \quad (5)$$

The retail density of a street segment is represented by retail p_i , where i represents a street segment; LEN_i to the length of a street segment; SUM Retail POI is the sum of the total number of retail numbers in each street segment.

Land use diversity is a metric used to assess the extent to which a variety of categorised functions are present within a predefined region (Dhanani et al., 2017; Yoshida & Tanaka, 2005). In urban studies, an entropy-based measure of diversity is often employed, and this study adopts Shannon's Diversity Index to account for the mixture of land uses within a specific unit (Equation 4). The following formula represents how land-use diversity is calculated in the study:

$$H = \sum_{i=1}^s p_i \times \ln p_i \quad (6)$$

Shannon's Diversity Index is represented by H in this equation, where i is the number of land uses and p_i is the proportion of land uses i relative to the total number of uses provided in each street segment.

After conducting the analyses, statistical tests are performed to investigate correlations between the integration of the street network, retail density, and functional diversity. Additionally, a statistical comparison of values is carried out to examine the proximity to the canal in London and the geometric relationship with the canals (whether they are perpendicular or parallel to the canals) in Amsterdam. This comparison aims to determine whether the canals have an impact on the street network in terms of potential movement, density, and functional distribution.

4. Results

4.1. Background and Urban Context of the Case Study Areas

In the early 17th century, Amsterdam implemented new expansion strategies to address increasing population density, stimulate economic growth, and manage water in the Dutch landscape. One of the key elements of this plan was the construction of the Grachtengordel,

also known as the Canal District in English, which was built between 1613 and 1663. In 2010, this area was designated as a UNESCO World Heritage site and comprises Amsterdam's four main canals: the Singel, the Herengracht, the Keizersgracht, and the Prinsengracht. The total length of the main canals in Amsterdam is 72 km, while the canals within the heritage site measure 12.5 km, with an average width of 4 m. To regulate water levels in the city canals, a sophisticated system was developed to control and release water as needed.

The construction of inner-city waterway structures and the accompanying neighbourhoods was driven by the commercial use of the canals. As Amsterdam continued to expand, the circular Singel Canal was the first to be built, followed by a series of parallel canals that connected to the growing area. The Grachtengordel plan stood out for its distinctive features, incorporating the aesthetic and classicist preferences of the era. The result was a symmetrical and regular layout with rectangular blocks and lots that achieved a balance between appearance, functionality, and profitability (Berghauser Pont & Haupt, 2021).

Regent's Canal, on the other hand, was constructed between 1812 and 1816, spanning a length of 13.8 km with a width of 4 m and featuring 13 locks. It originates from Paddington Arm (Grand Union Canal) and terminates at Limehouse, connecting to the River Thames. The canal also includes two branches known as Hertford Union Canal and Limehouse Cut. Unlike the canals in Amsterdam, which have always been integrated into the city's landscape alongside urban expansion, Regent's Canal follows a more peripheral pattern characterised by linear strips of industrial activity (see Figure 1). This research aims to explore how this disparity influences the relationship between canal structure, streets, and land use distribution in these two case study areas.

During the industrialisation period, both countries experienced economic prosperity, and the canals served as both workplaces and living spaces for tradesmen. Wealthy merchants in London and Amsterdam transformed the canal banks from being part of the cities' sewage systems into comfortable areas for production and residential purposes. This transformation continued until the decline of sea trade in the late 19th century. However, renewed interest in nature and the revitalisation of canals has led to the resurgence of canal-side urban areas as regeneration zones during the post-industrialisation period.

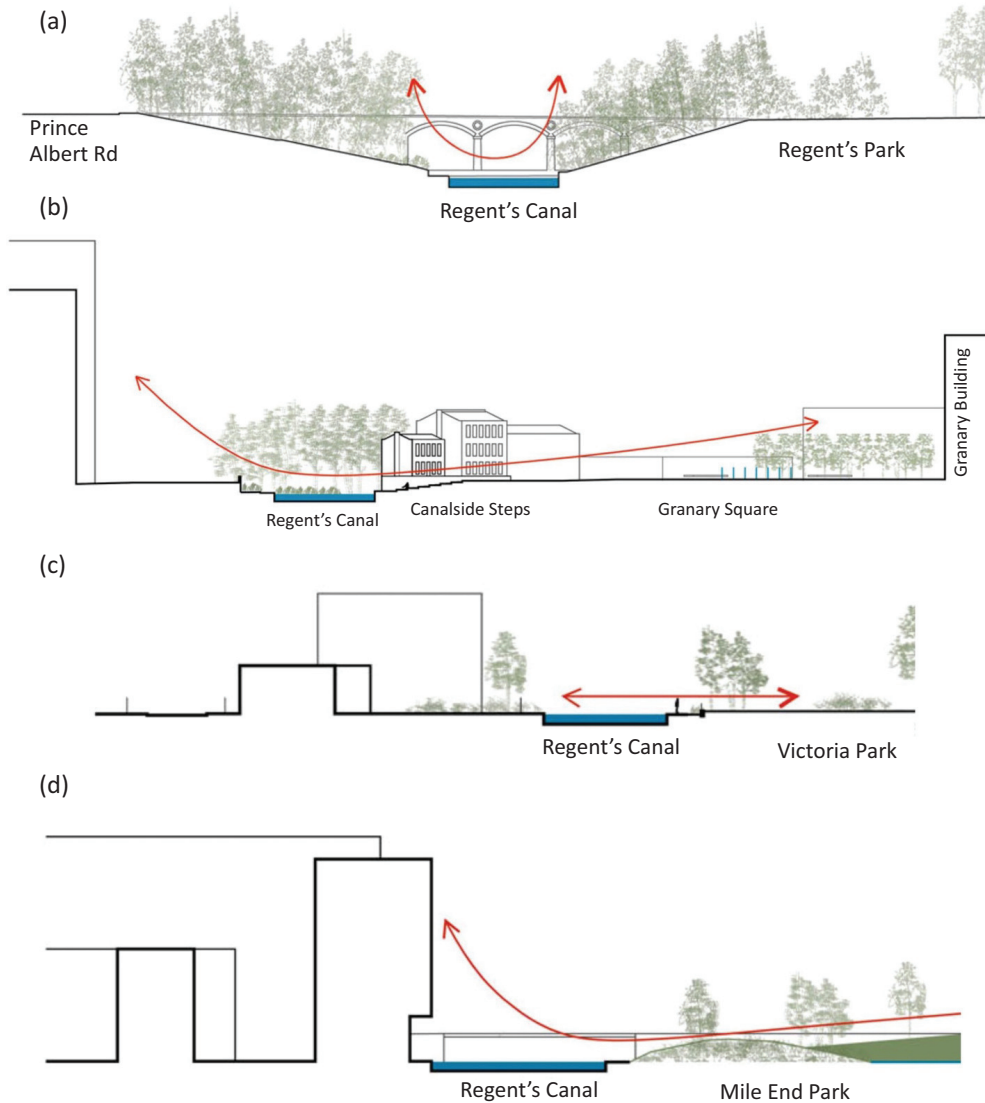
Different sections of Regent's Canal, such as Camden Lock to York Way, and the Grachtengordel, a historic district, encompass a mixture of water and green spaces along with buildings, streets, and railways. These areas possess distinct urban elements, structures, and functions, making them special and unique.

Regent's Canal offers a wide range of activities and possibilities, constantly evolving and capable of generating new meanings. In the Regent's Park residential development, the design of the canal-side effectively

addressed residents' privacy concerns by implementing a V-shaped cross-section, with the canal positioned between slopes adorned with vegetation (Cabau et al., 2021). In contrast, the King's Cross area, a former industrial zone, underwent a regeneration project that exemplified how industrial heritage can be adapted for contemporary urban living. The circular concourse, serving as an entrance to Battle Bridge Place, emerged as a

pivotal link in the pathway leading to Granary Square. Another significant connective element formed by the canal is observed in the cross-section between Victoria Park and Mile End Park Area. In this case, the southern boundary of the park, marked by the canal, was separated from the towpath by a masonry wall, resulting in a lack of connections between the two, unlike the situation in Regent's Park area (Cabau et al., 2021; see Figure 2).

Regent's Canal Cross Sections — London



Heerengracht and Keizersgracht Cross Section in Grachtengordel — Amsterdam

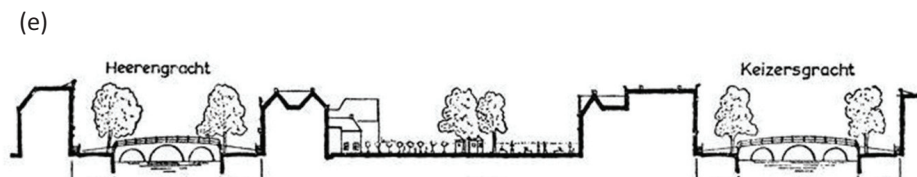


Figure 2. Cross-sections of Regent's Canal. (a) Cross-section of Regent's Canal through Regent's Park, (b) cross-section of Regent's Canal through King's Cross, (c) cross-section of Regent's Canal through Victoria Park, (d) cross-section of Regent's Canal through Mile End Park. Source: Cabau et al. (2021, pp. 292, 296, 300). (e) Cross-section between Heerengracht and Keizersgracht in Grachtengordel. Source: Peter (n.d.).

Regent's Canal allows for diverse site developments of varying scales and footprints due to its long and linear structure. The canal's character is defined by the topography and spatial features of each bank, with a towpath situated on one side. Conversely, the Amsterdam canal system is seamlessly integrated into the cityscape, characterised by uniform facades, equally sized and arranged houses, and a dense network of canals featuring numerous bridges and towpaths on both sides, without any level differences (see Figure 2).

4.2. *The Analysis of Street and Canal Network*

This sub-section aims to provide a spatial analysis of Amsterdam and London, employing a series of space syntax analyses to explore their configurational urban structures, street networks, and urban canal networks. Through qualitative evaluation and quantitative comparison of the case studies, the spatial conditions of selected neighbourhoods are examined, shedding light on how canal-side neighbourhoods and navigable canal structures are integrated into the overall urban fabric.

To facilitate a large-scale quantitative comparative analysis spanning a 5 km radius model, angular segment analysis has been conducted across Amsterdam and London. The analysis of Amsterdam's street network reveals that Grachtengordel is among the most integrated areas of the city on both global and local scales. In contrast, the results of the analysis for London demonstrate that while the Camden Lock area exhibits good integration with the city structure, the King's Cross area is significantly segregated at both scales (see Figure 3). Moreover, the analysis findings illustrate that the spatial impact of Regent's Canal varies across different sections of the canal, influenced by the waterbody's location and its interaction with the city's street network.

While London's canal system follows a linear structure, Amsterdam boasts a more intricate and extensive network composed of multiple interconnected canals. A key objective of the Dutch Mobility policy is to improve accessibility for all individuals while promoting safe, environmentally friendly, and carbon-free public transportation. To achieve these goals, the policy strongly emphasises the integration of waterways into smart logistics and mobility planning. By utilising water transportation for both people and goods, carbon emissions can be reduced, and vehicles can be removed from the roads. The Ministry of Infrastructure and Water Management employs models to assess the required capacity for roads, waterways, and rail networks, making investment decisions accordingly (Rijkswaterstaat, 2022). As part of this process, the study examines the spatial configuration of the waterway network to further explore its potential as a mode of transportation.

Analysing the canal structure of Amsterdam in isolation reveals that the Leidsgracht and Prinsengracht canals are the city's most integrated waterways. Figure 4 illustrates how they shape the city's overall movement

patterns and serve as highly navigable channels within the foreground grid. The analysis results also highlight that the canal network continues to play a significant role in Amsterdam's transportation infrastructure for the transfer of resources, products, and goods, among others.

The results of the street network analysis for canal bridges aim to determine the likelihood of these bridges being traversed on the shortest paths between all areas within an 800 m radius across the entire street network. In the analysis area covering the entire city, Amsterdam features a total of 731 bridges spanning its canals, with the Grachtengordel area alone accounting for 55 bridges. In comparison, London's Regent's Canal is crossed by 43 bridges. This indicates that, on average, Regent's Canal has approximately 3 bridges per km, while Amsterdam boasts an average of 10 bridges per km. Notably, the canal bridges in both cities exhibit higher mean values for NACH (number of all-space connections through a bridge) and NAIN (number of all-space integrations through a bridge) than the respective street networks of the cities as a whole. The maximum NACH and NAIN values for bridges in Amsterdam far exceed those observed in London (see Table 2). It can be observed that bridges serve as effective connectors between islands, and the canal system in Amsterdam does not create significant divisions between these islands.

The analysis findings of the 400 m buffer area around the canals were compared with the street network in both cities to gain a better understanding of the morphological impact of the canal structure on the street network. Statistical analysis was employed to compare the entire street network of the cities with the 400 m-buffered area from the canals, which approximates a five-minute walking distance and can be considered as the canal-side area. In Amsterdam, no significant difference was found, whereas the mean values of NAIN with 800 m and 2,400 m radii exhibit considerable differences in the statistical analysis results of the comparison between the 400 m-buffered area and the entire street network of London. The mean integration of the canal-side area is lower than that of the city on both local and global scales.

Another statistical analysis was conducted to examine whether Regent's Canal had distinct effects on the north and south sides of the canal in terms of the potential movement within the street network. The t-test analysis comparing the north and south sides of Regent's Canal reveals significant differences in the mean results of the space syntax analysis at both the local scale (800 m) and the global scale (2,400 m). Specifically, the south side exhibits higher normalised integration and choice values.

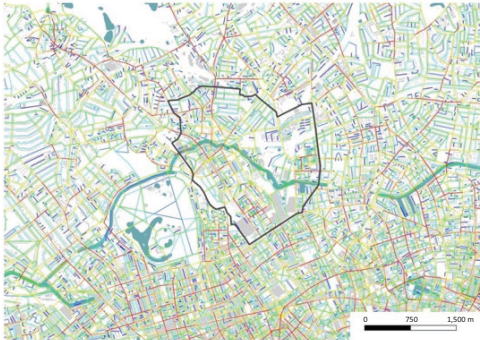
The next phase of the study aims to identify the specific location where the difference in NAIN values between the north and south sides of Regent's Canal occurs. To achieve this, the analysis is conducted based on the proximity to the canal. The street network is

divided into three catchment areas on both sides of the canal: 0–400 m, 400–800 m, and 800–1,200 m. This division allows for the determination of the significant difference in potential movement within the background net-

work between the south and north canal-side networks. The results of the paired T-test clearly indicate that the significant change between the south and north sides occurs within the 0–400m canal-side area.

London

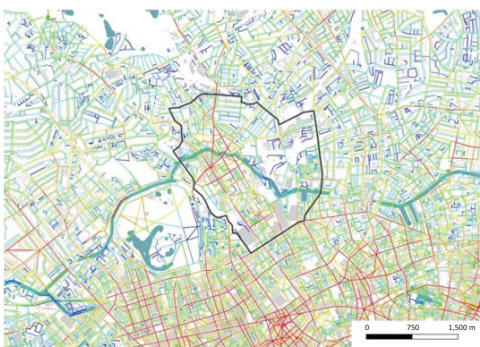
NACHr800



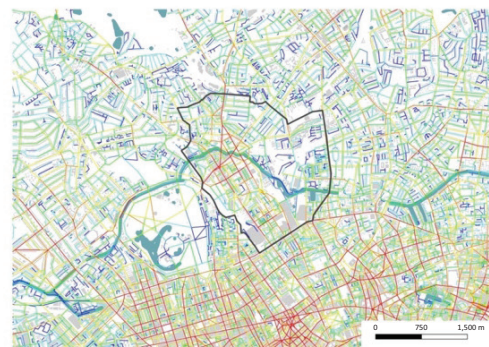
NACHr2400



NAINr800



NAINr2400



Amsterdam

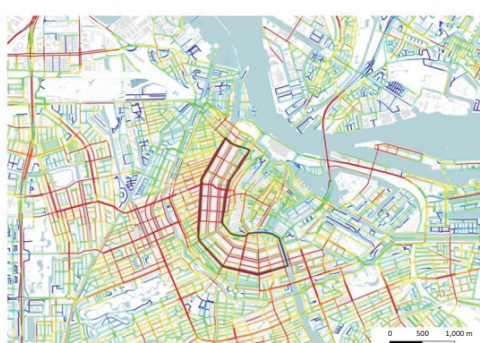
NACHr800



NACHr2400



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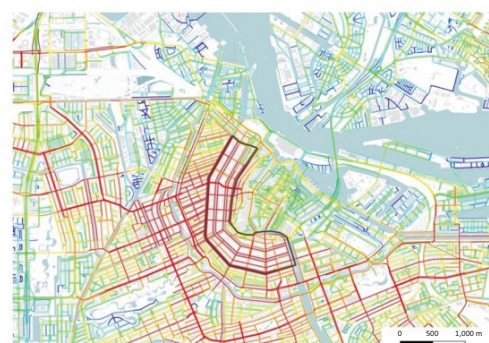


Figure 3. Angular segment analysis of London and Amsterdam. Notes: NACH stands for “normalised angular choice analysis” and NAIN for “normalised angular integration analysis.”

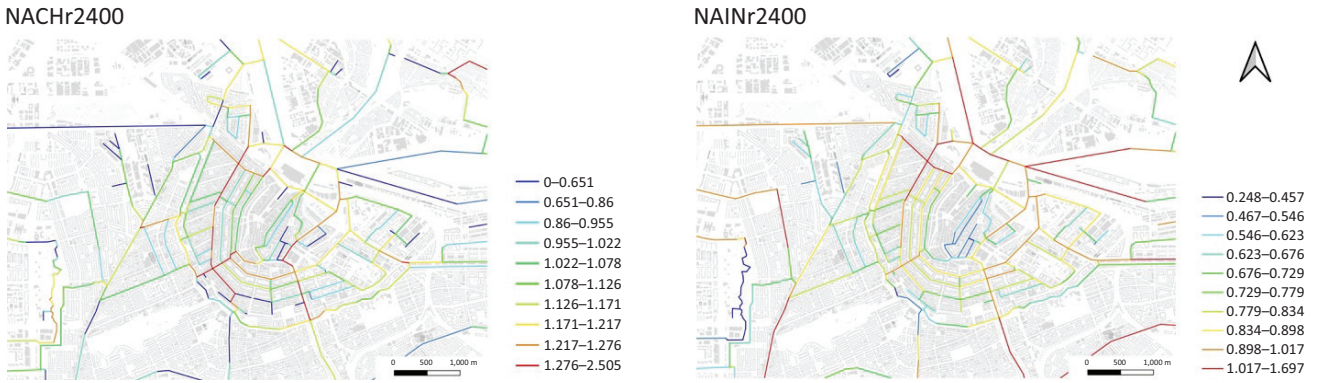


Figure 4. Canal structure of Amsterdam.

Table 2. The comparison of NACH values of bridges, canal-side, and street networks.

	NACHr2400 m				NACHr800 m			
	London		Amsterdam		London		Amsterdam	
	Mean	Max	Mean	Max	Mean	Max	Mean	Max
Bridges	0.90	1.47	1.05	1.38	1.19	1.37	1.06	2.39
400 m buffered area from canals	0.91	1.44	0.95	1.38	0.92	1.6	0.99	2.33
Street network	0.90	1.47	0.94	2	0.92	1.6	0.99	2.5

4.3. The Analysis of Land Use Distribution

The objective of this sub-section is to investigate the impact of the spatial conditions surrounding navigable canals on local socioeconomic activities. As such, the study examines three socioeconomic variables: land use distribution, retail density, and land use diversity. By analysing the relationship between land uses, street spatial configuration, and canals, valuable evidence is obtained, indicating a correlation between canal structure, network accessibility, and local socioeconomic activities.

Eleven types of land use, including community services, health facilities, industry and business, education, mixed-use, recreation and leisure, religion, retail, transportation, utilities, infrastructure, and residential, are plotted into GIS for analysis. Residential function dominates the land use distribution in both case study areas. In Grachtengordel, retail and business functions prevail among the non-residential land uses, while in Regent’s Canalside, mixed-use and retail functions are the most prominent non-residential functions (see Figure 5).

The analysis of land use distribution carried out using various catchments from Regent’s Canal reveals that the proportion of retail land use increases as the proximity to the canal increases (see Figure 6).

The space syntax measures have been applied to two variables related to retail distribution: the total number of retailers per street segment and the retail density based on the POI data for retailers on each street segment (see Figure 7). Pearson correlation analysis was con-

ducted to determine the statistical significance of the retail variables in relation to the space syntax analysis results. In the analysis of Grachtengordel, no correlation was found between the geographic distribution of retailers. On the other hand, the analysis of Regent’s Canalside indicates that local-scale potential movement has an impact on the number and density of retailers. However, this study does not support the hypothesis that potential movement dominates retail activities in canal-side areas, as suggested by Hillier (1996). One possible reason for this is that the canal network and canal-side regeneration projects have influenced retail distribution. For example, the King’s Cross regeneration project has significantly increased the number and density of retailers.

In Amsterdam, streets that run diagonally to canals have a higher retail density compared to parallel streets, as depicted in Figure 7. Lesger and Delaney (2011) conducted a study on the retail layout and urban form in Amsterdam during the mid-18th century and found that the majority of retail activities occurred in and near the old town of Amsterdam. Furthermore, they observed that retail distribution patterns were aligned with streets that had axes leading towards the old town (see Figure 8). The current empirical data and the results of this study’s analysis demonstrate a clear correspondence, indicating that the highest concentration of retail establishments is still found along the series of streets with axes oriented towards the old town of Amsterdam. While the accessibility of street configurations does not affect retail locations, the structure of the urban grid does have an impact on retail distribution.

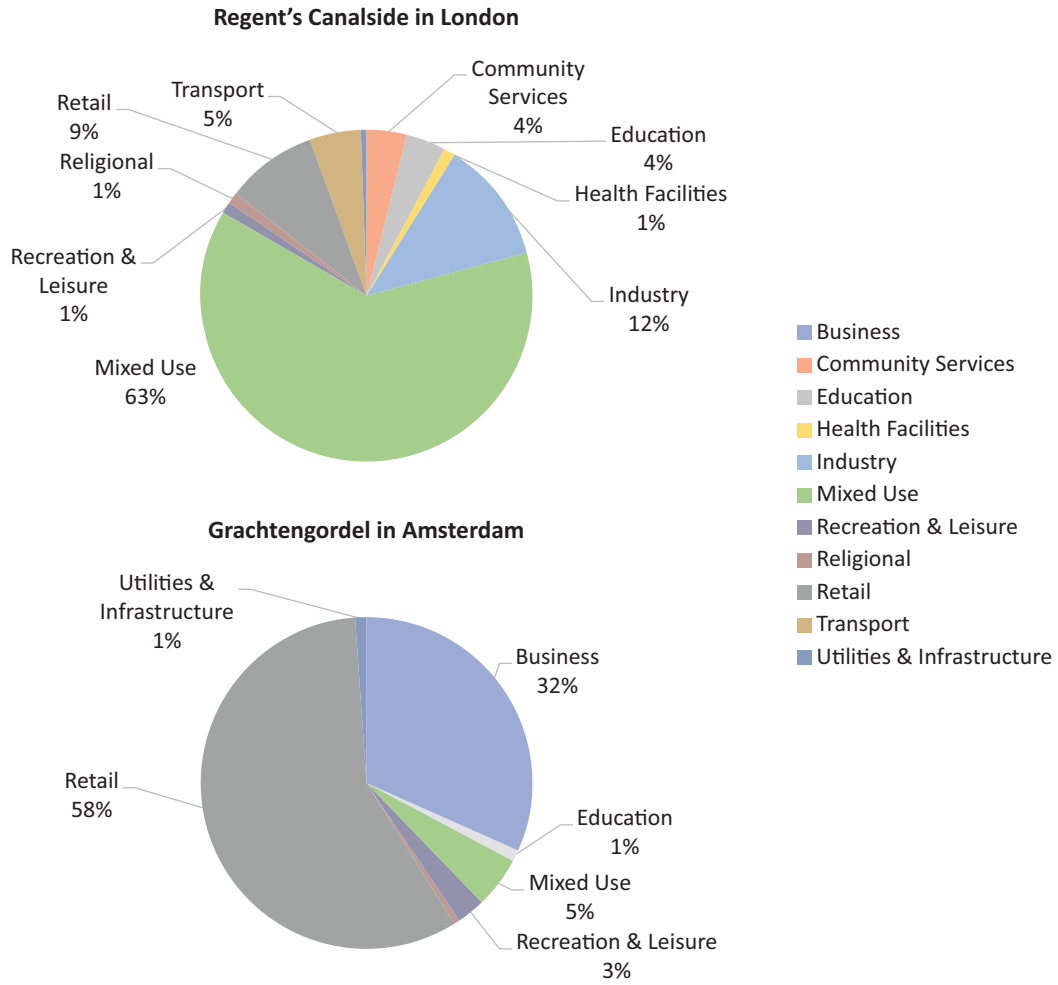


Figure 5. Non-residential land use chart for Regent's Canalside and Grachtengordel.

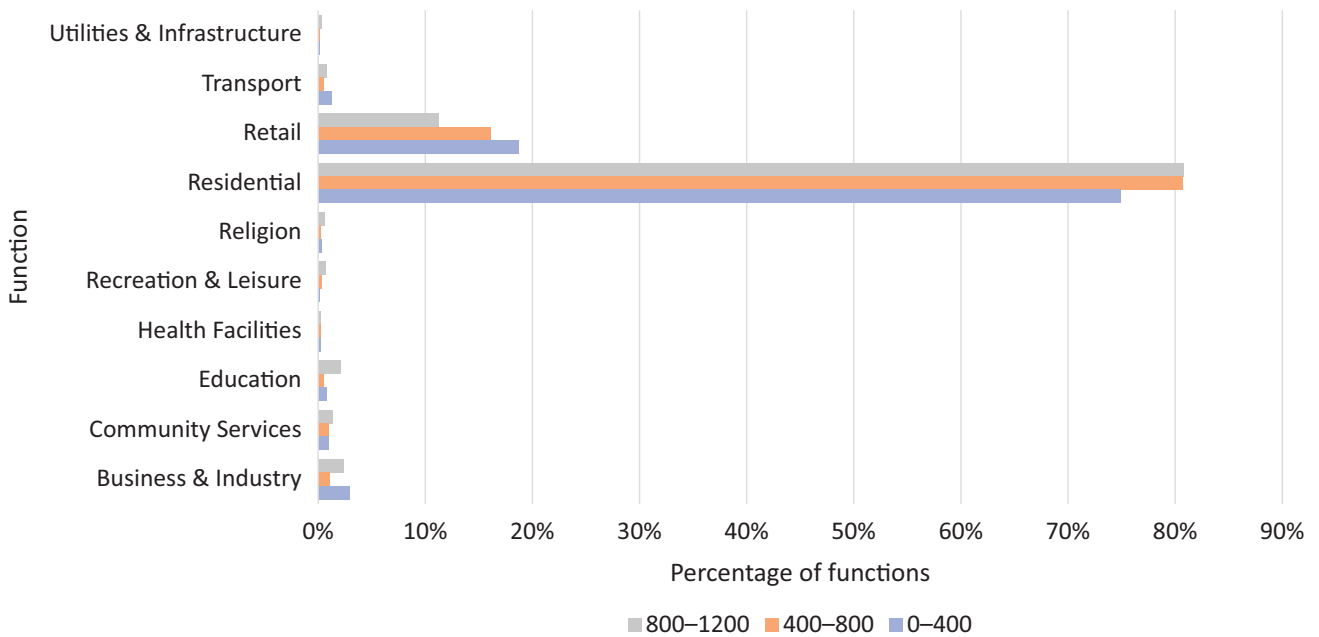


Figure 6. Land use chart for Regent's Canalside in different catchments.

London



Retail Density 0 500 1,000 m

Amsterdam



Retail Density 0 250 500 m

Figure 7. Retails in Regent’s Canalside in London and Grachtengordel in Amsterdam: Retail distribution is on the right and retail density is on the left.



Figure 8. Amsterdam’s shopping streets in 1742. Source: Lesger and Delaney (2011, p. 29).

When examining retail density and functional diversity in the Grachtengordel street network, it is evident that diagonal streets have a higher retail density compared to parallel streets. Additionally, the analysis shows that canals do not offer inherent advantages in terms of retail density, but they do have a significant impact on functional efficiency, primarily due to their high diversity. This diversity is evaluated using Shannon’s Diversity Index.

5. Discussion

The conducted research aimed to investigate the relationship between canals, functional diversity, and street accessibility in Amsterdam and London. The study involved a comprehensive analysis of the spatial arrangements in both cities to understand the geometric interplay between the canal and street networks. While Regent’s Canal exhibits a linear structure, Amsterdam’s canals are organised in a regular grid system with cells. The study revealed the significant role played by diagonal streets in the canal grid of Grachtengordel in shaping the distribution of retail establishments. Comparing these findings with Lesger and Delaney’s (2011) spatio-historical analysis of retail distribution in mid-18th century Amsterdam, it is evident that the spatial distribution of retail units continues to be oriented towards the old town.

Furthermore, the study explored the spatial patterns of land uses in close proximity to the canals. It was observed that land use types near the canal (within 0–400 m) exhibited a higher concentration of retail units. In the case of London, the percentage of retail units increased as one approached the canal. However, there was no significant correlation found between retail distribution, integration, and choice space syntax measures in both cities. To answer the question of whether retail density follows the high potential mobility pattern, the analysis suggests that, in the canal-side setting, the answer is no. The study demonstrates that the distribution of functional activities exhibits distinct spatial patterns in the canal-side context compared to other parts of the city.

In London and Amsterdam, there are distinct variations in the spatial distribution of functions. The difference in the spatio-functional context related to canals can be attributed to the contrasting urban structures of the two cities. Amsterdam follows a planned regular grid structure, while London’s development evolved from the centre, absorbing diverse villages, and suburbs, and exhibiting a multi-functional use of Regent’s Canal across different zones and sections. Hillier and Vaughan (2007) describe the formation of cities as a two-step process. On one hand, streets organise space to optimise movement and co-presence, emphasising the importance of public spaces that bring people together. On the other hand, the residential space process focuses

on controlling mobility within residential areas and establishing relationships between residents and strangers. This study suggests that London and Amsterdam leverage the relationship between space and movement in diverse ways. The canal structure can be understood through the lens of the public space process, influenced by unique microeconomic factors specific to each city. The canal process shapes the overall structure of each city.

When comparing different sections of Regent's Canal, it becomes evident that certain areas prioritise the privatisation of housing development over other values. Examination of section drawings of the canal revealed that when buildings are tall in relation to the canal, the enclosed character of sections where buildings reach the water's edge diminishes, creating a dark environment. Conversely, when buildings are set back in the drawings, new spaces or paths created on the right bank may be insignificant and hinder the potential for developing new routes along the canal as public spaces. Additionally, some developments lead to the disappearance of spontaneous greenery and the isolation of new buildings, resulting in an overall loss of value.

This study offers valuable insights for future urban design or regeneration processes in the canal-side contexts of both cities. The analysis methods employed in this study can systematically inform the design idea generation and development phases. The analysis results can provide clarity on the project brief, context, specificities, and other relevant spatial, social, and economic factors that are crucial for urban design options. Moreover, the same analytical tools can be utilised to critically evaluate design options, assessing the impact on potential movement, land use distribution, and density patterns before and after the design interventions.

6. Conclusion

The primary objective of this study was to deepen our understanding of the relationship between canal networks and their surrounding areas. By employing analytical approaches and advanced spatial analysis techniques, this study has made a valuable contribution to the field of urban studies. It explores the variations in spatial culture, local socioeconomic activities, and functional utilisation of navigable canals and canal-side neighbourhoods across two distinct geographic locations. The study concludes by emphasising the significance of analytical methodologies based on space syntax in enhancing the integration of canal systems within cities.

One of the main challenges faced in cities is the impact of canals on mobility, which can lead to complex community severance. While canals are designed as transportation networks to enhance mobility, historic canal-side areas can also contribute to increased functional diversity and local development within the urban environment. When examining the organisation of a city, it is often perceived as consisting of multiple layers of

infrastructure that support its social and economic operations. These interconnected layers develop together, resulting in diverse interpretations of the city's geographical scope. Dutch cities are renowned for their nearly flawless rationality, achieved through the use of surveying and drawing instruments. Amsterdam seamlessly fits into this pattern, reinforcing the top-down planned urban pattern essential for water management in the water-dominated environment of the Netherlands delta. This pattern influences everything it encounters, shaping models of planning and spatial design to conform to its own scale and geometry. Therefore, the growth of Amsterdam can be easily understood as the coevolution of two distinct phenomena based on the hierarchy of its streets and canals.

On the other hand, the expansion of large cities with an organic character, such as London, involves the assemblages of elemental units such as streets, waterways (rivers and canals), and railways, which have emerged over decades in relation to each other without a distinctive top-down urban planning approach. The introduction of railways in the 19th century decreased the use of waterways and provided waterside industrial areas with railways, as seen in King's Cross, enabling the transportation of heavy goods over long distances. This shaped the urban growth pattern of London, with waterside areas having a unique character as canals, railways, and streets overlapped in different sections.

The research examined the significant spatial and functional influence of the canal structure on accessibility and functional diversity in London and Amsterdam, each with a distinct relationship between the canal system and the street network. The study revealed correlations between street accessibility, retail density, and functional diversity, demonstrating that canals play a role in urban functionality. In Amsterdam, the geometric relationship between street and canal networks appeared to influence the distribution of functions. In London, however, the distribution of functions varied depending on the distance from Regent's Canal.

The research methodology and outcomes have implications for the functioning of canal systems in modern cities across various scales. The strong network accessibility of canal-side neighbourhoods can contribute to the successful optimisation of both local and global urban processes. There are several exciting potential directions for future research. Firstly, the inclusion of new cities in the study, particularly in larger global cities, would be valuable. Secondly, a comparative investigation of multiple canal-side neighbourhoods within a single city would be a novel approach, allowing for an exploration of different geographical conditions and spatial elements that influence canal impacts within a single urban context.

Acknowledgments

We would like to extend our profound gratitude to professor Laura Vaughan, whose insightful contributions

significantly enriched this study. Her expertise and guidance were invaluable throughout the process. This work was supported by the Republic of Türkiye, the Ministry of National Education, which provided a postgraduate scholarship to the first author. We affirm that this institution had no influence on the design or execution of the study, thus ensuring no conflict of interest.

Conflict of Interests

The authors declare no conflict of interests.

Supplementary Material

Supplementary material for this article is available online in the format provided by the authors (unedited).

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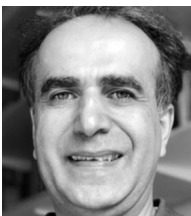
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