University College London

UNDERSTANDING FUNCTIONAL URBAN CENTRALITY

SPATIO-FUNCTIONAL INTERACTION AND ITS SOCIO-ECONOMIC IMPACT IN CENTRAL SHANGHAI

A thesis submitted to the Bartlett Faculty of the Built Environment, University College London, in candidacy for the Degree of Doctorate of Philosophy

Bartlett School of Architecture

By

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2017

I, Yao Shen, confirm that the work presented in this thesis is my own.

Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

2017

To Liuchi and Simiao.

ABSTRACT

A deeper understanding of the structural characteristics of urban settings is a prerequisite to evaluating the effects of urban design and planning proposals more efficiently. This thesis aims at shaping a new, comprehensive approach to uncover the structure of cities through the investigation of a diachronic spatio-functional process and the socio-economic impacts of such a process. It proposes a spatial network-based framework, in which individual street segments, indexed by space syntax centrality measures, are utilised to develop a series of more complex urban function connectivity measures by an analysis of the spatial network and land-use patterns in tandem. The specific application of this approach in Central Shanghai is conducted with a threefold focus: firstly, to trace the evolutionary interdependence between the spatial grids and the land-use distribution; secondly, to explain the varying economic value of the spatio-functional relationship in the housing market; and thirdly, to capture the impact of the spatiol-functional interaction on the variation of co-presence.

The outputs confirm that the centrality structures of the spatial network and the land-use distribution affect each other over time; however, certain degrees of inconsistency are observed, suggesting a distinct complementary relationship between these two systems, which is further validated by the improvement of the proposed model's predictability of urban performance. The findings verify the hypothesis that urban spatio-functional synergy is a strong determinant of the formation of urban function regions, the delineation of housing submarkets, and the discrepancy of the spatial co-presence in the city. These results demonstrate that urban performance is directly affected by the way the spatial and functional structures of the city interact. Such findings support the proposition that understanding the complexities of the spatio-functional interaction in a morphological analysis can enhance the efficiency of urban design and planning interventions, which aim to improve socioeconomic conditions in cities.

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ACKNOWLEDGEMENTS

This thesis is a summary of a long academic journey. It would not have been finished without the sincere help given by many gifted people. I own my first and deepest gratitude to my principle supervisor, Dr. Kayvan Karimi. Without his supervision and encouragement from the preliminary to the concluding stages, this research would not have been possible. His brilliant theoretical thoughts, immense advice, long-lasting patience through these years helped me grow the idea of this research and opened the door for my future academic life. I am grateful for the tremendous opportunities he provided to developing my teaching skills. My heartfelt thanks also go to my second supervisor, Professor Laura Vaughan, for her insightful comments on my research and academic writing, continuous encouragement and shared interests.

My sincere thanks are also given to Tao Yang, Stephen Law, Chen Zhong, Ye Zhang, and Ying Long for their endless support on enhancing my study and their invaluable friendship in my daily life. My gratitude is extended to all of the talented staff and fellow students in Space Syntax Laboratory for their selfless sharing of experience.

I am extremely grateful to the Chinese Scholarship Council for funding my doctoral research fully. This financial support reduced my family burden and enabled me to be a better pilot of my academic research.

I would like to express my appreciation to Professor Michael Batty for offering me an opportunity to participate in an exciting project as a post-doctoral researcher and giving me much treasured supports.

I am sincerely thankful to my family members for their warmth, love, support and sacrifice over years. I am deeply indebted to Liuchi and Simiao, my wife and son, my intimate partners in life, for staying by my side always.

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CHAPTER 01

INTRODUCTION

1 THE MOTIVATION

The main motivation in this thesis is to investigate how urban form and function interact with each other, thereby reshaping the performance of social processes. This research is pursued by developing a framework to quantify the spatial and functional centrality structures, tracing their interaction in urbanisation processes, and estimating their impact on various aspects of urban performance.

Uncovering the production process of social life in urban spatial settings is one of the essentials in the development of modern urban planning and design (Lefebvre 1991). Spatial structure refers to a set of spatial relationships arising out of the urban form and its underlying interaction between various urban entities (Anas et al. 1998). In the socio-spatial dialectic, social events are argued to be formed through space, to be constrained by space and to be mediated in space (Soja 1989). Evidence of how the society is reproduced spatially has been found in many ancient cities, where social hierarchies coincide with the spatial organisation of human settlements to a large extent (Lévi-Strauss 1963; Hillier and Hanson 1984). In contemporary societies, modern technologies have significantly exploited human mobility, leading to unprecedented urban sprawl over the last century and a half, and thus (re)shaping the urban context with numerous dispersed, hierarchical and interrelated hubs (Castell 2011; Buliung 2011). The complexity of modern city systems has consequently been issued as a challenge for reclaiming the theoretical significance of urban form in the procedures of contemporary social life and for advancing relevant methodological developments.

Modern urban design has been utilised as a primary tool to address the socioeconomic ills of cities in history. Closely linking socioeconomic status to design features, this idea of spatial determinism has been criticised, however, for its 'naive' spatial interventions, with over-simplified geometries and its failure to address the *organised complexity* of social, economic and cultural life in the post-war era (Jacobs 1961; Webber 1963). This criticism stems from practical considerations, given that a series of large-scale urban regeneration projects have had disastrous consequences. The scarcity of successful reflections on these criticisms by urban designers has further intensified the marginalisation of urban design in mainstream contemporary theories of urban studies. In parallel with the 'social turn' in modern planning history, in which the focus of modern urban planning was shifted from the individualist invention of 'ideal' public spaces to the collaborative planning of functional and democratic spaces (Healy 1997), important theoretical developments in urban design emerged from the 1960s through the 1980s, which have in return contributed to the 'spatial turn' in social sciences. Neo-Marxist urban planning theories have emphasised the importance of the built environment—the 'second nature', an artificial nature—in urban production and consumption processes (Lefebvre 1974; Harvey 2010). Concurrently, extensively efforts have been made to investigate the definable spatial logic of the qualities of cities. Kevin Lynch (1960), for instance, proposed a classification of urban spatial elements for generating visual quality across spaces. Christopher Alexander (1977) quantified the pattern properties of urban form and its relation to the aliveness of urban life. The structural properties of urban form have been explored by Hillier and Hanson (1984), who developed a configurational study of the urban structure called space syntax, which focuses on the interrelationship among spatial elements in which each is determined by its relation to all others. These developments, indeed, shaped the theoretical foundations for the social meaning of urban form, but the need to determine the role of urban form in social processes persists (Talen and Ellis 2002). To produce a deeper understanding of the dependency between contemporary spatial and social structures, scholars require theoretical and methodological advances, as well as empirical validation; such advances are essential to bolster their arguments for any social good that could be brought in by urban design.

The spatial structure of cities has its roots in the recognition of urban centres and the notion of *centrality* in urban system. In general, spatial structure has two principal aspects: the morphological dimension, which refers to the locations, sizes and boundaries of the centres, and the functional dimension, which addresses the significance of the interrelationship between those hierarchical centres (Burger and Meijers 2012). These two principles interact with each other with some level of correlation, but empirical studies at the intra-city scale offer very little to show a robust causal connection between the functional and morphological changes in cities (Hall 2002; Burger and Meijers 2012). In the term's usage, the normative definitions of these aspects of spatial structure can be reflected in various scenarios. In geographical research, a series of analytical methods with diverse datasets have been employed to measure these two crucial aspects, which vary from using arbitrarily selected thresholds of urban population densities, employment, or land-uses (e.g., McDonald 1987; Thurstain-Goodwin and Unwin 2000) to adopting network properties based on flows of people (e.g., Thiemann et al. 2010). The focuses of these methods fall mostly on functionality, but they tend to treat the morphological features of urban cases as merely outputs of the statistical performance of the functional attributes of each case. This treatment somewhat simplifies the morphological elements of geographical studies, constraining their significance in meaningfully guiding urban design. This trend is reversed in configurational studies using space syntax, which analyse the -geometrical nearness of urban street networks, whereas the functional dimension is generally accounted for as a dependent product of distributed public spaces (Hillier and Penn 2004). The space syntax theory proposes that spatial urban structure shapes movement and then movement shapes functions in the city (Hillier 1996). Space syntax representations of spatial structures can efficiently capture as spatial descriptions functional patterns in historic or informal settlements. However, they have less explanatory power regarding the functional structures of the planned built environments, suggesting the necessity of methodological developments for advancing the knowledge of the relationship between form and function in contemporary cities. Furthermore, post-modern cities are more polycentric than before, due to urban digitalisation; thus, a new science of cities is emerging as a requirement to address the complexity between urban functional flows and fixed locations and to reveal spatial structure with greater exactness (Batty 2013).

This thesis is primarily motivated by a proposition that the functionality of the city is influenced by both spatial and functional layouts, simultaneously. Specifically, it hypothesises that on the one hand, spatial structure shapes the functioning procedures of cities, whist on the other hand, the functional layers of the city shape social processes. This research details the difference between these two mechanisms. The social effects of the functional built environment have been referred to as *multiplier effects* stemming from physical design in space syntax theory, in which attractions adapt themselves to more intensive development. These multiplier effects have not been further investigated in space syntax theory, but relevant explanations can be found in the theory of geographical economics. In fact, these multiplier effects can be said to originate from the processes of densification, diversification, and cost-savings, driven by economic agglomeration (Krugman 1998; Ottaviano and Puga 1998; Fujita et al. 1999), which would shift the centrality structures of urban activities in the city. Consequently, spatial accessibility measures are the ways in which cities are seen from an aggregated and static perspective to describe long-term urban change, since the land-use patterns are the consequence of spatial configuration. Conversely, economic studies tend to focus on the interaction between land-uses, revealing the short-term change of land-use patterns but lacking the methodological capability to model long-term outcomes. Therefore, recognising the linkage between the spatial and function assemblages can provide a more advanced understanding of centrality patterns in the city, whereby the social processes can be unfolded more explicitly than has been the case in previous configurational studies.

Recent developments in related fields create favourable conditions for the relevant exploration. Contemporary geographical and configurational research enables more advanced studies into the spatial configuration and its occupancy (e.g., Batty 2017; Omer and Kaplan 2017). Methodological rigour in spatio-social science, on the other hand, can create opportunities for quantifying explicitly and robustly the relationship between the configurational variables and other dependent social variables. In addition, urban big data and the related computing approaches with improved hardware efficiency have been yielding various new insights into theoretical and empirical propositions about urban form in urban planning and design (e.g., Liu et al. 2015). Based on these multi-dimensional improvements, it is suggested that the field is now in a position to enhance the way in which the theory and method of the social significance of the urban form can be systematically enriched to create a more explicit, comprehensive and dialectical reflection of increasing urban complexity in contemporary cities from an urban design perspective.

2 RESEARCH SETTINGS

2.1 Research aims

This thesis focuses on the configurational aspects of the urban spatio-functional process and its related socio-economic consequences. The primary aim of the research is to develop *a method of measuring the land-use system,* a method capable of enriching and improving the existing spatial network centrality measures with consideration of the spatial network's functional dimension—the land-use patterns; correspondingly, this thesis looks to make more productive the tools in the relevant research, urban design, and planning practices, helping to address the current challenges faced in contemporary urbanisation. Thus, such a method aims to relate urban land-uses to urban form (the spatial configuration) and other aspects of urban performance.

The second critical aim of this research, therefore, is to explore *the extent to which the urban grid and the land-use patterns interact with each other at various scales and simultaneously influence urban performance*. The 'configuration' here is defined as the spatial relationships of connectivity as the result of the geometric layout of the spatial elements, including public spaces, function amenities, and the travel routes that connect them. The 'performance' denotes the different socioeconomic functionality that the built environment can deliver. In the present thesis, examples of urban performance that are conditioned by spatial configuration include issues such as the value of residential properties and the spatiotemporal co-presence between local and the non-local residents in the public space. In considering these issues, the method of analysing urban functional configuration could help to develop a deeper understanding of how the changes of centralities can be related to the spatial shift of land-use systems. Such a method can also generate a fine-grained basis for spatial developments and land-use planning solutions or decisions to revitalise social performance. The proposed method aims to provide the possibility of initiating a type of 'soft' spatial intervention in which fine-grained land-use design is the new focus to sustain the urban performance without changing the urban form significantly. Such an approach would be particularly helpful in urban environments, such as historic centres, in which major physical changes are restricted. Central to all of this will be the understanding of the spatial variation of the land-use system beyond the urban form throughout various urban scales.

This research attempts to deliver a method of *urban function connectivity*, which represents the perceived land-use patterns through the spatial network to uncover the conditionality of the land-use patterns to urban spatial configuration. This notion is multi-dimensional, capturing principal aspects of the interaction between urban functions that shape the structure of functions. These principles represent essential mechanics for land-use change, resulting in a shift of the functional centrality structures. The first dimension of urban function connectivity is function density, which is related to the densification of urban functions. It captures the concentration or strength of land-use activities, which are related to the size of local attractions (e.g., Christaller 1933; Robic 1982). Another dimension is function diversity, a cross-sectional description of the functional diversification process, where complementary land-uses are said to co-exist to produce multi-purposive movement across locations of different land types (Hanson 1980). Unlike the concept of density, diversity is not necessarily linked to the absolute size of attractions, but is related to the assemblage of components (Zhong et al. 2015). The third critical dimension of land-use centrality structures is the cost-savings process in which the willingness of people's movement reduces with the increase of travelling distance (Fotheringham 1981). Two distance metrics matter in decision-making processes regarding travel: the metric distance, representing energy expenditure, and the geometric distance, which reflects the cognitive cost required to be overcome when moving through the city. The interplay amongst these three processes leads to the shift of the integrated functional centrality structures.

The emerging *function region* structures are also important for uncovering the typologies of function centralities in cities. This typological structure showcases how urban spaces can be distinguished into the stated three principal processes of (re)shaping the centrality structures, which further illustrates the dominated functions in the densification, diversification, and cost-saving processes. Arguably, these four issues—density, diversity, distance and region (zoning)—are contained in the notion of urban function connectivity and are all concepts widely adopted in planning and design research and practice. Consideration of these issues enables future applications of the method introduced in various scenarios.

The proposed framework for quantifying functional centrality structures in this thesis is scalable and compatible with emerging spatial data generated by the locational service. The recent growth in the provision of location-based services has inspired people to share their location preferences in social media networks, through which ubiquitous user-generated evidence of location choices has fashioned a new generation of 'human knowledge' regarding urban spaces in fine-grained detail (Wyly 2014). While it offers new opportunities for research, the use of social media data has its limitations, for instance the sampling problem, context-related uncertainty, lack of theoretical composition and so on (Boyd and Crawford 2012). However, the finer resolution of these datasets has the potential to enable people to ask questions different from those based on conventional data, which is often aggregated and out of date (Shelton et al. 2015). This study uses points of interest (POIs) and check-in data in modern social media as a novel representation of land-use locations to measure the functional centrality structures, demonstrating a way by which volunteered geographical information can be properly adopted in syntactic analysis of patterns of functions. All the data adopted in this study are anonymous and publically accessible so that the ethical issues of using the data can be properly addressed.

The research aims to revive the focus on land-use patterns in configurational studies to reclaim their significance in the estimation of people flows, as urban functions are the origins and the destinations for travel behaviours. However, this revival does not entail that the existing space syntax models should be taken out and replaced. It is considered that the urban function connectivity model can complement and enhance the current space syntax model theoretically and methodologically, although the urban function connectivity measures could perform better as individual indicators than the space syntax centrality indices can provide at present. In this sense, this research explores whether the spatio-functional model, containing the function connectivity and space syntax centrality measures engaged at different scales, can productively contribute to the understanding of urban transformation process and temporal performance. To unfold these arguments, the central hypothesis and a series of research questions that need to be addressed are formulated and explained in the following sections.

It is evident that Chinese cities are currently experiencing a transition towards a market-oriented economy in a centrally-planned form (Yeh 1999; Wu 2002). However, the spatial context of Chinese cities has been continually formed largely by modern urban design ideas and methods, resulting in an inability of the spatial form to meet the social requirement of post-reform cities, as well as the mismatch between spatial and functional structures (Wu et al. 2006). This phenomenon is also evident in large cities of other developing countries all over the world. In this dissertation, Shanghai City, a microcosm of rapid urbanisation in Chinese over the past 150 years, is chosen for empirical investigation. The shifting morphological and functional complexity in Shanghai makes it as an ideal place to test the hypotheses of this thesis. The richness of historical spatial data and the availability of the socioeconomic performance data in Shanghai provides strong support, facilitating the comprehension of its spatial and functional centrality structures and their relations to social vitality. Against the background that the global rate and speed of urbanisation are great, and that urban expansion and regeneration are still the worldwide strategies for development, the knowledge produced by Shanghai's example can provide fruitful references for the future studies and urban design practices.

2.2 Research questions and hypothesis

This research hypothesises that *the interaction between the spatial and functional aspects of the spatial configuration of cities affects the performance of the built environment*. Consequently, the overarching question of this research is as follows: *To what extent is urban centrality explained by the distributions of land-uses through spatial networks, and thus, how do urban functions interact with spatial configuration to impact economic performance and social interaction in urban centres*?

To respond to the main question of the research, a set of more detailed research questions are introduced. The first thread in this research aims to provide a better understanding of the natural interaction between the spatial network and the land-use system, and begins with a study that describes the urban dynamic evolution process in Shanghai City at the street level (research question 1) and moves to a more in-depth study on predicting urban performance (research question 2 & 3).

1) *How does the interplay between land-use distribution and spatial network configuration, namely the spatial-functional interaction, shape urban centrality at various scales over time?*

This question involves the investigation of three aspects: a) whether the functional centrality structures stemming from the land-use network differ from the centrality structures indicated by the spatial network during different periods in history; b) if such a difference exists, whether these two types of centrality structures correlate with one another in the urban evolution process; c) whether this relationship remains unchanged from place to place in the city throughout the history. By pursuing the answers to these questions, the spatial dynamics, the functional dynamics and the relationship between them can be unfolded.

Traditional typo-morphology research emphasises the urban programmes and spatial typology and hypothesises that the typology of urban form is the evidence of the urban evolution process. Related examples include the Conzenian School's work (e.g. Moudon 1997), the research produced by the Italian School from the architectural perspective (Cataldi et al. 2002), and the studies conducted by the French School about the spatiality of sociocultural elements (Pinchemel 1983; Darin 1998). Although land-use patterns have been discussed in these studies, they have not been sufficiently measured and adopted as the core object of analysis due to their dynamics. Configurational studies, on the other hand, have emphasised the centrality patterns of the spatial network and argued that urban evolution is a centrality-shifting process, in which the interaction between spatial elements at various scales impacts the future construction of urban centres and their hierarchical systems (Hillier 1999). In space syntax theory, the generic influence posited by spatial structures on the reproduction of land-use distributions is emphasised, whereas in geographical studies the land-use system is claimed to be a vital driving force instead of being only the existing status for urban change. Therefore, the proposed spatio-functional interaction model would in principle be a suitable approach for describing urban centrality structures and capturing incentives for future urban change that are produced by the relationship between spatial centrality and functional centrality in different areas where the spatial elements are organised. This thesis intends to contribute to this important theoretical and methodological proposition through a morphological analysis of urban transformation.

Urban centrality, a form of accessibility, has been used as the economic and social indicator to assess urban planning and design proposals (Geurs and Von Wee 2004). According to space syntax theory, socioeconomic processes are influenced by the movement which is the product as well as the mediator of the spatial and functional built environments (Hillier 1996). Unfolding the connection between spatio-functional interaction and socioeconomic performance contributes to the verification of the significance of urban design in addressing social issues; in return, it can also benefit the production of knowledge regarding the social effects of urban centrality structures, particularly how these structures might be perceived by people in various social processes, thereby influencing the spatial variations of social performance. In this thesis, two basic social processes, which are shaped by urban structures and movement, are given extensive attention: the valuation of residential properties, and the face-to-face encounter between different groups of people. These two processes are deeply entrenched in space syntax theory and geographical research. The former provides the evidence of a fundamental route for how urban structures are translated to economic values. The latter is a reflection of ‘co-presence’, which is considered a type of social interaction effecting other inequality issues in sociology and is crucially enabled by physical conditions.

Capturing the economic and social translations of urban structures, therefore, is an essential foundation for recognising the distinct generic roles that spatial and functional centrality structures play in social and economic theory, as well as a vital scope for verifying the values of spatio-functional interaction through questioning their impact on social and economic consolidation in societies. Moreover, the increasing availability of publicly accessible data describing house price patterns and physical encounter distributions, coupled with continuously emerging data mining tools, makes this type of research possible for the first term. For a long period of time, urban studies on the cities of developing nations have suffered a deficiency in data collection. This trend has been reversed because of the popularisation of modern communication technologies. In this study, asking-house-price data are used as an alternative estimation of transaction data (Chandler and Disney 2014), and the physical co-presence patterns are mapped based on the individual trips calibrated from the check-in records of social media users. Taking advantages of these data in terms of spatial resolution, coverage, and sample size is conducive to the plausibility of the proposed studies (despite their limitations, which are described in Chapter 03).

Based on the above discussion, the second and third questions of the research are defined as follows:

2) *What is the impact of spatio-function relationships on the urban economic performance identified by house price patterns?*

This thesis acknowledges the importance of location characteristics in shaping housing markets, so it carries out a case study of spatial economics. In existing studies of housing-price patterns from the configurational perspective (Law et al. 2013; Xiao 2016), discussion of the interaction between the spatial network and land-use system is limited. To fill this gap in the literature, this research question deals with the explicit relationship between spatio-functional centrality structures at different scales and housing-price patterns. Three detailed perspectives can be identified in this question: firstly, the research intends to explore whether the functional accessibility measures at different scales have a significantly positive or negative impact on housing prices by controlling the potential influences of the spatial accessibility measures; secondly, it investigates whether the impacts of spatial centralities and functional centralities are spatially uniform; and thirdly, it tests whether the functional centrality indices contribute to the identification of the housing submarkets with spatial centrality metrics. Answering this research question not only helps to validate further the proposed method but also contributes to the analysis of the spatial heterogeneity of house prices and the delineation of housing submarket patterns. These results and methods could also benefit planners, designers, and policy makers to understand how spatial design and land-use allocation will be priced across submarkets with different price effects. Quantifying spatially varying influences exerted by the spatial and functional layouts across spaces and confirming the boundaries of housing submarkets can enhance the precision of relevant interventions for stabilising housing markets in the city.

3) *Does the interaction between spatial configuration and functional distribution explain the patterns of physical co-presence in the city?*

This third question investigates the extent to which the interaction between the spatial network and land-use system at different scales will affect the temporal pattern of physical co-presence between local random visitors and non-local people. The first issue here is whether the function connectivity measures have any additional influence on the presence of the local and remote users sensed by the social media check-ins records by controlling the impacts of spatial centrality factors. The second question asks whether and to what extent the function connectivity and space syntax centrality measures affect the spatiotemporal presences between the local and the non-local visitors across hours. The third concern is about the extent to which the emergent modes of spatiotemporal encounters can be predicted by the spatial and centrality structures. Studies have recently suggested that the spatial network and the accessible opportunity density can be considered as one type of social capital between persons in space, which have both been empirically detected as significant configurational factors influencing people's co-presence in the public space (Marcus and Legeby 2012; Legeby 2013). Following these efforts, this research further explores the roles that other key aspects of land-use systems might play in facilitating potential co-presence between different social groups. By using the social media check-in dataset, this part of research can fully analyse the whole city at the street level on the dimensions of space and time. Besides the validation of the spatio-functional model in social research, the novelty of this study relies on uncovering the social capital of different urban development strategies (e.g., compact development, mixed-use, etc.).

By seeking the answers to these research questions, the expected findings of this thesis could be of great value for urban designers or planners and decision makers in deploying an effective methodological framework to measure the spatial network and the land-use system with the same theoretical propositions, in understanding the shifting relationship between spatial confirmation and land-use patterns in the urban evolution process, and in evaluating the social and economic results of particular design proposals, land-use plans and zoning policies based on the spatial and functional context in which the study area is embedded.

2.3 Research scope

In attempting to look for the organisational properties of urban spatial structures, this thesis attaches itself to an investigation of centrality patterns in the spatio-functional context, which intends to bridge between configuration studies and accessibility examinations in geography. Configurational studies have produced powerful methods of measuring the structural properties of the spatial fabric but expected land-use is normally used as a dependent variable. Explorations on geographical accessibility, by contrast, represented another type of centrality measure across geographical landscapes capturing the spatial agglomeration patterns of the functions. These approaches, however, have largely neglected the influences exerted by city form, thereby being absent from the research on urban design and morphological studies. With the aim of augmenting the current theoretical and practical development of measuring the spatial structures of cities, this thesis investigates whether developing a joint model of these two types of centrality measures can improve the predictability of various types of urban performance from an urban design perspective. To achieve this goal, this work does not intend to copy mechanically any concept or method, from geographical research to configurational studies; instead, it focuses on developing a novel, comprehensive method of measuring the geometrical centralities of spatio-functional settings, specifically within the well-established framework of configurational analysis. The findings of this research are expected to confirm the necessity of quantifying the functional context in conventional built-form studies for addressing the complexity of contemporary cities.

Social studies is another body of theory in which this thesis is grounded. Existing research has produced many crucial insights into the spatial clues of socioeconomic observations. These insights, however, are mostly based on predefined spatial units, such as the administrative area, census unit, or grid cells, which cannot account for the impact of public spaces, the real arena in which social activities occur. Efforts made by researchers in the space syntax community have filled this gap. It is argued in space syntax studies that urban streets are not only the rudimentary elements forming the configurational centralities, but also the basic units for social analysis. Space syntax research has demonstrated that there is an interdependence between spatial networks and their social significance when considering these as disaggregated data. Inspired by these efforts, this dissertation aims to use the configurational centralities of social studies as vital independent variables to predict dependent socioeconomic patterns. One prominent advantage of configurational studies, the space syntax model, in particular, is the fine resolution that it offers for analysis. Using street segments as units enables the results to be spatially scalable, thus avoiding the so-called modifiable areal unit problem (MAUP) (Openshaw and Openshaw 1984). On that subject, this research does not try to use aggregated spatial data, such as census data, which lacks information about demographic differentiation across spaces within the census units; instead, it uses location-based data about land-use and social performance with geocoded coordinates that can be accurately assigned to the street segments. In this manner, the robustness of the analyses and conclusions can be secured at a disaggregated level by removing the MAUPs.

This research adopts a series of quantitative methods, including data mining, spatial regression models, and clustering analysis, to exploit the configurational logics of social performance, which are concepts employed in social and economic studies. These approaches can produce fruitful results, comparable with other models that employ different variables, whereby bringing together the knowledge that has been well-established in the theory of social science, spatial economy, and configurational studies. The encouraging results produced by these approaches make them viable alternatives for cross-validation of the core argument in this thesis. Shanghai, a typical modern city in the process of rapid urban growth, is selected as the study area instead of any other organic city due to its values regarding the complexity of its spatio-functional contexts and the availability of data resources. It is argued that the analytical methods and the generated results in the case of Shanghai can serve as valuable references for those cities in the trend of rapid urban growth or large-scale urban regeneration.

3 STRUCTURE OF THE THESIS

This thesis contains seven chapters, as briefly outlined and represented in Figure 1-1.

Chapter 02 reviews the related literature on location theory of the land-use system and configurational studies on the built environment. By discussing the theory and the methods of capturing city centrality structures in these two fields, this chapter describes the potentials of incorporating these two theoretical approaches to fill the gaps in knowledge. It is also argued that spatio-functional interaction is essential for social and economic processes and place solidarities and that it, therefore, has great significance for urban performance. Against this background, this chapter ends with discussion of the relationship between spatial configuration and land-use patterns and how far this relationship can contribute to producing an advanced understanding of the nature of the urban transformation and other performance.

Chapter 03 concentrates on developing a methodological framework for this thesis. It begins with an introduction of the framework and the spatio-functional model that is adopted for the whole thesis and represents the ways in which urban function connectivity and space syntax centrality measures can be incorporated and related to other social performance. A summary of all the methods that will be applied to the analytical chapters and an introduction to the case study and the related data and method structure are also described. The second part of this chapter introduces the graph representation of spatial configuration and related syntactic techniques in the space syntax theory. Two centrality measures in the spatial network segmental analysis, including the angular integration and choice, are introduced. By constructing the path-point and network interface models, this chapter proposes a framework to measure the urban function connectivity through the street network with the function nodes in a dual-graph representation of the land-use distributions through the spatial network. The three core variables applied are 'accessible urban density', 'diversity' and 'cognitive distance'. The chapter continues by comparing the frequency distributions and the mapping results of the centrality structures generated by space syntax centrality and function connectivity measures for preliminary verification of the complementarity between these two types of accessibility for the analysis of spatial structures. This chapter ends with a discussion of the study's methodological limitations.

Chapter 04 presents the first empirical studies on the urban evolution process on the basis of the spatio-functional interaction model. It starts by examining the spatial centrality process and the functional centrality process indicated by the space syntax centrality measures and urban functional connectivity measures, respectively, in the history of the urbanisation process of Central Shanghai, China. To investigate the dynamic interaction between spatial centrality structures and functional centrality structures, the second stage of the analysis undertaken in this chapter focuses on the shifting correlation between the centralities at various radii during different historical periods. The chapter then moves to the third stage of analysis, in which the change of the detected function regions with different composition of spatial and functional accessibility variables is the new focus. The findings of this chapter indicate that the functional patterns are not necessarily the results of the design of the spatial networks. The results also suggest that the synergy between spatial and functional centrality structures at multi-scales can distinguish the developing stages in the city's history, can influence the transformation of the centre structure, and can predict the memberships of the defined function regions. This chapter thus verifies the importance of land-use patterns as a crucial layer in morphological analysis and provides references to the applications of the spatio-functional model in the analysis of the urban evolution process of other cities.

Chapter 05 presents an empirical study of the relationship between multi-scale spatio-functional interaction and spatially heterogeneous house-price patterns in Shanghai. Due to the spatial heterogeneity of housing-price patterns, the mixed-scale hedonic model is employed, allowing us to identify explicitly the price effects of configurational variables. Through model competition, the stationary and non-stationary centrality variables are defined. The non-stationary factors are further applied in the spatially constrained clustering analysis to delimit the housing submarket patterns. The results of this chapter provide evidence that function connectivity measures are the statistically significant factors for estimating the variation of house prices in the study area, and that adding these variables can significantly improve the predictability of the model with only the space syntax centrality factors and the structural variables. It is found that spatial and functional centrality measures on the local levels simultaneously showcase significant spatial variation and play vital roles in defining the submarkets with the structural variables. This study verifies the effectiveness of the function connectivity measures and confirms the necessity of adding them in the hedonic model as the location variables with space syntax centrality metrics. The findings of this study can enrich current understanding of the importance and the complexity of spatio-functional interaction in housing valuations and ensure the economic effects of urban design with greater spatial precision across submarkets.

Chapter 06 studies the influence of the spatio-functional interaction on the physical co-presence between local random visitors and remote guests of public space in Central Shanghai. Based on the mobility patterns recorded by the social media datasets, this chapter firstly describes the spatiotemporal presence patterns of the defined random users and the remote visitors in every street through the spatial network and then quantifies the balance between these two groups of space users. Multiple regression methods are employed to assess the influence of individual centrality variables by controlling the effects of other factors. In the second stage, the network centralities and the temporal co-presence attributes for streets are utilised to group urban streets into spatial communities indicating different modes for how spatiotemporal physical encounters are driven by distinguishable spatial conditions. It is shown that both spatial and functional centrality measures are significant for the variation of people's presence through streets. The results of analysing the degree of balanced co-presence suggest that the areas maintaining higher degrees of spatio-functional synergy can generate more opportunities for local people and visitors to encounter, both physically and temporally. This chapter yields the insight that a land-use system can also provide valuable insight for increasing the accuracy of estimations of the social consequences of urban design.

Chapter 07, the last chapter, brings together all the findings of the previous chapters in light of the existing built-form theories and location theory, as reviewed in Chapter 02, and then it theoretically explores the underlying syntactic principles of spatio-functional interaction that account for urban evolution and socioeconomic performance based on the conclusions drawn in Chapters 04, 05,and 06. Aside from the development of urban function connectivity, defined as a multi-variable and multi-scalar accessibility measures—and beyond the formulation of the spatio-functional interaction model, which contains the spatial and functional network centralities—this research addresses the effectiveness of the proposed methods, the academic relevance of the morphological analysis and the estimation of socioeconomic performance, as well as the potential to augment urban design for revitalising urban form under different spatial restrictions.

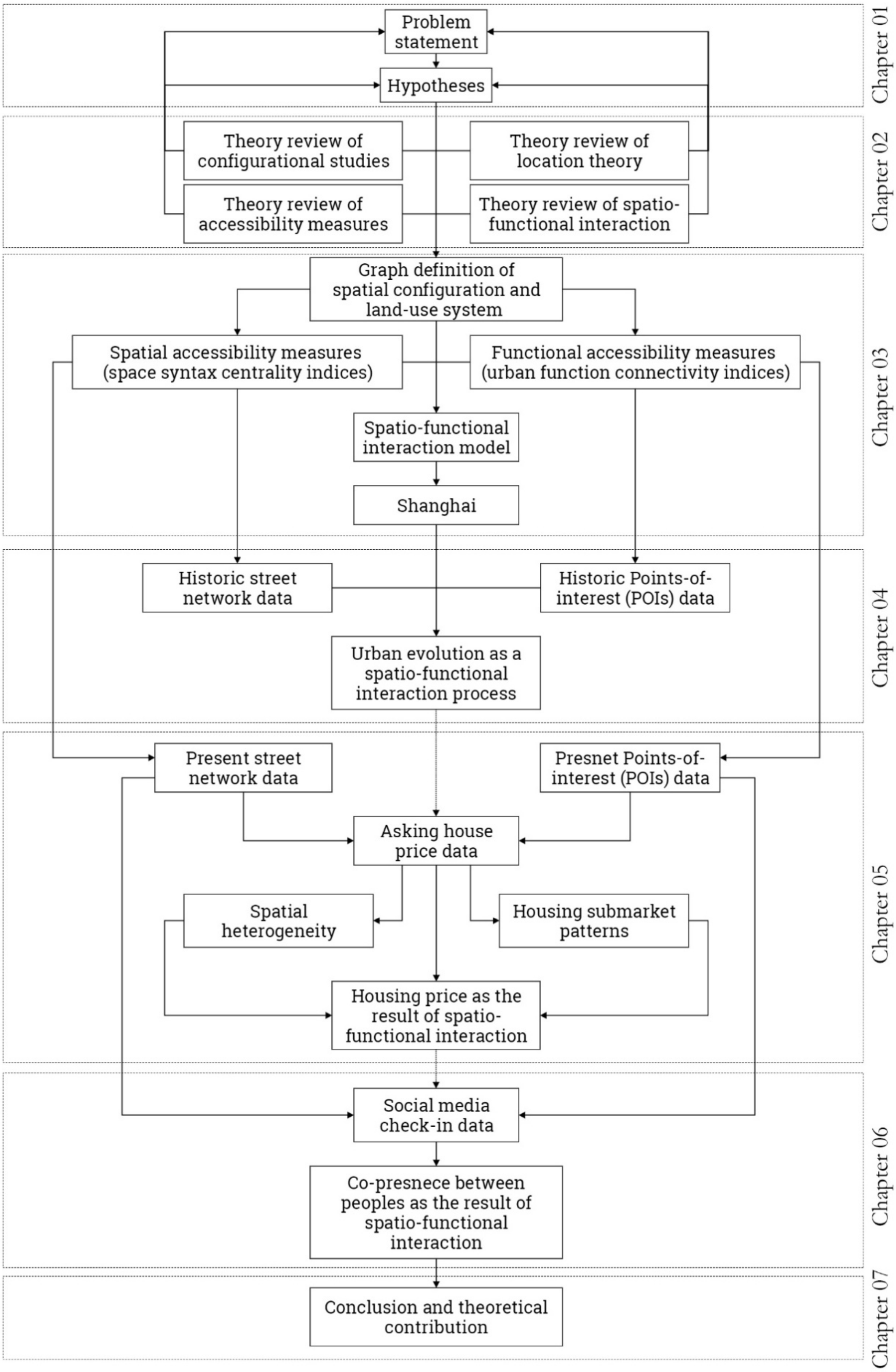


Figure 1-1

The structure of the thesis

CHAPTER 02

LITERATURE REVIEW

1 INTRODUCTION

This chapter introduces a literature review of the conceptualisation, definitions, expressions and measures of urban centrality structures in existing theories and empirical studies. The main focus of this chapter is to place the issue of urban centrality in its wider context and to provide a comprehensive understanding of its various meanings. Detailed reviews of other specific theoretical and methodological issues addressed in this thesis are discussed in various chapters in due course.

Urban centrality, referring to the conceptual importance of urban centres and describing the organisation of urban systems, has become a core concept in physical planning over the past seventy years. However, ambiguity in its definition remains despite the fact that related concepts have been widely used in research and practice. The importance of a 'centre' can be expressed as a nodality on the basis of the internal characteristics of the centres, or can be defined as centrality—the relative prominence of centres—with external relations of centres. By addressing the interplay between the internal and external characteristics of the centres to give a more comprehensive understanding of centres in the complex urban system, the concept of centrality has evolved to its advanced version—accessibility—by approximating the external relations of centres, using the distributions of the internal characteristic of cities.

In general, there are two principal dimensions in the modern concept of centrality: the spatial and the functional (Green 2007; Meijers 2007; Burger and Meijers 2012). The spatial dimension captures the size, shape, and locations of the centres; while the functional dimension signifies the flows that interlink the centres. The discrimination in the ways of conceptualising and measuring the spatial and functional elements in urban system leads to two mainstreams: a geographical perspective and a configurational perspective. In geography, and transport geography in particular, the land-use and the transport components are utilised to gauge the potentials between land-uses in places. The observed urban land-use patterns, in this framework, are (re)produced by the interaction between land-use for reallocating locational advantages within an economic process. Configurational studies focus primarily on the geometrical nearness between spatial elements, illustrating the fundamental impact of the built environment on the (re)formation of urban centres. The configurational theories emphasise the spatial efficiency resulting from the organisation of the spatial layouts of the core resources for which various land-uses compete.

The conceptual distinction of centrality between these two fields leads to methodological developments and relevant applications in planning and design practice. The outputs from the built-form studies have been introduced and adopted in practice, but largely under-examined in socio-economic research. Geographical research, on the other hand, links locational advantages with economic production, but neglects the geometrical nature of the built environment. Although these two theories have been formed with different propositions, their concerns for urban space, land-use patterns, and processes in which they manifest in socio-economics are equally shared. Urban centrality, or "accessibility," as it was dubbed in its later form, developed in these two fields with a similar concern for urban performance, indicating the necessity and possibility of bridging them to generate mutual benefits for both sides and to empower the current operation of centrality structures for greater refinement in planning and design.

Based on the awareness of the complementarity between these two theories, extensive efforts have been made to develop joint approaches to produce a more comprehensive and explicit explanation of the observed urban centrality structures and the related functionality. These encouraging exertions provide rich foundations for the exploration in this research, in which the geometries of the spatial and functional built environment are the main factors driving social processes.

This introductory section presents a short introduction to the definitions in relevant theory and models, the different groupings and components of centrality measures, and the aim of the literature review. The origins of centrality and its principal dimensions are discussed in Section 2, while Section 3 and Section 4 describe and review the theoretical and methodological propositions of centrality measures found in the literature, categorised by two main perspectives on centrality structures, including geographical and configurational studies. These two sections also contemplate how centrality measures can be used as a basis for social and economic evaluations of the changes of the patterns of land-uses and physical layouts in these two sections. Section 5 synthesises the conclusions of the literature review.

2 CONCEPTUALISATION OF CENTRES

2.1 Recognition of centres

Defining urban centres is a core task in the study of urban-system organisation, a task shared by many fields across various scales: urban geography, regional science, built-from studies, social research and spatial econometrics. The study of the patterns of centres originates from urban location theory and traces back to the milestone work produced by Christaller (1933; 1966) and Lösch (1954) on central place systems. However, the precursors of their work can be traced back to classic location models, such as the agricultural location model (Von Thünen 1826) and the industrial location model (Weber 1909), which inspired the well-known monocentric city model with bid rent[1] deviations, pioneered in the 1960s by Alonso (1964), Muth (1969) and Mills (1972). The Alonso-Muth-Mills model, a typical form of neoclassical

[1] 'Bid rent' refers to the amount the land users are willing to pay for land.

economics relying on a highly conceptualised urban spatial structure, accounts for the spatial relationships between different sectors to understand the motivation underlying the formation, functioning and evolution of cities. Being similar to its successors, the Alonso-Muth-Mills model illustrates that different land users will compete with one another for land that is close to the city centre. The central business district (CBD) is the area in which people are much more willing to pay more for land, and their desire tends to be less for land that is farther from the central area (Figure 2-1). Land-use zones are spatially differentiated with bid rent lines associated with different slopes indicating the varying decaying influence of the CBD from its core towards the suburban areas of the city. For instance, rent that commerce users are willing to pay is the steepest line, which indicates that the bid rent for commerce declines faster for every unit of distance from the centre than for all other land-uses. The monocentric city model, although it has been weakened due to increasing urban complexity, still provides an ideal model for defining the centres with the concentration of demands and its relation the distance cost.

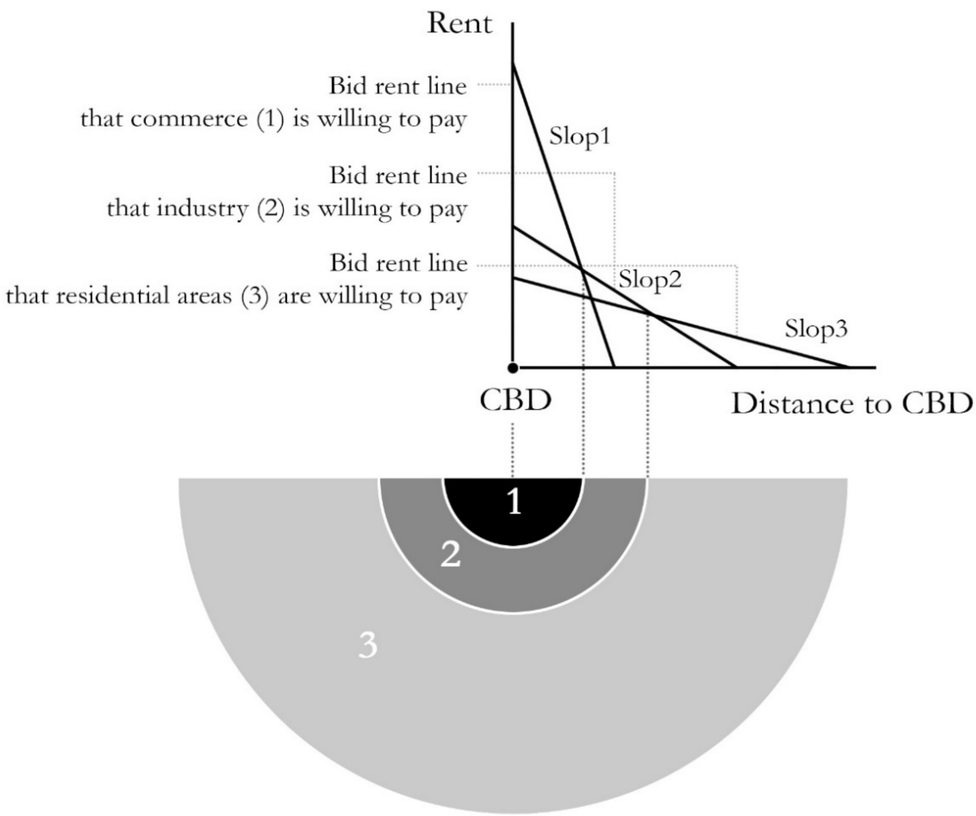


Figure 2-1

The monocentric city model with the bid rent curves for different types of land-uses (Alonso 1946)

The monocentric city models were further developed in the work of Christaller (1933), Lösch (1944), and their predecessor, Galpin (1915), who proposed the so-called *central place theory*, in which centres are refined as central places with an inherent hierarchy. The central place models provide a logic regarding the distribution, size, and number of centres (Berry and Parr 1988) by capturing the market share patterns confined by the core-periphery relationships (Berry and Pred 1965). In a central place system, urban centres are hierarchically distributed according to their absolute importance indicated by the amount and variety of goods and services they can provide. Given that, centres in the lower order are grouped around the higher-order centres for the provision of urban services and products (Clark and Rushton 1970). Consequently, it is assumed that the trade between centres of the same size is unnecessary, as they supply the same goods and services, and the service areas of central places in different orders monodirectionally overlap, thereby forming a tree-like pattern where service extends from higher-order central places to cover the zones of lower-order ones (Figure 2-2).

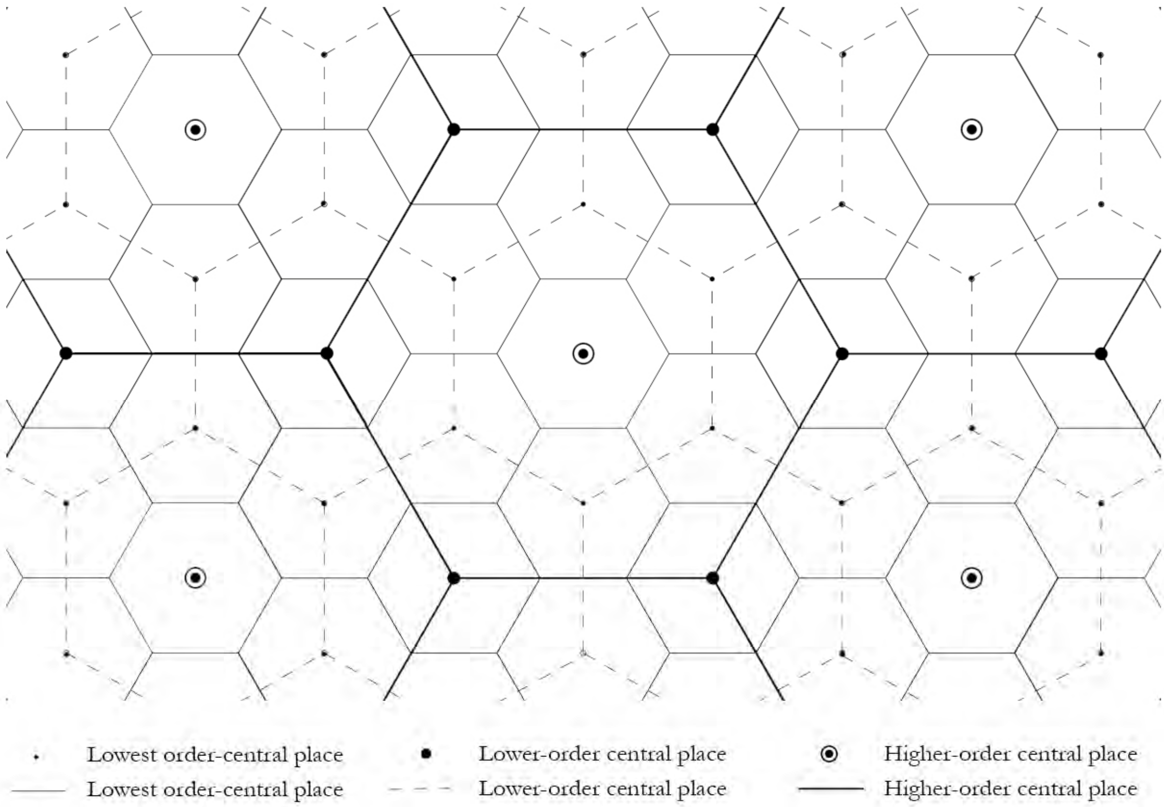


Figure 2-2

The central place model (Christaller 1933)

The central place model is constructed based on two key elements: the first is *economic distance*, which is the maximum distance people will travel for certain type of goods, associated with the *range* to define the hexagonal service areas of centres; the second is *threshold* for identifying the levels of the central place. Equipped with these two elements, the central place theory suggests that the urban system consists of a set of variously sized self-governing centres and the interaction between them. It also provides an approach by which to identify the boundaries of the centres by the subdivision of the markets (Dacey 1965), which have been extensively discussed in one-dimensional location models (e.g., Hotelling 1990).

The central place model has been criticised for its idealisation of urban reality and based on the relaxed assumptions that the landscape is homogeneous and isotropic, and that all the citizens would always travel rationally (Berry and Garrison 1958). Moreover, it is hard to find any service area for a central place that is exactly hexagonal, as proposed, due to the spatial variations of transport conditions (Batten 1995).

However, the existence of these limitations cannot negate the plausibility of the meanings produced by such a simple model. Firstly, it introduces a way to use the provision of services in places to define the absolute importance of centres. Secondly, it emphasises the essentials of the inter-level and intra-level interactions among centres. Thirdly, it introduces a framework for translating the hierarchical systems of urban centres across spatial scales. The model's novelty inspired the Chrisrallans and Löschians to develop other models built on the central place theory, along with the idea of hierarchical urban systems in general (McPherson 1981).

Extensive work has been conducted with the aim of extending and modifying the formal model. For instance, in Figure 2-3, a bid rent surface is mapped with the hierarchy and threshold within Christeller's central place theory to aid the understanding of the intra-city land value surface (Nagle 2001). Also, the existence of the hierarchical structure of the centres has been proven with economic data to follow relaxed scaling laws at the national and regional levels (e.g., Gavaix 1999; Soo 2005) and at the intra-city level with ubiquitous data on people's activities (Jiang and Jia 2011). Importantly, as an application of the general system theory in the urban landscape, the central place model emphasises the hierarchy of centres' importance, in which a principal centre manifests in its size as well as its connections to the surrounding subordinate centres (Cliff et al. 1965).

It is argued that the general contribution that the central place theory made is reclaiming the significance of the centres' hierarchy in the definition of centres, and advocating attention to the absolute importance in the nodal area of a centre, and its relative importance embodied by nearby sub-centres of different hierarchical orders. Though facing increasing challenges explaining spatial reality, Christaller's central place theory provides valuable insights for the birth of the following theories and methods of defining urban centres.

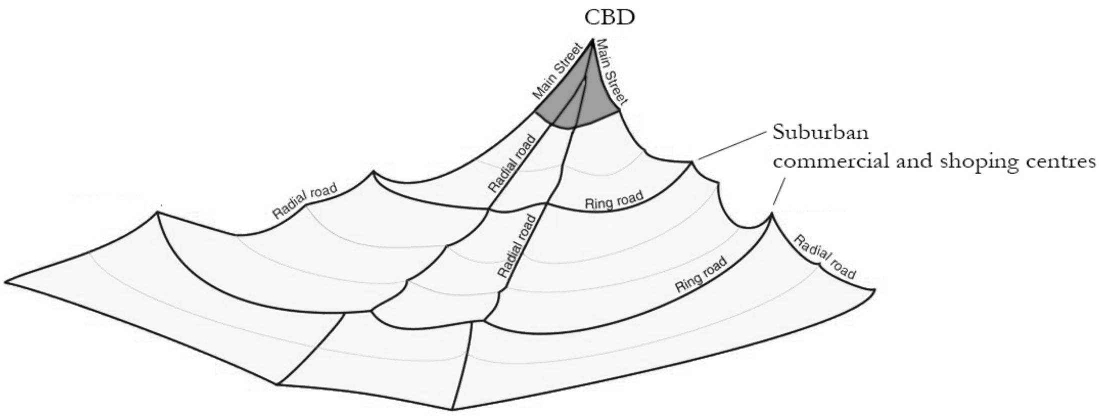


Figure 2-3

A bid rent surface indicated by Christaller's hierarchy and thresholds within the central place theory (Nagle 2001)

2.2 Nodality, flows and centrality

Urban centres are defined according to their importance. Based on Christeller's work, Preston (1971, 1975) generalised and categorised the importance of centres into two main types: absolute importance, or "nodality," in his words, and relative importance, that is, centrality. The nodality of a centre can be measured by its size in terms of population, total sales, and so forth, along with the variety of the services it can supply (Preston 1975; Lukermann 1966) within its boundary, whereas the centrality of a centre is captured by the amount of the services offered to the other centres (Preston 1975; Barton 1978; Marshall 1989). In other words, nodality is related to the importance of centres for all users, whereas centrality is the importance of centres remotely recognised by external users from other centres. This idea was proposed by Preston (1975) in a mathematic form where the centrality of a centre in a closed urban system is the difference between its nodality and local importance represented by the size of local markets (Figure 2-4). The key concept to define and distinguish these types of centres' importance in this model is *urban flows*. Centrality is here identified as a non-local importance, quantified by the incoming external flows which are a subset of nodality.

In fact, central places were originally ordered taking into account their external relations to other central places in the original work by Christaller (1933), assuming that the centrality of central places correlates with their local importance in his classic model. This assumption highlighted the contribution of the external relation of centres to the hierarchy of centres, but failed to explicitly extract centrality from the local importance of central places, which led to the absence of centrality in the post-war modified central place models. There are several reasons for this failure from both theoretical and technical perspectives. The hierarchical system of centres in the extended model was directly related to the patterns of city size, and the relations of centres are one type of products of the market occupancy (Beckmann 1958; Parr 1969). Meanwhile, a lack of data regarding the interactions between centres and effective methods to estimate the urban flows has delayed the exploration of the centrality structures (Thompson 1974; Coffey 1998). Consequently, the attention paid to measuring the centrality structures of cities from an inter-centre point of view is relatively limited before the 1990s.

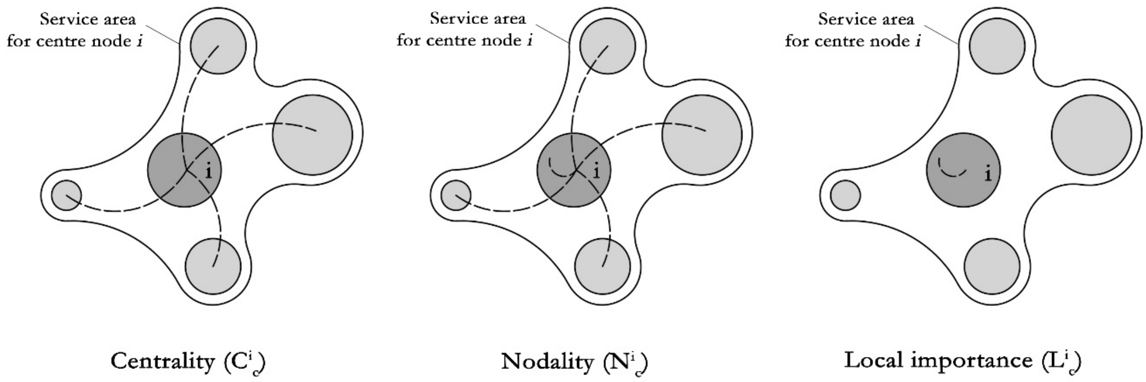


Figure 2-4

Local importance, nodality and centrality indicated by flows in a tight urban system: $C_c^i = N_c^i - L_c^i$ *(Preston 1975)*

Modern cities, in tandem with the development of new transport and information technologies, have been increasingly evolving into being more polycentric than that in history (Anas et al. 1998). In his book *Edge City: Life on the New Frontier*, Joel Garreau (1991) argued that the *edge city*, a multitude of dispersed and interacting hubs where urban services are concentrated outside the traditional central business districts, is a modern standard urban form unlike that of the 19th century, characterised as a monocentric sample, after which the so-called 'polycentric development' or 'polycentrism' attracted vast attention. It was argued that the trend toward polycentric urban structures driven by the local economies of agglomeration (Strange 2008) can reduce average commuting times (Gordon et al. 1991; Cervero and Wu 1997), improve commiserations for inter-firm collaboration and trade (Turok and Bailey 2004), and provide a solution to social cohesion (Musterd and van Zelm

2001). Furthermore, many studies have yielded empirical results indicating that the centrality structures capture the inherent polycentricity of urban systems that cannot be described by the pattern of local nodality (e.g., Preston 1975; Short 2004; Burger and Meijers 2012).

At an intra-city level, Bertard (2001) has highlighted the importance of urban flows for indicating the spatial structures of cities and summarised cities into four main types according to the patterns commuting trips (Figure 2-5). He argues that most cities in the world are 'composite cities'—a combination of the classic monocentric model with the polycentric model—where the central business areas are the hinterlands, surrounded by scattered sub-centres. In composite cities, people are oriented by a range of various travel needs across centres instead of the single demand assumed in the classical location theory. It was also pointed out that to portray the distributions of urban flows—a schematic of the complex trajectories of people's habits of movement—is an effective way to understand the spatial structure of cities, as the city with fully self-sufficient centres without any inter-centre connections does not exist (Bertaud 2004).

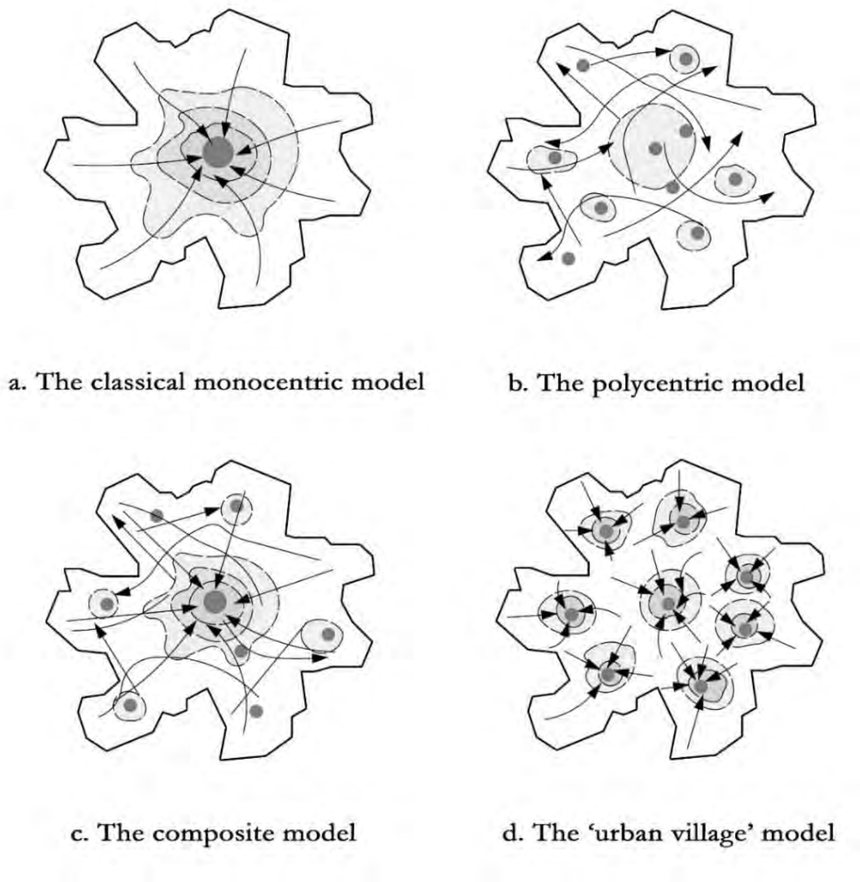


Figure 2-5

The typologies of cities defined by commuting trips (Bertaud 2001)

Despite that the interrelationship between the centrality structures and the local nodality structure has been challenged (Preston 1975; Short 2004), urban centrality structures have attracted more academic attention, as they capture the inherent structures of cities. It has been empirically recognised in the Dutch urban regions that an urban system with centres that are more evenly characterised by similar nodality does not entail an increase of the evenness of inter-centre connections (Burger and Meijers 2012). Therefore, constructing functional polycentricity has been claimed to be more essential for the agenda of the polycentric development than spatial polycentricity (Hall and Pain 2006).

The discussion on the formation of centrality via spatial interventions occurred also among the urbanists, planners and designers who proposed their ideas of urban structures in spatial plans. Among those works, Howard's *garden city* (1898; 1902) had a profound influence on the subsequent physical design of cities throughout the world (Mumford 1945). He suggested that each garden city could accommodate 32,000 people in the area of 1,000 acres, constrained by a green belt. Six wards were allocated in it and enveloped by boulevards. He further extended the single city model to one consisting of several garden cities, termed *social cities* (1898). The social city model aimed to consolidate the local nodality of centres and to foster the centrality structures. The plan of the social city impacted the spatial layouts in the models proposed by other theorists, such as the *neighbourhood unit* (Perry 1929), the *regional city* model (Calthorpe and Fulton 2001), and so forth.

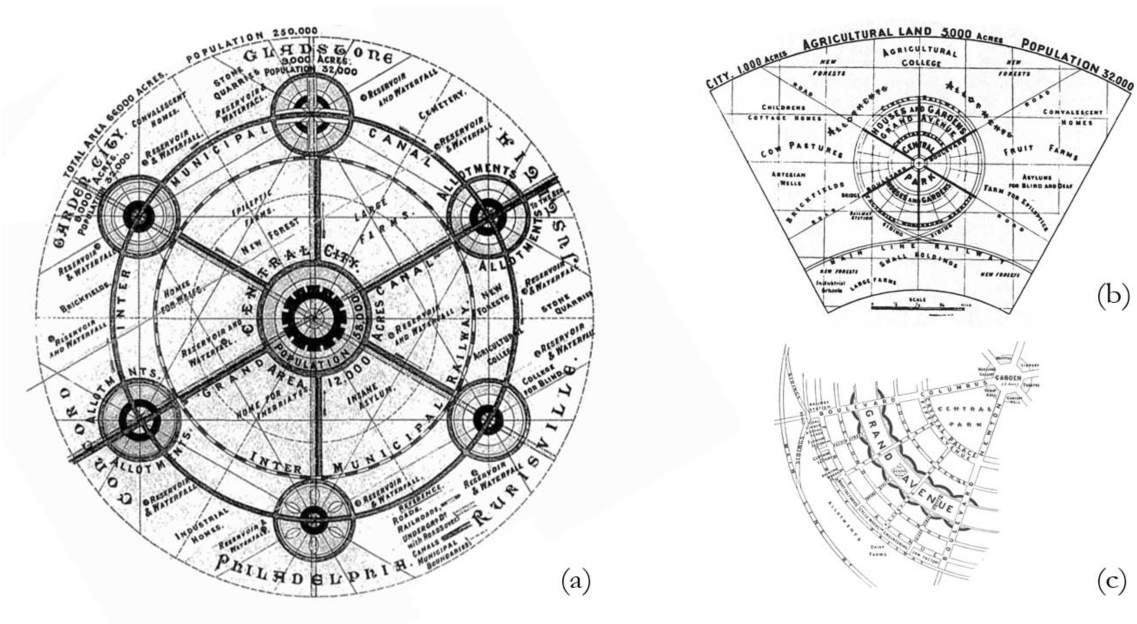
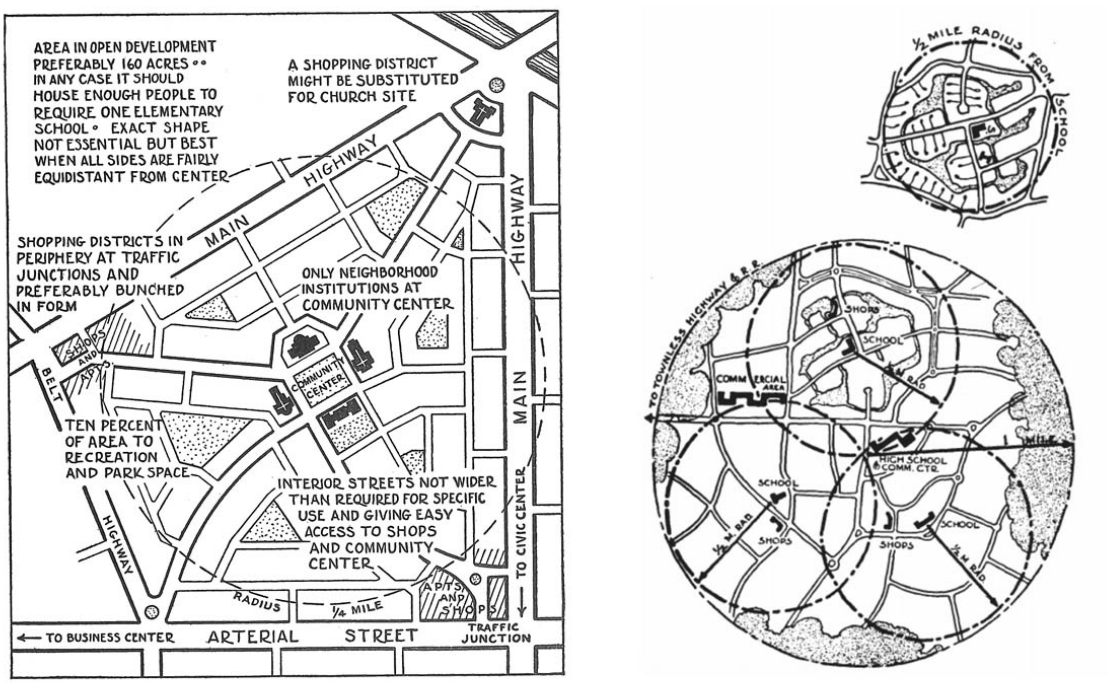


Figure 2-6

The diagrams of (a) the social city (b), garden city and (c) ward (Howard 1989)

Inspired by the garden city models, Perry (1929) proposed a new paradigm for the organisation of physical form at the intra-city scale for the *neighbourhood unit:* a local centre for communities in the modern cities. In his work, the neighbourhood unit was bounded by the major arterials and sized according to the walkable catchment area of an elementary school or other social complexes located in the geometrical centre. The neighbourhood unit emphasised the nodality of residential units by blocking passing traffic and encouraging internal walking services, which has been promoted and adopted in practice. The well-known *Radburn principle* is an extension of Perry's neighbourhood unit into a regional system for the motor age, in which the superblocks were spatially divided by the main roads and connected by green footpaths (Stein 1942). Beyond the contribution on reshaping modern residential areas, Perry's and Stein's work highlighted the importance of a geometrical centre for the formation of the real functional centres. This indication exerted significant impacts on later urban design. Relevant examples include the urban quarter model (Kier 1977), the urban village model (Aldous 1992), the model of the transit oriented community (Katz 1994), and so forth.



(a) (b)

Figure 2-7

The diagrams of the neighbourhood unit (Perry 1929) and the Radburn principle (Stein 1942) (Gallion and Eisner 1950)

To design clear spatial constraints and simple geometrical cores for enhancing the local nodality of centres is a notion that has been widely criticised since the 1960s and the raised awareness of urban complexity which accompanied that decade (Jacobs 1961). By abstracting cities as interrelated patterns, Alexander (1965; 1977) claimed that the liveness of a city could hardly be captured by its clearly defined parts; rather, each part has to indicate its relationships to other patterns and to the city as a whole. He criticised the conventional models representing urban structure with nodes in a hierarchical or interactive order for aggregating centres mechanically and failing to reflect the functional reality of cities. By introducing the graph theory, he proposed the *semi-lattice structure*, represented as a well-connected network graph where any two parts of a city were overlapped, and their shared elements belong to the whole structure (Figure 2-8); he further argued that a functional city is a synthesis of all the interconnected patterns, thereby producing a wholeness (Alexander 1987). Although Alexander neither represented an ideal spatial form for his semi-lattice structure nor detailed its social consequences, his argument that the large centre manifests on the basis of the interaction between sub-centres from the bottom up accords with arguments concerning centrality structures in location theory. Out of this agreement came fruitful insights for the following work on uncovering centrality structures from the urban design perspective.

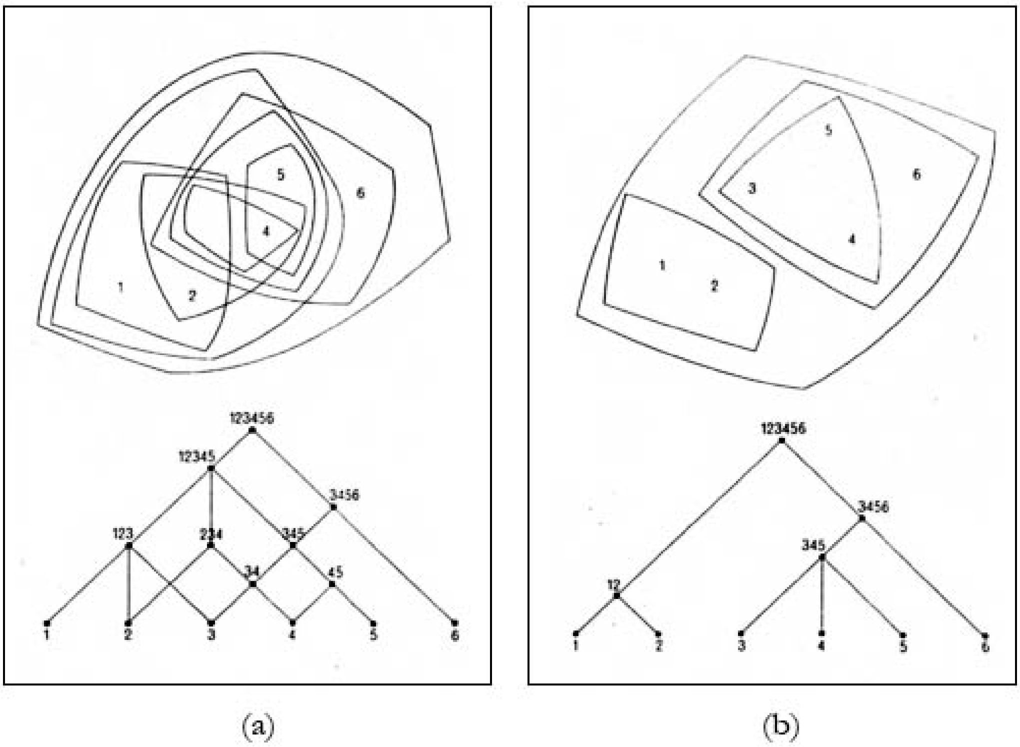


Figure 2-8

The diagrams of (a) a semi-lattice structure (b) and a tree-like structure (Alexander 1987)

It is relative simple to draw a parallel between the development of centrality in an urban system and centrality in network analysis. In graph theory, centrality is traditionally represented as a series of node-level properties relating to the structural importance (Borgatti et al. 2009). Although the network analysis normally focuses on the centrality in nodes, this node centrality is deeply rooted in the patterns of network flows. To a large extent, a network is a description of path systems through which something flows. Accordingly, the importance of the network elements is conceived in relation to the flows transferring across the network (Borgatti 2005). This focus implies that the meanings of centrality will change in accordance with shifts in the ways flows are defined and quantified (Borgatti and Everett 2006). Thus, network analysis explicitly quantifies the measures of centrality in mathematical forms, thereby enriching understandings of the formation of network structures and providing tools to analyse them. Interest in network analysis has increased significantly since the 1990s, following claims that the present urban systems may be considered 'networks' because of the manner in which the polycentric structures of modern cities have evolved against the background of economic growth (Batten 1995).

At the global scale, the term 'city network' was formulated to reveal the global location strategies for placing offices in different global cities (Taylor 2001). Indicators of 'graph centrality' have also been applied for understanding the patterns of economic flows, such as international trade (Smith and White 1992), the news flow (Kim and Barnett 1996), intra-urban service links (Provan and Sebastian 1998) and social capital (Borgatti et al. 1998). Meanwhile, they were also employed to detect the most influential persons in a friendship network (e.g., Borgatti and Everett 1992; Wasserman and Faust 1994; Gest et al. 2001), the hub locations in airline network (e.g., Jaillet 1996), and high-risk individuals for epidemic diseases in cities (e.g., Christley et al. 2005). Moreover, it has been claimed that network cities were capable of maintaining more diversity, creativity, locational freedom than traditional monocentric cities due to the advantages of 'concentrated deconcentration' (Hall 1984; Batten 1993; 1994).

Urban theory was preoccupied with monocentric models concentrating on the local nodality of centres. However, the evidence of the polycentricity of urban centres in modern cities against such an oversimplified idea is growing dramatically. Although the debate continues concerning whether the definition of centres should be constructed based on their internal features or external urban flows (Burger et al. 2011), the centrality structures, produced by the interaction between centres at various levels, were recognised to be effective descriptions of the inherent spatial structures of cities, which was hardly captured by the patterns of nodality in monocentric city models (Ross 1992). Due to the absence of detailed flow data, subsequent extensive efforts have been made since the 1950s to approximate the centrality structures by using a certain characteristic of the city system, which upgraded the concept of centrality to its modern form: accessibility.

2.3 Dimensions and typologies of centrality/accessibility

Accessibility, an advanced form of centrality originating from location theory, as discussed, has become a core concept adopted to assess urban planning and design and the relevant decision-making processes since the 1950s. Inspired by the definition of 'potential' in gravity theory, Hansen (1959) defined accessibility as 'the potential of opportunities for interaction', which was measured by relative nearness from place to place or from people to people. A similar idea was earlier proposed by Stewart (1948), who applied Newtonian formulae of gravitation to quantify 'the interrelation of people' by measuring so-called 'demographic gravitation'—the attractive force for population agglomeration—in social physics (Stewart 1950). Subsequently, accessibility was re-identified and operationalised in various ways, thereby making its meanings dimensionally inconsistent. For example, it can be defined as the chances reachable through a particular type of transportation (Dalvi and Martin 1976), or richness of choices (Burns 1979), or the benefits brought by facility improvement (Ben-Akiva and Lerman 1979). In general, two elements are essential for most of the definitions of accessibility: the opportunity at a place and the cost of realising it. Therefore its usual form normally, in relative terms, approximates the difficulty of realising all opportunities from one place (Batty 2009). In this sense, accessibility can be interpreted as a compound cost-benefit difference across spaces generated by the city structure.

It has been argued that there are two principal dimensions of the urban spatial structure: morphological and functional (Bruger and Meijers 2012). The morphological aspect refers to the distributions of the centres, namely the patterns of local nodality, whereas the functional aspect addresses the interaction between nodes, such as the commuting flows or trading connections. Accessibility combines these two aspects by conceptualising the local nodality and the distance between nodes as benefits and costs of interaction, respectively (Batty 2009). This relationship has been described in the classical versions of accessibility: in the gravity model, the spatial interaction (T_{ij}) between location i and location j is a function of their integrated nodality, the result of multiplication between the weights of the centre (W_i*W_j) at those two locations, mediated by the level of separation (d_{ij}) (Rodrigue et al. 2013) (Figure 2-9a). The gravity model was extended, and the modified models can be elaborated into two main types, including the potential model (Wilson 1967) and the retail model (Hotelling 1929; Reilly 1931). The potential model could be considered an application of the gravity model in a complex urban system. Consequently, the accessibility of an urban node is quantified as the sum of the interaction between it and all other locations (Figure 2-9b). The accessibility patterns, therefore, vary from place to place across the geographical landscape because of the unevenness of the urban resources and their connections. There was another type of spatial interaction focusing on delineating the boundaries for urban nodes along the connection between nodes. It assumed that the boundary (B_{ij}) of the service areas for two centre nodes along the path interlinking them could be measured, with the result that the cost of interaction is subdivided by the ratio of node weighs at two locations. All three of these models implied that the urban spatial structures indicated by the accessibility measures combined nearness, and the opportunity to account for nearness was valuable in the classical location models because flows patterns could be detected and the interplay between the morphological and functional aspects of the urban system could be mapped.

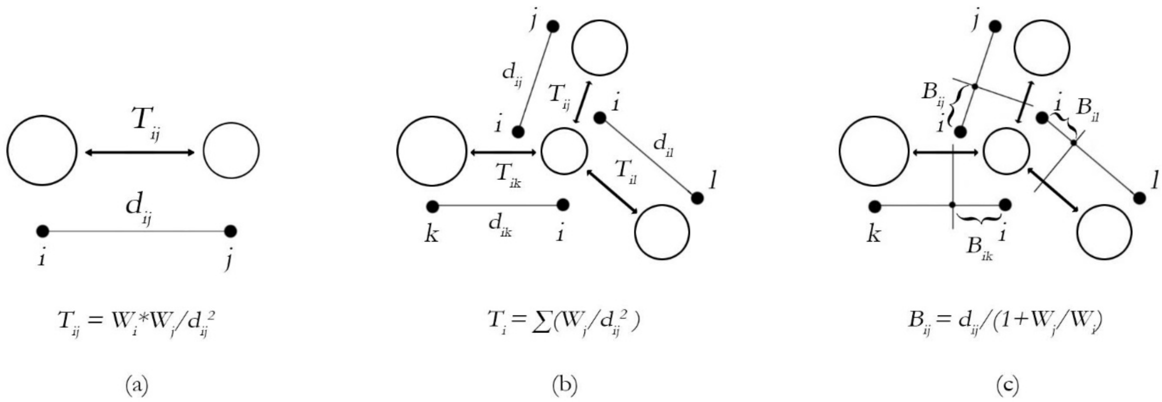


Figure 2-9

Three basic types of spatial interaction models: (a) gravity model, (b) potential model, and (c) retail model (Source: Rodrigue et al. 2013)

The components of accessibility can be identified from different perspectives according to the details of the requirements on the practical and theoretical sides. Researchers have tried to distinguish accessibility metrics in various groupings. For example, Bhat et al. (2000) grouped the existing accessibility indices into five types, including the gravity models, cumulative opportunities models, utility-based models, spatial separation models and time-space models. The former three models were further grouped, as the location-based model in which the agglomeration of opportunities was assessed with the cost indicated by the straight-line distance on the basis of the assumption that urban opportunity landscape is heterogeneous, while the impedance of physical infrastructure is soothed (Geurs and Von Wee 2004). By reversing this assumption to presume urban opportunities were evenly distributed, it could be easy to demonstrate that the distance between opportunities could be thought of as reciprocal to accessibility at a finer scale in the spatial separation models. Some specifications in this type of accessibility model were established based on the network analysis when graph theory was introduced to the geography in the 1950s and 1960s. The subset of graph-based indices, unlike other metrics in the spatial separation models based on average times, travel speed or costs, was less favoured in the transport research than in built-form studies. The time-space models could either be explicitly treated in person-based measures to discover the variations of accessibility for different groups of people at a certain place, or they could be implicitly considered as time-effecting accessibility for a location (Miller 1991; Geurs and Von Wee 2004). This kind of model has been discussed in a limited manner, as such study requires a huge volume of high-resolution temporal data (Hägerstrand 1970). This trend was expected to change recently due to the increasing availability of locational data emerging in the big data era (Batty 2013). Although there were some differences between these accessibility measures from the points of views in the theoretical and methodological propositions, the relationships between them could still be integrated in a land-use transport interaction model, in which land-use distributions and transport systems are two basic components constrained by the temporal components and perceived by the individual components (Geurs and Von Wee 2004) (Figure 2-10).

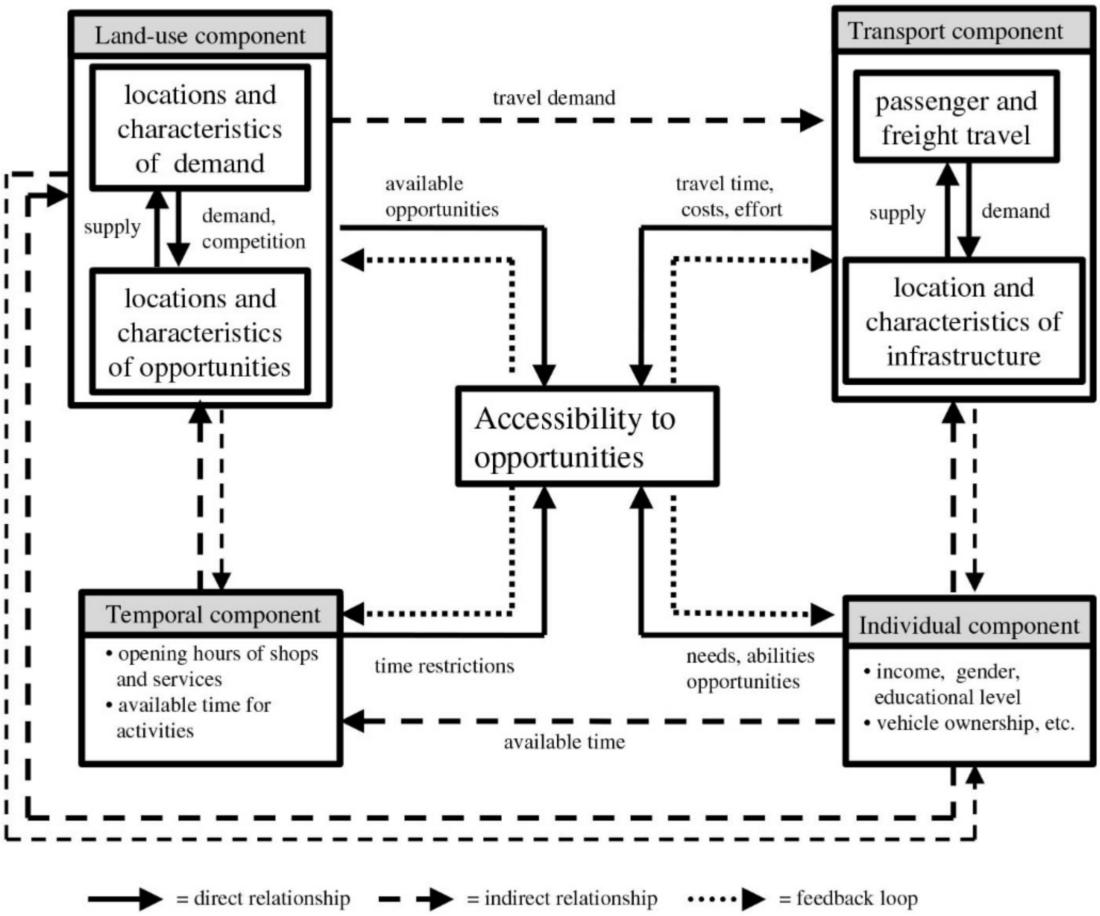


Figure 2-10

Relationship between components of accessibility (Geurs and Von Wee 2004)

Another type of accessibility has rarely been mentioned in accessibility studies in geography, but has been widely adopted in configurational studies on the urban form. It is termed as 'the third type accessibility' by Batty (2009) with a specific focus on the way in which urban built spaces are physically connected to other spaces as a configuration. This type of network accessibility was measured based on the dual-graph representation of the physical built environment, which could be thought of as a mirror of the primal graph used in traditional studies on geographical accessibility. Consequently, the focus on accessibility in this type of model shifted to links in the primal graph instead of the nodes (Porta et al. 2006; Batty 2017) (Figure 2-11). This type of model has been extensively studied and further developed as a theory called space syntax, which has been empirically employed in the studies on the relationship between the design of the built environment and urban flows (Hillier and Hanson 1984; Hillier 2007). The cost for interaction in the space-syntax model is cognitive, including topological and geometrical distance, key factors in human way-finding processes, as verified by empirical evidence (Montello 1997). In the paper *Cities as movement economies*, Hillier (1996) argues that the structuring of urban flows by the spatial configuration leads to the land-use change, thereby characterising the performance of cites. This argument shed light on the theoretical position of urban design in the interaction process between land-use patterns and urban movements and provided a valuable reference for later urban studies on the spatial performance of cities from the perspective of urban design.

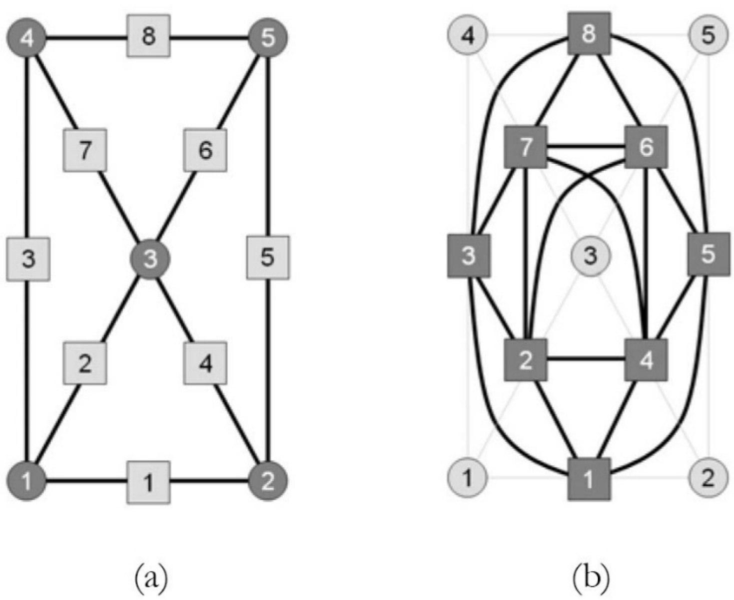


Figure 2-11

The (a) primal and (b) dual representation of a planar street network (Batty 2017)

As the measure of nearness in the urban system, accessibility provides insight into urban centrality structures from different angles. However, these differences in types of accessibility, in turn, raise barriers to the production of a comprehensive understanding of urban spatial structures. Consensus has arisen that an urban spatial structure maintains several critical components, such as land-use patterns, urban flows and underlying physical systems. Nevertheless, the ambiguous ways these components are specified in association with the determinants of flows have resulted in considerable confusion about their interaction. To have explicit descriptions of urban spatial structures requires a unified theory of accessibility, and of the urban spatial structures, in general. Considerable progress made recently suggests the potential to synthesise *functional accessibility* (i.e. the geographical accessibility of the land-use and transport systems) and *spatial accessibility* (i.e. configurational centrality) in order to uncover the way that the physical structure relates to human behaviours (Batty 2009; Karlström and Mattson 2009). The theoretical and metrological proportions of these two main categories of accessibility require more efforts to be further developed for approaching the essential junctions between these two main bodies covering similar topics.

3 GEOGRAPHICAL ACCESSIBILITY

3.1 Definitions of land-use systems

Distribution of land-use happens through a complex system, reflecting the configuration of urban activities (Geurs and Ritsema van Eck 2001). Ambiguity has been common in definitions of the land-use system in the existing literature, from architectural studies to natural resource management, on the basis of various spatial scales. In transport geography, two concepts have been argued to be involved in the meanings of land-use patterns: urban forms and urban spatial structure (Rodrigue et al. 2009). 'Urban forms' here refer to the spatial imprint of an urban transportation system and the adjacent physical infrastructure and activities, such as the road network, railways, and the like, whereas 'spatial structure' denotes a set of relationships related to an urban form and its interactions with people, freight and information, such as the movement of people and the flow of information. In this manner, urban forms are considered to be the spatial and visible representations of urban spatial structures, which consists of functional relationships. This conception suggests that human activities, either economic, social or cultural, imply a multitude of functions, such as production, consumption, and distribution. These functions occur within an activity system where their locations and spatial accumulation form future land-uses. Hence, the land-use system is a complex activity system representing the spatial configurations of the activities.

3.2 Interaction between land-use and transport systems

Functional accessibility in geographical studies is the interface between land-use systems and transport structures. This definition can be traced back to Hansen's well-known idea that accessibility is 'the potential for interaction' (Hansen 1959). Recently, there has been a large range of studies developing redefinitions, measurements and applications covering various aspects and scales (Harris 2001). In that research, the interaction between land-use patterns and the transport system, well-known in transport research as the land-use transport interaction (LUTI) model, has been the subjects of many studies. The mutual impacts between land-use allocations and urban movements have been considered in the literature (Mitchell and Rapkin 1954; Meurs and Haaijer 2001). Wegener (1994) modelled the interrelationship between land-use distribution and transport system as a closed feedback cycle, illustrating the primary roles that accessibility plays in the location-related decision-making processes that underpin urban development and the emergence of urban activities. The prototype of this idea dated back to the 1960s when Lowry (1964) developed the *Model of Metropolis*, which consists essentially of a residential location model and the job location model, co-nested. The key characteristics of Wegener's wagon wheel conceptual model can be summarised as follows.

1) Since people's movements are basically destination-oriented, the patterns of land-uses, such as residential, industrial or commercial, across the urban area determine the locations of human daily activities, such as living, working, shopping or education.
2) The distributions of urban activities generate the utilitarian travel demands through the transport system with different distance costs.
3) The distributions of infrastructures in the transportation system or the patterns of land-uses adjust spatial interactions and can be gauged with accessibility measures.
4) The distribution of accessibility in space co-determines the location decisions of the newly generated land-uses, and so results in changes to land-use patterns.
5) While subject to external interventions, such as the change of economic conditions and geo-policies, this system is effectively closed and is evolutionary.

In Wegener's wagon wheel model, accessibility is the key node to make the land-use transport interaction loop. On the one hand, the distributions of accessibility lead to separations between localities whereby location decisions are made at different places for different types of land-use according to the relative accessibility of different areas. On the other hand, these patterns of accessibility, in turn, are effected by the travelling behaviours of consumers, which are reshaped by the activity landscapes (Figure 2-12).

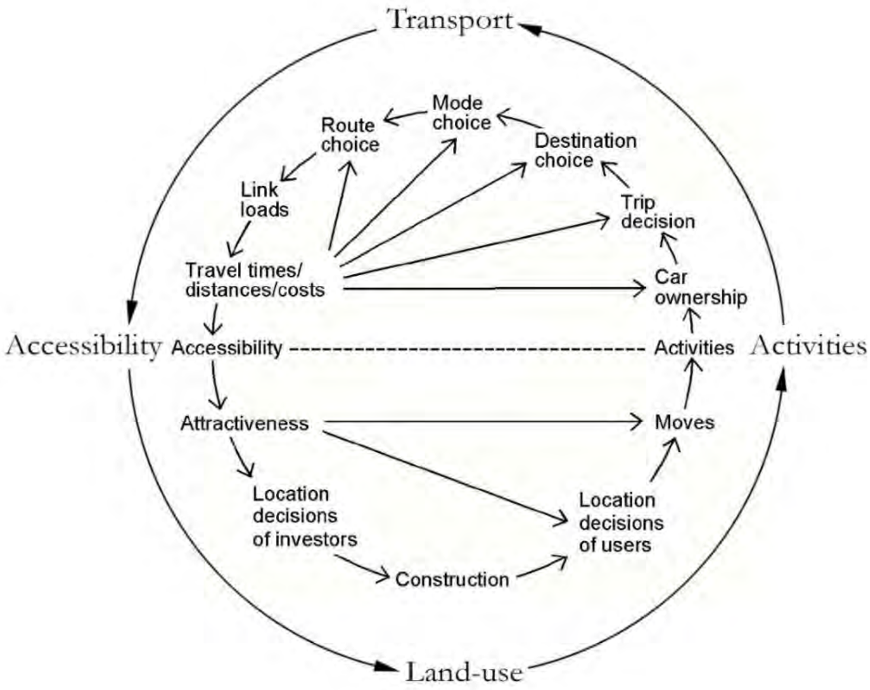


Figure 2-12

'Wegener's Wagon Wheel' conceptual model of land-use transport interaction (Wegener 1994)

This model also postulated that the demand for travel does not derive its utility from the trip itself, but originates from the need to reach the locations where activities/trips take place (Van Wee 2002). This idea seems self-evident, but it remains important to stress the derived nature of travel demand, since this aspect of travel offers opportunities to influence travel behaviours by designing specific land-use patterns. As a consequence, the urban spatial structure could be understood as the output of the land-use transport interactions. In a pilot model, Bertaud (2001) has discussed and provided a good example regarding the influence of the interplay between the distance accessibility to the central business district and between places on the distinction of the spatial structures (Figure 2-13). In his model, it was discovered that the overall distance accessibility to the city centre and between urban places are simultaneously the main determinants for the shape of the spatial structures, by controlling the average density of the hypothesised urban system constant. Also, the outputs of Bertaud's experiment implied that the accessibility contributed more to the morphological variation of structures, rather than to the average nodality, which confirmed the describability of geographical accessibility about the spatial structures. Therefore, accessibility, the interconnection between land-use and transport system, is certain kind of potential depending on the degrees of their interactions. In this sense, accessibility can benefit from knowledge of observed land-use distributions and the resulting urban spatial structures.

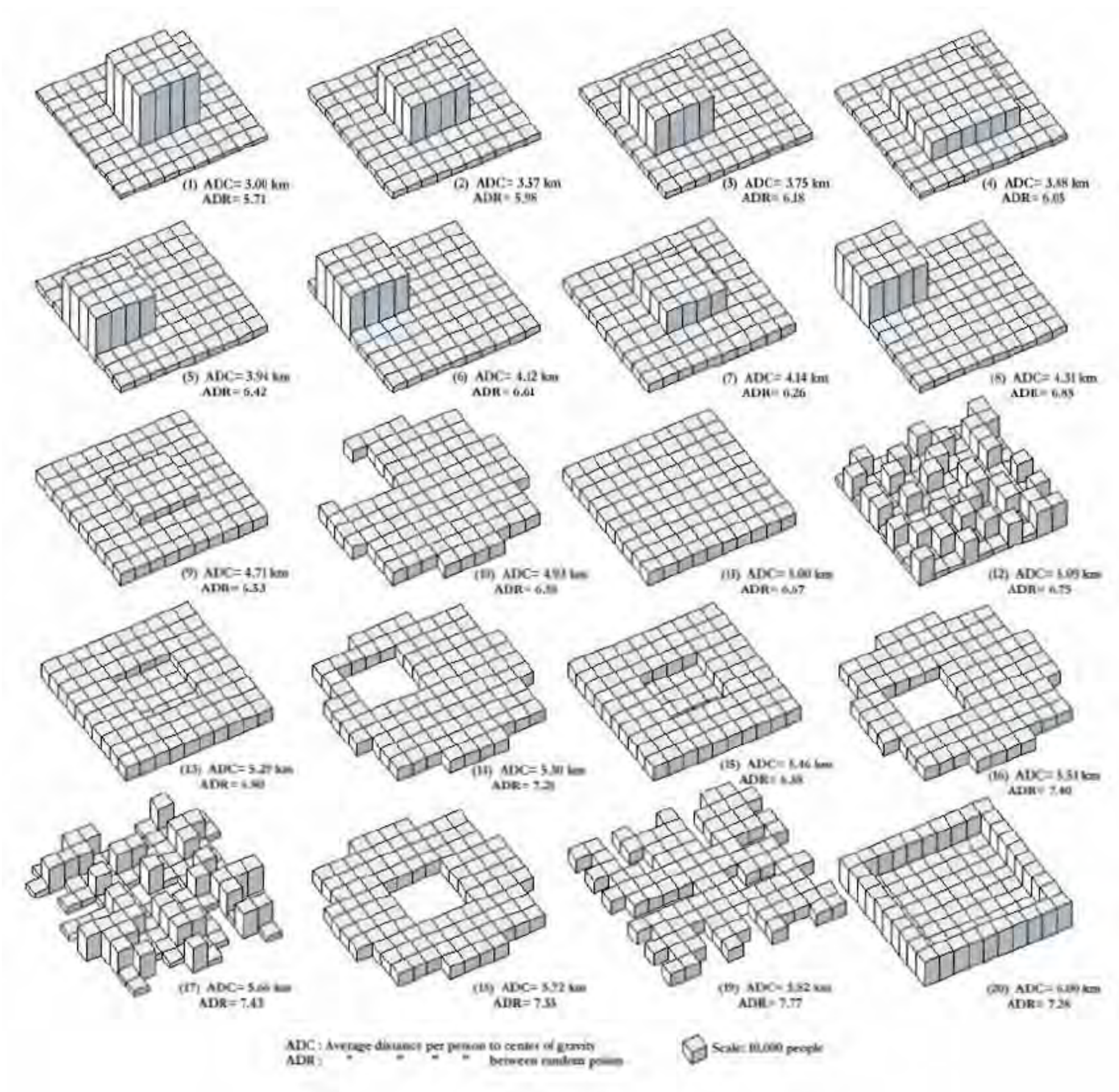


Figure 2-13

Variation of the spatial structure based on settings on the average distance to the centre of gravity and between any two pairs of places (Bertaud 2001)

3.3 Typical measures and settings

Urban land-use patterns are recognised to be vital for creating urbanity, vitality and the 'sense of space' within an urban physical setting and for city legibility (Canter 1977; Punter 1991; Montgomery 1998). Over the years, an extensive range of measurements have been developed and applied spanning various issues and spatial scales for building up deeper knowledge about land-use distributions (Kwan 1998; Harris 2001). With the recent trend that the measurements are becoming more and more complex, the results of accessibility studies are more accurate. In existing literature, commonly employed appraisal methods for quantifying accessibility include the average weighted travel cost measures (Gutiérrez et al. 1996), densities (Gutiérrez 2001), spatial interaction models (Wilson 1970; Shen 1998), opportunities' configuration methods (Weibull 1980), system dynamics models (Chang 2006; Wadell 2011), and so forth. These methods have in recent decades been adopted in many relevant fields such as employment chances competition (Geurs and Ritsema van Eck 2003; Cheng and Bertolini 2013), allocation of healthcare facilities (Wan et al. 2012; Dewulf et al. 2013), and prediction of housing prices (e.g., Capozza and Helsley 1989; Adair et al. 2000). Thus, geographical accessibility measurements are the indicators that depict the land-use system with transport developments and represent the impacts of the land-use pattern on the functional situations of the society in general.

Accessibility is a slippery concept that is properly used, depending on the required measurement, with various detailed definitions (Pirie 1979). In the well-cited review, Geurs and Van Wee (2004) distinguished four main categories of accessibility indices in existing studies, including infrastructure-based measures (e.g., Ewing 1993; Ypma 2000), location-based measures (e.g., Handy and Niemeier 1997; Van Wee et al. 2001), individual-based accessibility indices (e.g., Recker et al. 2001; Waddell 2001), and utility-based accessibility metrics (e.g., Martinez and Araya 2000). Among these types, location-based accessibility measures are the very basic and widely adopted methods, since they directly represent the land-use system, reflecting the patterns of the amount, quality and interaction of the opportunities supplied at each destination (Van Wee et al. 2013). Other types of methods, due to the shift of their focus to one certain dimension of accessibility, for instance the individual or temporal aspect, and the requirements of other specific datasets, present easily obscured descriptions about the urban spatial structures. As a consequence, location-based measures that have been commonly studied are the focus here.

There are three main groups of location-based accessibility measurements including contour measures (also known as density measures), potential measures and the balanced spatial interaction model (Geurs and Van Wee 2004) (Table 2-1). A contour measure, as its name suggests, is a type of iso-chronic measure that counts the amount of opportunities reachable within a given cost (d_{ij}) or calculate the cost required to access a fixed quantity of opportunities (O_j) (e.g., Bruinsma and Rietveld 1998). By using a negative exponential cost function ($e^{-\beta d_{ij}}$), potential measures follow the logic in the gravity models to estimate the accessibility of opportunities in the space in question for all other spaces (Stewart 1947). To address the effect of competition, the traditional potential measures have been enhanced with a competition factor (W_{ij}) calculated by dividing the opportunities within reachable area from original place i, known as the supply potential, by a demand potential from location i (Weibull 1976; Von Wee et al. 2001). Meanwhile, the double-constrained spatial interaction model further extended the potential model from another perspective in which the balancing factor a_i and b_i secure the volume of the trip flows from location i to j, equal to the amount of urban activities in the original location i and the destination location j (Wilson 1970; Van Wee et al. 2001). Recently, the construction of the location-based accessibility indicators has been improved as the consequence of technical development and increased data availability. Chen et al. (2011) estimate the block-based accessibility indices using algorithms developed in a GIS platform. Thill (2009) has proposed a model called GIS-T, with a particular focus on the transport component of accessibility to enhance its instrumentality and visualisation quality. Moreover, with the development of volunteered geographical information (VGI), a research stream has been concentrated on mapping and calculating accessibility based on detailed information about local amenities (e.g., Paez et al. 2013).

Table 2-1

Location-based accessibility measures (Geurs and Van Wee 2004)

Measures	Equations
Contour measures	$A_{(i,d_{ij}\leq d_{max})} = \sum O_j$
Potential measures	$A_i = \sum_{j=1}^{n} O_j e^{-\beta d_{ij}}$
Adopted potential measures	$A_{(i,d_{ij}\leq d_{max},d_{jk}\leq d_{max})} = \sum_{j=1}^{n} \frac{O_j}{d_{ij}^{\beta}} \times W_{ij}, W_{ij} = \frac{\sum_{k=1}^{n} \frac{O_k}{d_{jk}^{\beta}}}{\sum_{k=1}^{n} \frac{D_k}{d_{jk}^{\beta}}}$
Measures with balancing factors	$a_i = \sum_{j=1}^{n} \frac{1}{b_j} D_j e^{-\beta d_{ij}}, b_j = \sum_{i=1}^{m} \frac{1}{a_i} O_i e^{-\beta d_{ij}}$

These measures basically operated on large scales with administrative boundaries or arbitrarily fixed units such as grid cells, since they largely relied on spatially aggregated data, such as census data. The distance cost in all these measures can be either physical or non-physical, such as straight-line distance or travelling time along transport networks. From a technical point of view, these distance metrics are filled into a cost matrix to abstract the interaction between places as the Euclidean distance length that was recorded in the transport systems. Thus, in geographical accessibility measures, the distance connections between places via transport networks are more influential than their relative patterns on the accessibility structures.

3.4 Geographical accessibility as a socioeconomic indicator

3.4.1 Accessibility as a driving force of urban transformation

The urban built environment is a dynamic canvas on which human, space, and land-uses interact. Understanding the mechanism by many factors driving land-use change has been the focus of urban studies across disciplines, locations and scales. Models of land-use change have been argued to be effective tools to analyse the causes and consequences of land-use change in order to better uncover the functioning of the land-use system and to sufficiently support relevant planning and policy (Verburg et al. 2004). Approaches to modelling land-use change include statistical models (e.g., equation-based models, regression models, probability models, etc.), system dynamic models (e.g., land-use transport interaction models), and heuristic models (e.g., cellular models and agent-based models) (Parker et al. 2003). The statistical models are very mathematical in some ways, relying on a static or equilibrium solution. Based on sets of statistical relationships constructed in accordance with economic theories of agglomeration and diffusion, the statistical models can specify cumulative land-use change over time (Kaimowitz and Angelsen 1998), but the linear programming approaches in such methods have limited the level of complexity. The existing accessibility structure in this type of model was assumed to be linearly associated with its future form. The system models normally construct a structure with intermediary functions to interlink differential equations representing the main factors, and the feedback loops have also been taken into account to make the model dynamic (Gilbert and Terna 1999).

In system models, accessibility interacts with other factors iteratively with explicitly defined consequences. In heuristic models, the roles that the accessibility structures play were different, although both of them can produce fruitful emergent patterns of urban land-use structures in future. Typical cellular modelling approaches operate over the grid cells, and the future states of cells shift depending on transition rules calibrated by the cells' local spatiotemporal neighbourhoods (Hegselmann 1998). In this framework, relative accessibility for different cells is kept updated at each step and directly impacts the transit of cells' states in the next step until the projected time period for simulation has passed. The accessibility structures in cellular models are directly involved in the spatial process as cellular models focused on transitions in space, whereas the relationship between the accessibility patterns and the urban change is relatively indirect in agent-based models where human (re)actions are the cores. The agents in the system, representing a wide variety of urban entities such as people in different demographical groups, public and private sectors, and even a certain type of land-use, share the environmental conditions and make decisions in reaction to the changing environment (Janssen and Jager 2000). Accessibility patterns, in this manner, can be general conditions shared by all the agents; on the other hand, the impacts of their specific forms might vary significantly for different groups of agents. Although accessibility functions in different ways in these models, its essential roles have been broadly accepted. The outputs produced by these models also provide evidence for the development of urban theory. For instance, the economic agglomeration processes proposed in the new economic geography have been sufficiently verified by the cellular models (Fujia and Krugman 1999) (Figure 2-14). It has been argued that urban change could be understood as an emergent phenomena driven by the change of accessibility (Batty et al. 1999).

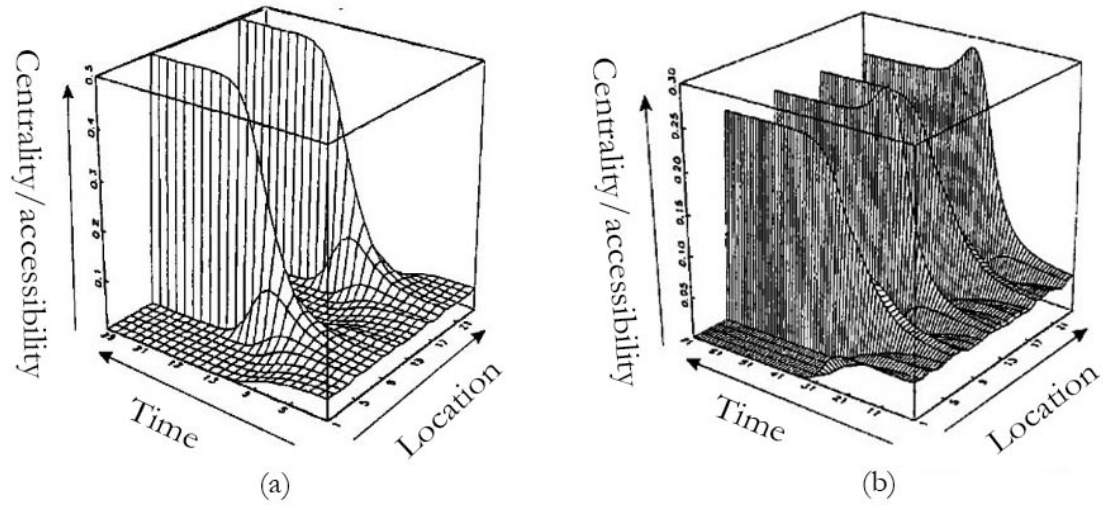


Figure 2-14

Evolution of cities of (a) two centres and (b) four centres in cellular models (Fujita and Krugman 1999)

3.4.2 Accessibility as an economic indicator

Generally, increased accessibility resulting from land development projects is considered an important benefit for people, firms and other economic entities. Improved accessibility can attract more people because of the increased trip convenience and enriched destinations for potential travel; on the other hand, other land-uses are placed nearby as the result of the decreased cost for complementary interaction and improved size of the consumer market, thereby enhancing the efficiency of economic production (Forslund and Johansson 1995).

Accessibility has been analysed at various levels for measuring the patterns of user/non-user benefits, productivity, employment and housing prices. Conventionally, the benefit of improved accessibility has been analysed as the result of the improved transport system or changes of other land-uses' locations (Neuburger 1971). In transport geography, improvement of accessibility via the transport system resulting in a reduction of travel time and cost has been analysed in a traditional cost-benefit analysis (Banister and Berechman 2000), while in location analysis, consumer surplus has been used to analyse equity between different social groups (Martinez and Araya 2000). Moreover, the impacts of accessibility have been measured as parts of the gross domestic product at regional scales (SACTRA 1999) or as priced in the income of retailers at the micro level (DiPasquale and Wheaton 1996). In addition, shifts of accessibility distributions have been studied in the relation to the changes of employment market (Geurs and Ritsema van Eck 2001).

Another key aspect of economic effect widely discussed in planning research has been the non-user benefits brought by the enhancement of accessibility. People are more likely to live close to different activities although they do not often actually participate in those actives. Multiple empirical studies have shown that most of the urban movements are normally multi-purposes (Eaton and Lipsey 1982), which has also been addressed as the evidence to explain the success of shopping malls (Eppli and Shilling 1996). Furthermore, the price effects of accessibility have also been widely discussed in studies of housing prices. Hedonic models, in which urban users value various elements differently in determining house prices, have been adopted to quantify the impacts of accessibility on the observed price of houses as an externality of spatial economics (Kockelman 1997). Chen et al. (1998) have argued that accessibility to a railway station might simultaneously exert positive effects and negative nuisance effects on residential property price, causing a peak of the combined effect to emerge at a certain distance away from the station (Figure 2-15). Consequently, the economic performance of areas can be reflected by accessibility, according to existing literature. However, reliable quantitative estimates of economic values of land-use change will still probably be difficult to derive, representing one field in need of further study.

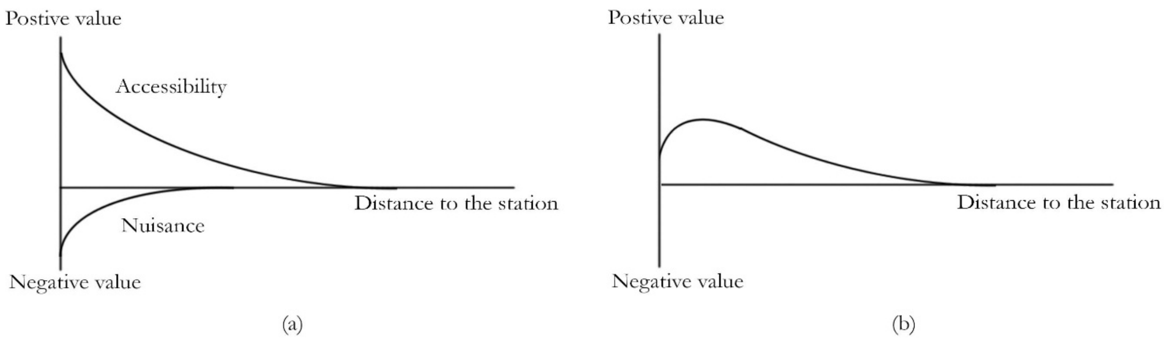


Figure 2-15

Individual effects and combined effect of accessibility on housing price (Chen et al. 1998)

3.4.3 Accessibility as a social indicator

Accessibility measures are also employed in the evaluation of the social implications of urban activities, which spans the encounter, welfare delivery, equity, safety, social segregation and inclusion. Accessibility to different urban opportunities impacts the location where people prefer to live, work, receive education, recreate and relax. In this way, levels of accessibility to land-uses are very essential in the socioeconomic decision-making processes (Bruinsma and Rietveld 2000). Donald Appleyard (1982) explored the relationship between urban movements and street-based social interaction and liveability, stating that high accessibility for car users on the roads led to low intensity of social interaction. Furthermore, the change of accessibility is valuated differently by various groups of people, categorised according to their income or demographic features (Kandel and Poort 2000). Through the economic cost-benefit analysis of accessibility enhancement as a result of infrastructural projects, the costs and benefits have been recognised to be differential for people at various income levels in different locations (Kandel and Poort 2000). Location-based accessibility measures were adopted to evaluate equity of opportunities. Specifically, potential accessibly measures to employment and public health care centres could be used as a function of the location of residences and the household socioeconomic status to represent the social equality of urban services (Wachs and Kumagai 1973). Black and Conroy (1977) found that job accessibility for male and female workers was differentiated by the transport systems. Some scholars have also used accessibility as a kind of social good and assumed its disparities to be a type of inequality. As an example, Schürmann et al. (1997) introduced some indicators to measure existing disparities in regional accessibility to examine the influences of the Trans-European Network on the equality of accessibility in the European Union.

Geographical accessibility measures form a useful tool kit for examining the social impacts of land-use transport scenarios. Nevertheless, there are still some problems in the relevant studies; all the measurements adopted in these studies are too diverse to present very reliable results or conclusions (Geurs and Ritsema van Eck 2001). Further studies should also concern possible improvements regarding consistency between the disaggregated and aggregated results and conclusions.

3.5 Limitations

Geographical accessibility measures and location-based metrics, in particular, provide the possibility to quantify the underlying structure of urban functions and evaluate their dynamics explicitly. However, the existing geographical accessibility measures still have not apparently satisfied the same theoretical criteria, especially when they are used in morphological analysis and urban planning and design practice. Firstly, the measures typically have not taken into account the effects of urban space, although the distance cost nested in the transport network has been considered in some methods. Secondly, most of the existing methods have been based on the aggregated spatial units and commonly computed at the macro level. This method has resulted in low-resolution data, lacking descriptive detail. Thirdly, the cognitive cost component has been absent from current attempts. It has been proven that individuals' perceptions of accessibility to local services through public spaces are likely to be varied and include errors (Krizek et al. 2012). Therefore, the location-based accessibility measures should carefully consider the impact of people's travel behaviour so that the 'subjective accessibility' factor can be adequately reflected in the measures. Fourthly, the interaction between land-uses should be included in the models, as the conflicts or the collaboration between different types of land-uses might have different influences on the sense of accessibility for the citizens. Fifthly, the required data structure for calculating accessibility should be generic in order to secure methodological adaptability and compatibility in various data environments. Briefly put, the shortcomings of geographical accessibility measures for the morphological analysis of land-use patterns are related to the naive exclusion of the effects and constraints of the network of public spaces, despite the fact that other aspects of transport systems have been extensively discussed.

4 CONFIGURATIONAL CENTRALITY

4.1 Definition of spatial configuration

Urban space is the arena where the social activities occur. In the *space syntax* theory, it has been suggested that social processes have their spatial logics and that, in turn, the spatial form has its social content (Hillier and Hanson 1984). In this manner, Hillier (1984, 1996 and 2007) has made a fundamental proposition that a physical city is an object whose spatial form is its social ordering. This argument corresponds to the viewpoints of neo-Marxists, such as Lefebvre, who have claimed the importance of space and suggested that social relations are reproduced through spaces (Lefebvre 1991). According to the *space syntax* theory, a physical city is typically abstracted as the spatial network, in Hillier's words, the spatial network of a city is 'a historic record of the spatial ordering driven by human activities', rather than a lifeless background of human behaviours (Hillier 2007). Following this proposition, an integrated theory of built space as configuration and a range of methods have been established, which have produced insightful references for morphological studies and urban design practice. The core concept in space syntax theory is 'configuration', which has been defined as 'relations taking into account other relations' (Hillier 1996). This notion is similar to the conceptualised view of centrality or accessibility, reviewed in previous sections, which emphasises the interrelation between any two structural elements in the urban system. The configuration in space syntax theory, thus, addresses a set of interactions among all the spatial elements rather than a simple relationship between two spatial elements.

In the *Social Logic of Space* (Hillier and Hanson 1984), a standard procedure to produce the syntactic representation of the spatial configuration is introduced. Any continuous space can be understood as the aggregation of 'convex spaces'[2] which maintain integral patterns where all the locations within their boundary are visually connected. Any a convex space can be summarised in one dimension by the longest straight line between any pair of locations within the boundary of the convex space. In such a representation, the convex space is represented by its axis, so the original continuous space can be described by a set of axial lines. By removing the redundancy, the minimal set of the longest axial lines representing the patterns of inter-permeability is formulated, termed an *axial map* (Figure 2-16b). In order to illuminate and analyse the configurational relations captured by connections between axial lines, the axial map is converted into a configurational graph where *axial lines are represented as vertices and the intersections of the lines as edges* connecting vertices (Figure 2-16c). The distance unit used in the axial map is topological; that is, each edge represents a step—a turn that is required to be overcome when someone travels from one node to another. The axial map, in this way, presents an objective graphic representation of a continuous space, which makes a spatial system quantifiable and calculable.

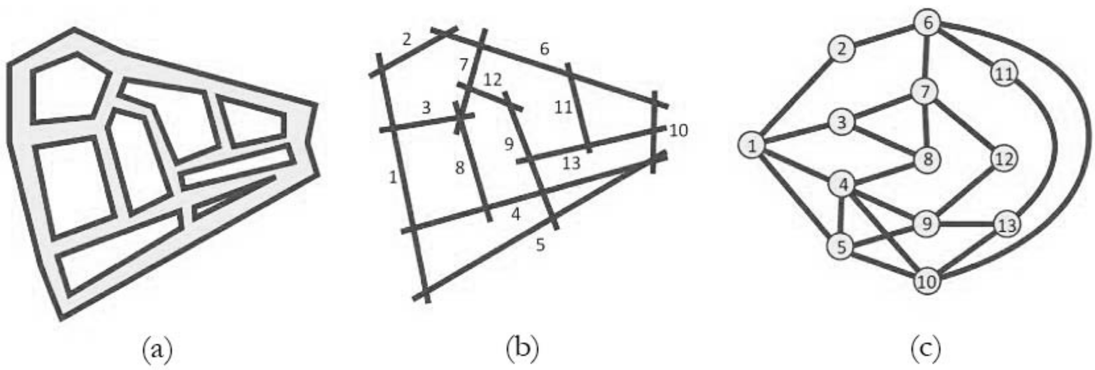


Figure 2-16

(a) The continuous pace, (b) and its associated axial map (c) and configurational graph (Hillier and Hanson 1984)

[2] From a mathematical point of view, a convex space in a Euclidean system, is a spatial region such that, for every pair of points in the region, the straight line connecting them should be fully contained by the region.

Axial maps capture the topological properties of the configuration of space. Recently, another geo-typological graph representation has been proposed and address the interplay between various distance metrics in the spatial configuration at a higher spatial resolution (Turner 2001b, 2004; Dalton 2001, 2003; Hillier and Iida 2005). By breaking the axial map at every intersection, the axial map generates the segmental map in which each segment turns out to be the node and the intersections of the segments are treated as edges in the generated configurational graph. In the segmental map, step depth measures are extended, and geometrical distance is introduced. The geometrical step is the basic distance unit in the segmental map, which refers to the angular change at every intersection of segments; accordingly, the geometrical distance between two segments equals the cumulative angular change along the least angular change route connecting them. The metric distance in the segmental map denotes the cumulative length along the shortest path, which is consistent with its definition in geography. In a space system, its segmental map is typically larger than its axial map, providing the different ways of representing and analysing the spatial configuration with regards to the metrical, topological and geometrical costs (Figure 2-17). It has been argued that the topological and geometrical costs influence human way-finding behaviours (Montello 1991). The axial and segmental maps, the dual graph representations of urban spatial systems, sufficiently address various formats of cognitive costs underlying spatial configuration that were neglected in its early understandings.

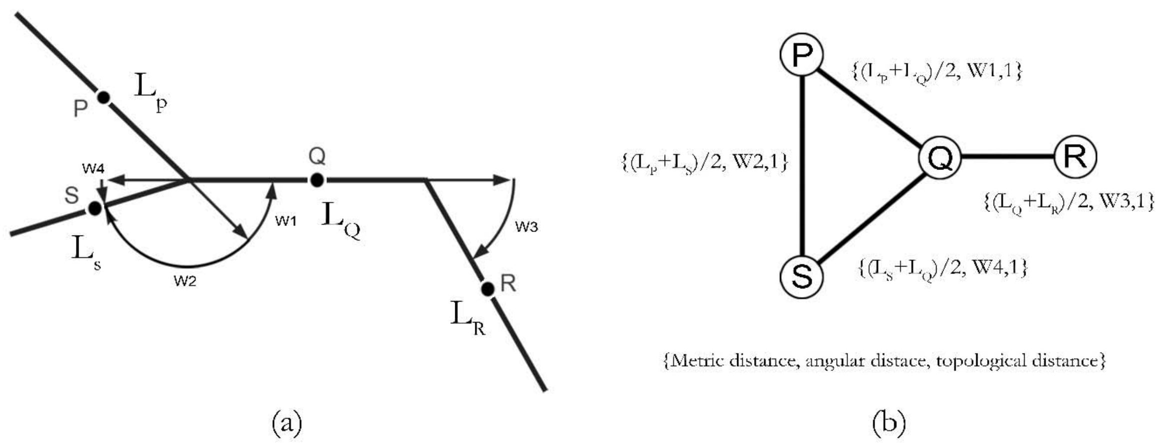


Figure 2-17

Distance properties in (b) a configurationally graph of (a) a continuous space

4.2 Movement economy

The outputs of numerous empirical studies adopting space syntax models suggested that the centrality of urban spatial structures was a strong predictor of the volumes of the aggregated urban movement flows (e.g., Hillier and Hanson 1984; Hillier et al. 1987; Hillier 1988). This observation indicates that the impact of the configuration on urban movement patterns was robustly significant at an aggregated level instead of a disaggregated level, where there were individual acts with high degrees of singularity. In other words, to a large extent, movement though the spatial networks can be considered a product of the functions of spatial configuration rather than a result of the other super-local features (Hillier and Hanson 1984; Hillier 1996). This movement, which is indifferently determined by the spatial configuration, was conceptualised as *natural movement*, indicating the inherent relation between urban flows and spatial layouts.

Based on the observation of the natural movement, Hillier further proposed the mechanisms of the interaction between space and flows and made dynamic the natural movement model. The mechanisms were packaged in a complex process termed as *movement economy* (Hillier 1996). In the movement economy process, there are three essential components interacting with each other uninterruptedly, namely spatial configuration, movement and attractions (Figure 2-18). In this framework, spatial configuration determines the patterns of urban movements in various types and then impacts the location decisions of land-uses, and other relevant urban spatio-functional characteristics. The distributions of land-uses, in turn, provide feedback effects and *multiplier effects* on urban movement patterns and their relation to the spatial grids. In this process, the land-use (re)allocation is self-adaptive according to the varying nature of movement-seeking in the seamless spatial network.

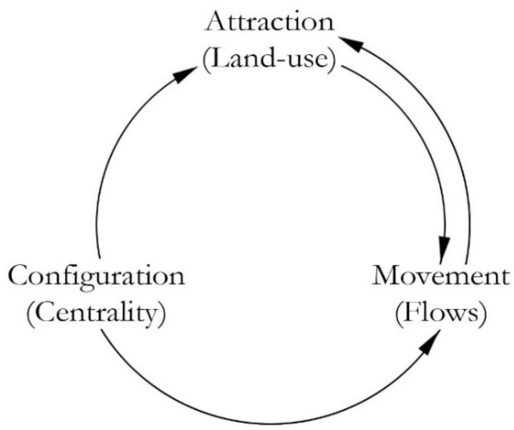


Figure 2-18

The diagram of the 'movement economy' (Hillier 1996, 2007)

In line with Hillier's theory of the movement economy, scholars have extended his model by adding the impacts of physical design and the typology of urban areas. Based on empirical studies of pedestrian patterns in traditional and contemporary urban districts, Lerman and Omer (2016) proposed a modified model in which the typology of urban areas dominates in the connections between the components (Figure 2-19). Other physical conditions might also have an impact on the patterns of movement. For instance, the poor quality of the walking environment, or the width of the streets might change people movement. This modified model enriched existing knowledge of the usage scenarios in Hillier's model and took into account the role of other urban design factors in configuration-moment interaction processes.

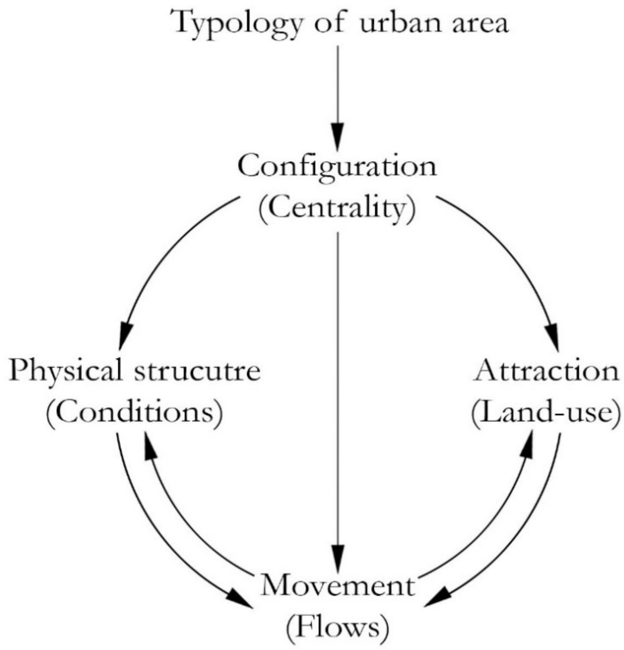


Figure 2-19

The modified diagram of the *'movement economy' (Lerman and Omer 2016)*

In general, Hillier's theory of movement economy provided novel insight into how urban space, as a complex spatial network, determines the observed movement of people and further influences the way that the land-use distributions are oriented by movement. Plus, the model of movement economy is dynamic, illustrating the lasting socioeconomic effects of urban design within the process of urbanisation. However, this model also demonstrated the essential role that centrality, or spatial accessibility, plays in triggering the feedback loops, which is similar to what has been proposed in the geographical land-use transport interaction model (see Section 3.2).

4.3 Typical measures and settings

There are three basic centrality measures in the space syntax model: *connectivity, integration,* and *choice* (Table 2-2*)*. Due to the fact that with these basic elements, an axis or a segment is abstracted as a node in the configurational graph, these measures were also called point centrality measures (Freeman 1977). The connectivity variable measures the amount of space directly linked to a root space. It indicates the super-local (the most localised) density of the spatial network. The integration measure captures the shallowness of the place in question to all other reachable spaces. From a mathematical perspective, the integration can be quantified as the reciprocal of the generalised total depth. The patterns of integration measurement can be treated as the maps of the *to-movement* potential, representing the probability that a certain space is the destination within the natural movement patterns. On the other hand, the choice measure, counting the times a space is passed, reflects the probability that a space is a mid-point in people's trips to other places. In this sense, it captures the potential of the through-movement. The integration and choice reflects two distinct elements of movement that the spatial configuration shapes in the nature of movement: passing and destining.

The variable of integration and choice can be measured at different scales. The infinite radius denotes the global scale, while smaller radii normally refer to the local scales. Accordingly, the integration at *Rn* is named as *global integration*, while the integration at *R*3 (three topological steps) is called as *local integration*. Similarly, through adjusting the distance of the radius for defining the reachable buffer area from a node in question, people can obtain the integration or choice centrality structures of a spatial network. The network analysis of the axial maps allow only the use of the topological distance as the radius. For the segmental analysis, the distance metric of the radius could be metrical, topological and geometrical. This feature of the analysis makes the angular centrality measures reflect the interplay between different types of costs in a connected spatial network.

Based on the introduction of the concept of spatial scales, two measures were developed to understand the inter-scale syntactic performance of urban areas. *Intelligibility* measures the degree to which the global structure of an area can be promptly understood by people when they experience it most locally. From a mathematical sense, it is quantitatively equal to the correlation coefficient representing the strength of the linear relationship between the connectivity and the global integration. In this manner, a readily intelligible network is the one in which its global structure can be sufficiently captured by its super-local structure. For example, in an intelligible city, the more spaces to which one space is directly connected, the more likely this space is the configurational centre for the city. Likewise, the variable of *synergy*, calculated by the coefficient of the correlation between integration at *R*3 and *Rn*, is also used to identify the interaction between local and global centrality structures. This measure was more widely used than the variable of intelligibility, since this measure relaxed the definition of the local structure and made it more compatible with the spatial networks in different cultures and sizes (Hillier et al. 1993).

Table 2-2

Commonly used measures of space syntax centrality

Name	Descriptions
Point centrality	
Connectivity	The degree of intersection (known as the degree centrality[3] in graph theory)
Integration	The degree of an element is closed to all other elements at a given radius (known as the closeness centrality[4] in graph theory)
Choice	The cumulative times an element appears as a node along the simplest or the shortest path between two other elements at a given radius (known as the betweenness centrality in graph theory)
Areal measures	
Intelligibility	The degree of the linear correlation between connectivity and global integration
Synergy	The degree of the linear correlation between local and global integration

4.4 Configurational centrality as a socioeconomic indicator

4.4.1 Configurational centrality as a driving force of urban transformation

Urban space provides and constrains the opportunities for urban development. It has been argued that the impact of configurational centrality on urban transformation is dynamic and global (Hillier 1996). The (re)formation of urban centres can be detected by the relation between different scales of configuration, and the urban transformation was considered as a centrality process in which the shifting patterns of attraction inequalities in any urban grid pervade the urban grid across various scales, determined by the movement economy process. Based on experiments of ideal layouts, Hillier (1999) argued that the reformation of *live centres*—the centres fulfilled with sectors and benefitting from intense movement—relies on a local process of grid intensification to increase inter-accessibility among spaces and a global process of optimising the topological centrality to the whole urban network. This theoretical proposition inspired subsequent efforts to track the transformation of live centres indicated by the co-presence of centrality at different scales (e.g., Karimi 2000; Karimi and Motamed 2003; Griffiths 2009; Feng et al. 2012; Shen and Karimi 2013). Apart from concerning the

[3] In graph theory, the notion of connectivity denotes the number of links incident upon a node.
[4] In graph theory, the notion of closeness refers to the reciprocal of the farness represented as the mean length of the shortest paths between two nodes in a connected graph (Bavelas 1950).

live centres, Karimi (1997, 1999) proposed an alternative perspective to trace urban transformation processes, in which shifting syntactic properties of the *primary elements*[5] were recorded and compared. By tracking the changing syntactic dominance of these primary elements, he (1999) distinguished two modes of urbanisation in organic English towns and in modern Iranian cities and suggested that incorporating the urban elements in the changing urban spatio-syntactic context could be an approach to address issues of conservation. Recently, drawing on Hillier's theory of *pervasive centrality* (Hillier 2009) and their empirical studies on suburban centres, Vaughan et al. (2009) argued that the functional adaptability of suburban centres in history was related to the synergy between syntactic centrality measures across scales (see also Vaughan et al. 2013; Dhanani and Vaughan 2013). Furthermore, scholars in the space syntax community have attempted to model the short term, fine-scale and dynamic impacts of urban morphology on the land-use agglomeration process. Using the agent-based modelling approach, Penn and Turner (2004) have discussed the morphological reasons, produced by the spatial configuration and retail location patterns, for the variation of average search efficiency in the simulations. They contended that the land-use location selections are movement-generated and that a core aim of land-use transformation is to maximise the service efficiency perceived by the consumers.

Urban transformation is inevitably reflected by the change of morphological distributions. Space syntax centrality structures proposed based on the shifting spatial network are powerful tools to portray the shift of urban centre structures in the long term, which has been proven in the cross-sectional analyses of urban evolution processes. The short-term effects of the spatial network on the patterns of land-use agglomeration can be simulated with the help of heuristic modelling approaches. Nevertheless, the short-term effects have not been validated in real case studies, and a proper linkage has yet to be made between the configurational centrality structures and the processes of land-use clustering, such as densification, diversification, spill-over. Filling these research gaps can contribute to formulating an explicit explanation of the multiplier effects in the movement economy model.

4.4.2 Configurational centrality as an economic indicator

For a long time, numerous conceptual, theoretical and empirical studies have attempted to formulate, model and quantify how the built environment is valued in people's daily economic activities. The research based on the space syntax model pioneered the relevant efforts. Some researchers explored the relationship between urban configuration and

[5] In Rossi's theory, primary elements are the elements capable of accelerating the process of urbanization in the city in a permanent way and also constitute physical structures of the city along with area. In short, they act as fixed points in the urban dynamics (Rossi 1984).

property performance and values. By focusing on the economic performance of two shopping malls, Brown (1999), for example, noted that the local urban configuration where these malls were embedded and the internal architectural configuration of the buildings affected the fate of those two malls. Kim and Sohn (2002) contended that integration centrality measure was an effective predictor of land value. Min et al. (2007) have pointed out there was a strong positive correlation between the integration centrality patterns and the distributions of the location propensity of urban industries. Desyllas (2000) investigated the configurational clues of office property rent in Berlin and suggested that spatial integration is a valuable explanatory factor for the shift of the high-land of office rent (see also Enström and Netzell 2008). Scoppa and Peponis (2015) have described how the syntax of the spatial network maintains a strong relationship with the commercial frontage density over the distance accessibly measures commonly used. Omer and Goldblatt (2016) suggested this relationship varies across cities depending on their typology: the correlation between retail activities and the centrality measure of the spatial network is weaker in the new towns than in the old cities.

Recently, extensive studies have been conducted to unfold how spatial accessibility is priced in the housing market. By using space syntax centrality as indicators of walkability, Mattews and Turnbull (2007) has discovered that the price effects of the integration index were opposite in different submarkets and claimed that the typology of the contextual spatial networks contributed to the portion of the house price. Chiaradia et al. (2009) have examined the relationship between street layout design and the council tax bands in London by holding other factors constant. The results of their empirical studies have shown that angular integration is more dominant than choice variables. Similar findings have appeared in the study conducted by Narvaez et al. (2012). In the past five years, hedonic models were widely and systematically adopted in house-price modelling with spatial centrality measures and other variables, out of which some robust findings emerged. Xiao et al. (2014) have analysed the correspondence between the change of centrality structures and the micro-level house price movement against rapid urbanisation in Nanjing, China. The findings of their work yielded that improved integration accessibility leads to higher property prices, but enhanced choice centrality is negatively related to the growth of house prices due to its nuisance effects caused by the congestion of traffic. It was also noted that centrality measures provide additional explanatory power beyond the traditional distance accessibility, such as distance to the CBD (Xiao et al. 2016). These findings coincide with the results of the case study on London's housing market (Law et al. 2013). Law (2017) has used community detection methods to delineate the local areas of the London's street network, investigating the extent to which these local areas could be treated as housing submarkets. The outputs of this work showed that the residuals of the hedonic models for the individual housing submarkets were reduced, indicating that the discontinuity of the spatial network shapes the sub-level house markets.

Spatial accessibility is a typical kind of public good (Webster 2010) influencing economy-related behaviours, such as pricing, location selection, and so forth. The literature has verified a strong global affiliation between the urban form and economic variations. However, the spatial heterogeneity of this interrelationship across urban contexts has not been addressed sufficiently as a focus. In additional, the interaction between configurational centrality and geographical accessibility variables for estimating the patterns of economic performance has not been explicitly defined.

4.4.3 Configurational centrality as a social indicator

Traditional social studies mainly consider people's tendency to seek the maximum benefit of social interaction with the minimum cost (e.g., distance, time, travelling fees, etc.), as in traditional transport geography models, but they have largely ignored the rich information contained in the spatial configuration of cities. Recently, equipped with space syntax centrality variables, some studies have connected urban design to social studies, investigating how urban form impacts social activities. Vaughan (1999, 2005, and 2007) has systematically examined the relationship between spatial segregation indicated by spatial centrality measures and socioeconomic segregation at the street level with first-hand census data. It has been noted that the clustering areas of immigrants might be the places with high local density but syntactical segregation from high-integration city skeletons, as was truly evident in the case study of Jewish settlements in London in the 19th century (Vaughan and Penn 2006). Based on these empirical observations, she has advocated that social research into segregation should not neglect its spatial nature (Vaughan and Arbaci 2011). This argument has also been supported by the empirical study from Omer and Goldblatt (2012), who discovered that the spatial integration variable is much more influential than the dissimilarity indices for explaining the residential differentiation in different areas. Moreover, through conceptualising spatial centrality as *spatial capital* (Marcus and Legeby 2012), one essential type of social capital directly influencing people's co-presence in public space, scholars in built-form studies have shifted their focus from residential segregation to segregation in public space (Legeby 2010). Legeby (2013) recognised that spatial centrality measures profoundly influence encounters between local and non-local residents.

Focuses has also fallen upon understanding the role of spatial design in controlling crime rates and anti-social behaviours. Hillier (2004) found that typology of the spatial layout varies, influencing average crime rates. The shallow structures of traditional streets were found to be associated with lower crime density than the deep and hierarchical systems of modern streets. This difference has been evidenced by previous findings in the research conducted by Hillier and Shu (2000), who explained that highly integrated streets encourage more pedestrian movement, thereby adding more eyes to monitor the streets. Nes and Rueb (2009) compared two groups of dwelling areas with and without serious social problems and found that anti-social behaviours are negatively correlated with spatial accessibility.

The literature suggested that there was a significant correspondence between the configurational centrality measures and the social performance in residential and public spaces. However, some issues could be explored in the following steps in order to generate deeper and more explicit knowledge of this interrelationship. Firstly, it has been recognised that the correlation degree between spatial centrality and social performance might vary across space. Consequently, the spatial heterogeneity of the spatio-social correspondence should be further studied. Secondly, social performance is highly temporal; the spatiotemporal relationship between built-form and social performance should be addressed in the future research. Thirdly, interactions between spatial centrality measures and other accessibility variables used in conventional social studies should be further calibrated and verified.

4.5 Limitations

Recently, the space syntax model has been discussed and extended by addressing theoretical and methodological demands on it. By taking to account the reachable density of the distribution of activities in space syntax model, Ståhle et al. (2005) have developed a toolbox called *place syntax* to calculate cumulative opportunities within the buffers defined by the metrical, topological, or geometric radius. With the emphasis on the value of perceived density, Marcus et al. have suggested that the space syntax model could be extended to a more general concept, spatial capital, with the possibility to translate urban form into other social, economical and cultural capitals (Marcus 2010; Berghauser and Marcus 2014). Simultaneously, another scope that has been focused on is modelling the interplay between reachable metric distance and directional distance to enhance standard space syntax in predicting human pedestrian patterns (Peponis et al. 2008; Ozbil et al. 2011), analysing the transit ridership (Ozbil et al. 2009), and modelling the pattern of commercial frontage (Scoppa and Peponis 2015). Omer and Kaplan (2017) introduced an agent-based model to account for the combined effect of the street network and land-use patterns on pedestrian behaviours. These studies implicitly consider the distinct possibility to improve space syntax model, although they do not form an integrated view.

The accessibility measures in space syntax have been plausibly proven to be powerful tools to reveal city structure and assess the centres' change. Nevertheless, it is still possible that some essential efforts can be made to enhance further the theoretical and practical implications of space syntax theory. A remaining shortcoming is that the space syntax model is relatively static; that is, the measures lack enough concern for the path-dependency of land-use change. Clearly, this shortcoming makes spatial accessibility metrics less suitable for analysis of short-term urban changes when the physical transformation is not significant. Due to the absence of land-use information, the applications of space syntax are often restricted to discovering the centrality pattern without sufficient ability to capture the typology of various spatial opportunities. Other substantial disadvantages are related to the objective definitions of axial and segmental maps and the lack of a standard GIS procedure to secure rigorous consistency between the models made by different users.

5 COMBINING GEOGRAPHICAL AND CONFIGURATIONAL CENTRALITIES

Uncovering the interplay between urban form and function in the built environment has theoretical and practical implications for the urban planning and design process. Geographical accessibility measures and geometric accessibility measures have oftentimes been employed to reveal the functional and spatial elements of the spatial system, respectively. Nevertheless, the aforementioned literature suggests that the developments in spatial and functional pattern analysis have separately contributed to the same topic. Emerging theoretical perspectives, data sources and analytical methods provide new opportunities for bridging spatial and functional accessibility analyses of the built environment, whereby a novel framework for spatial design and land-use allocation in urban design may be created.

Geographical and geometric accessibility measurements are different due to the different settings of distance and attractors in the opportunity configuration. In Table 2-3, the comparison between these two classes of accessibility indices regarding the various aspects and key components is reported. Here, the geographical and geometric accessibility measures are summarised as functional and spatial accessibility indicators, respectively, because spatial network and land-use locations are the primary concerns in those two accessibility computation models. Furthermore, the reduction of the cognitive cost results in geographical accessibility measures unsuitable for producing morphological meanings, as the transport network is normally abstracted as a cost matrix between places. By controlling energy consumption in travel (using metric distance as the radius), the space syntax theory, on the other hand, emphasises the cognitive cost that is the consequence of the design of the spatial network. Moreover, the representations of spatial and functional accessibility measures are presented on the basis of the dual graph and primal graph separately, which enable distance to be topological and metrical, accordingly. The graph presentations themselves cannot change the accessibility measurements of urban opportunity patterns, but the settings of distances and opportunities can. Additionally, the resolution of geographical accessibility measures is typically low with aggregated information, whereas spatial accessibility measures generate fine-scaled data without the modifiable areal unit problem (MAUP). Accessibility measures are also capable of acting as indicators to evaluate urban change. However, geographical and geometric accessibility measures are preferred for the different specified shifts. In the space syntax theory, land-use or other attractors are argued to be 'the multipliers on the basic pattern established by spatial configuration' (Hillier et al. 1993), but observed land-use patterns cannot perfectly follow the agenda proposed by the spatial network, due to various restrictions. The unpredictable activities' locations cannot be simply discarded either, however. Consequently, spatial accessibility measures are the ways in which cities are seen from an aggregated and static perspective to describe long-term urban change, since the land-use patterns are parts of the consequence of spatial configuration. In contrast, spatial economy research concentrates on the interaction between land-uses, revealing the short-term change of land-use pattern but lacking methodological suitability to model the long-term results. This is evident in many studies regarding land-use change by using cellular automata (e.g., White and Engelen 1993; White and Engelen 1997; Li and Yeh 2002) or agent-based modelling (e.g., Irwin and Geoghegan 2001; Brown et al. 2005). In those studies, the prediction accuracy of the future is also quite sensitive to the simulation and the calibration process, and the results, therefore, are very likely to be divergent when long-time prediction is expected.

Table 2-3

Comparison between the spatial accessibility measures (geometric accessibility metrics) and the functional accessibility measures (geographical accessiblility metrics) in various aspects

	Spatial accessibility measures	Functional accessibility measures
Alternative definitions	Geometric accessibility Space syntax centrality	Geographical accessibility Attraction accessibility Location-based accessibility
Opportunities	Spaces/axial lines/segments	Functions/land-uses
Distance	Cognitive cost: Topological/geometric distance Energy/economical consumption: Metric distance as the radius	Energy/economical consumption: Euclidian distances/traveling time/costs
Transport component	Spatial network (sight lines)	Transport network
Graph-making	Dual graph	Primal graph
Analysis resolution	Disaggregated levels (streets)	Aggregated levels (e.g., grid cells, census wards, administrative areas)
Dynamics	Static model	Static/dynamic model
Required data	Street network/axial maps	Land-use/jobs/census data and transport data
Description of evolution	Long-term changes	Short term changes
Driven forces	Movement economy Pervasive centrality The grid as generator	Spatial economics Agglomeration and proliferation Spatial diseconomy

The review of the literature in the fied shows that geographical and geometric measures vary theoretically and methodologically in many aspects, but it is clear that the marriage between these two categories of accessibility measures can enrich space syntax theory by opening up the methodological approach to connect with the functional dimensions of urban configuration. The possible incorporation should include the following aspects. Firstly, the space syntax theory can be further extended as the urban theory of opportunity syntax so that land-use patterns can be incorporated into the framework of morphological analysis and have their own syntactic meanings. Secondly, the cognitive cost through the transport system should be addressed in fine-scaled accessibility computation. The most straightforward approach to achieving this aim is to account for the geometric properties of the spatial network which is also the essential transport context in which people move freely. Thirdly, the proper spatial unit for the analysis should be carefully considered to produce high-resolution results with the increasingly available fine-grain data of street network and land-use amenities. Fourthly, the relationship between spatial and functional accessibility measures should be calibrated and verified in more basic research and empirical studies in order to clarify the insights brought by the analysis of spatial and functional configurations, respectively, and their interactive relationships in general. By interacting with ideas in geographical accessibility measures, it is necessary in the space syntax theory, as an open epistemological framework, to consider the functional dimensions of space, which are capable of accounting for its position in wider socio-economic processes by taking as its basis the interaction between urban form and function. One vital form of constructing this framework involves the development of the more advanced functional accessibility measures, the linkage between them and the measures in the existing space syntax theory, and the potential application of the spatio-functional interaction theory in the urban morphological analysis of socioeconomic nature.

CHAPTER 03

THE METHODOLOY

1 INTRODUCTION

This chapter focuses on the research design and related methodology developments for the whole thesis. Its goal is to investigate the way in which the public space and the land-use distributions can be described quantitatively in relation to the spatial network that connects them. It starts with the introduction of the research framework of the thesis, illustrating how the analytical parts are systematically organised, followed by the summary of the case study location and the associating data and method structure. It then outlines the model representations, concepts and measures in the space syntax theory to generate the spatial centrality indices including *angular integration* and *choice* for developing an advanced methodological framework for measuring the land-use patterns. By constructing a *path-point model/network interface model*, this chapter proposes a framework for measuring the *urban function connectivity* through the street network with the function nodes in a dual graph representation of the land-use system. Three proposed core variables are *accessible urban density*, *diversity* and *cognitive distance*. The interplay among these three principal dimensions is measured by a composite measure to capture a comprehensive understanding of the land-use distribution through the interface network. Meanwhile, the *function regions* are defined based on the function connectivity – *angular function closeness* - in various active land-uses at different levels. This chapter continues to compare the centrality structures and their frequency distributions that are captured by space syntax centrality and function connectivity measures in Shanghai for preliminarily verifying the complementarity between these two types of accessibility for spatial network analysis. It ends with a discussion of the methodological limitations and the possible further development.

2 THE STRUCTURE OF RESEARCH METHODOLOGY

2.1 The research framework

The overall research framework is illustrated in Figure 3.1. By following this structure, a broader picture is phrased about how the spatio-functional interaction model can inform the urban structure and place performance. There are five critical parts in this framework. The first two parts (A and B) are to construct the spatio-functional model and the remaining three parts (C, D and E) investigate the specific aspects of the diachronic interaction between these independent layers and its synchronic quantitative relation to the dependent urban performance distributions.

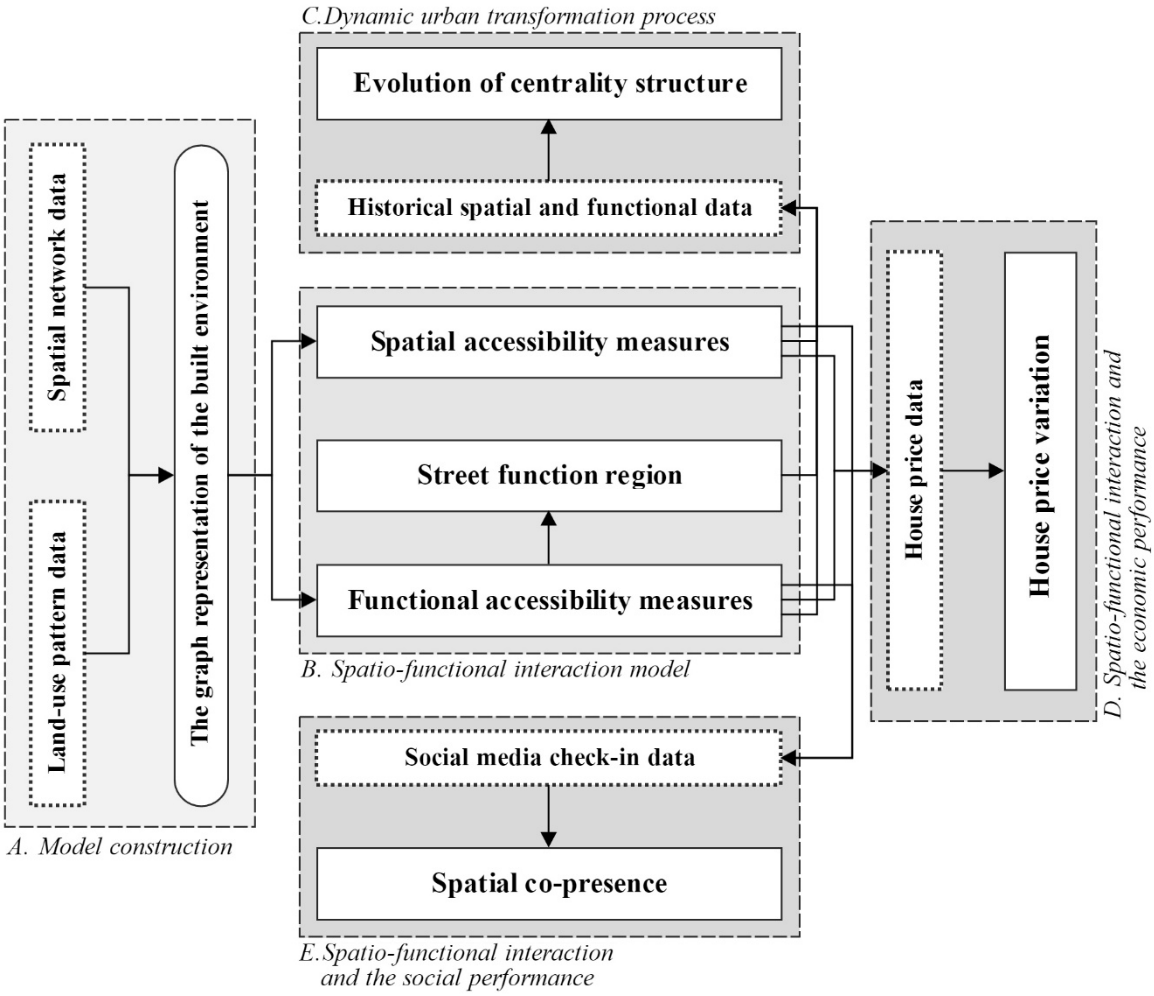


Figure 3-1

The research framework of this thesis

According to different purposes, the built environment can be abstracted in various forms. The graph representation, a mathematical illustration of the geometric relationships between spatial elements, makes the spatial configuration measurable. Because the spatial relationships are converted into the mathematical connections in such a model, the fine-scale analysis of large urban systems become possible. The graph representation of the built environment has been widely discussed in the review of configurational studies in the previous chapter. The straightforward approach is the primal representation based on the observed planar properties of the spatial network. Following the tradition of graph theory, this type of models considers the lines in the real world as the edges and the intersections as the nodes of the graph, i.e. the streets and road junctions are treated as the edges and nodes of the graph respectively (e.g. Crucitti et al., 2006; Porta et al., 2009). By inverting the identification of edges and nodes in the primal graph, the space syntax model uses directly the public spaces as the nodes or basic units in building graphs and the connections between spaces as the edges (Hillier and Iida 2005).

Recently, the buildings are argued to be a crucial part of the built environment representing the 'life between buildings' with clear origins and destinations (Gehl 1987; Stahle et al. 2005; Sevtsuk 2014). As the place accommodating various activities that are related to the destination-oriented movement patterns, buildings are suggested to be the critical elements that should not be neglected in the graph building. Nevertheless, it is recognised that buildings are not the actual units barring urban activities. One building could be occupied by various urban functions horizontally or vertically. As a consequence, a fine-grained dataset that records the detailed location-based activities is required. Related studies also suggested that building-based configurational analyses maintain a higher resolution than the street-based ones. However, it is important to realise that the typically building-based analyses are computationaly labour-intensive and require high-resolution datasets that are not easy to obtain. More importantly, using buildings as the basic units in the spatial network analysis is likely to increase the redundancy of the results, when the study covers a very large region and the research scale is simultaneously large. The streets, as the focus of public space, on the other hand, serve as a more efficient resolution setting for the computation and the interpretation of the results. The axiality and linearity of the cognitive space have been explored in the relevant findings of space syntax research, which led to the development of the axial model and the segmental model with the consideration of the topological nature of spatial configuration of cities (Penn 2001). Furthermore, the building morphology changes more dynamically than the streets system which is relatively stable for the analysis. Although the necessity of adding the location-based urban activities to the spatial configuration modelling is recognised, the street-based approaches are less time-consuming for the extensive spatial network analysis, which considers properly the human cognitive habits, than the methods using the building as the unit for graph calculation.

This research aspires to formulate a series of definitions of land-use configuration in the built form, which should be consistent with the space syntax theory in terms of graph-construction and computation methods in order to make reliable the comparison and the integration of analysis on the spatial and functional layouts. In order to address the above-mentioned shortcomings, two modifications have been made. Firstly, the points-of-interest (POIs) are added to the representation of the built form, representing the most comprehensive, location-based directory of urban activities. POIs are one type of the so-called volunteered geographic information (VGI) representing subsets of locations that may be found useful. They are not spatially constrained by building boundaries and used to represent any objects that matter in human navigation in the city. In Figure 3-2, the observed POIs pattern mismatch with the building layouts: in many areas, suggesting a more real and comprehensive picture of the functional aspect of the built environment. Meanwhile, POIs can be further inferred with their perceivable attributes, including inherent typology and popularity, to further characterise the public spaces, to which these functions are connected. These are the crucial factors for understanding land-use patterns, but not yet sufficiently addressed in existing studies. The unit of morphological analysis in this research is the street segment, which allows us to scrutinise every perceivable public space for the large landscape in a cost-effective manner.

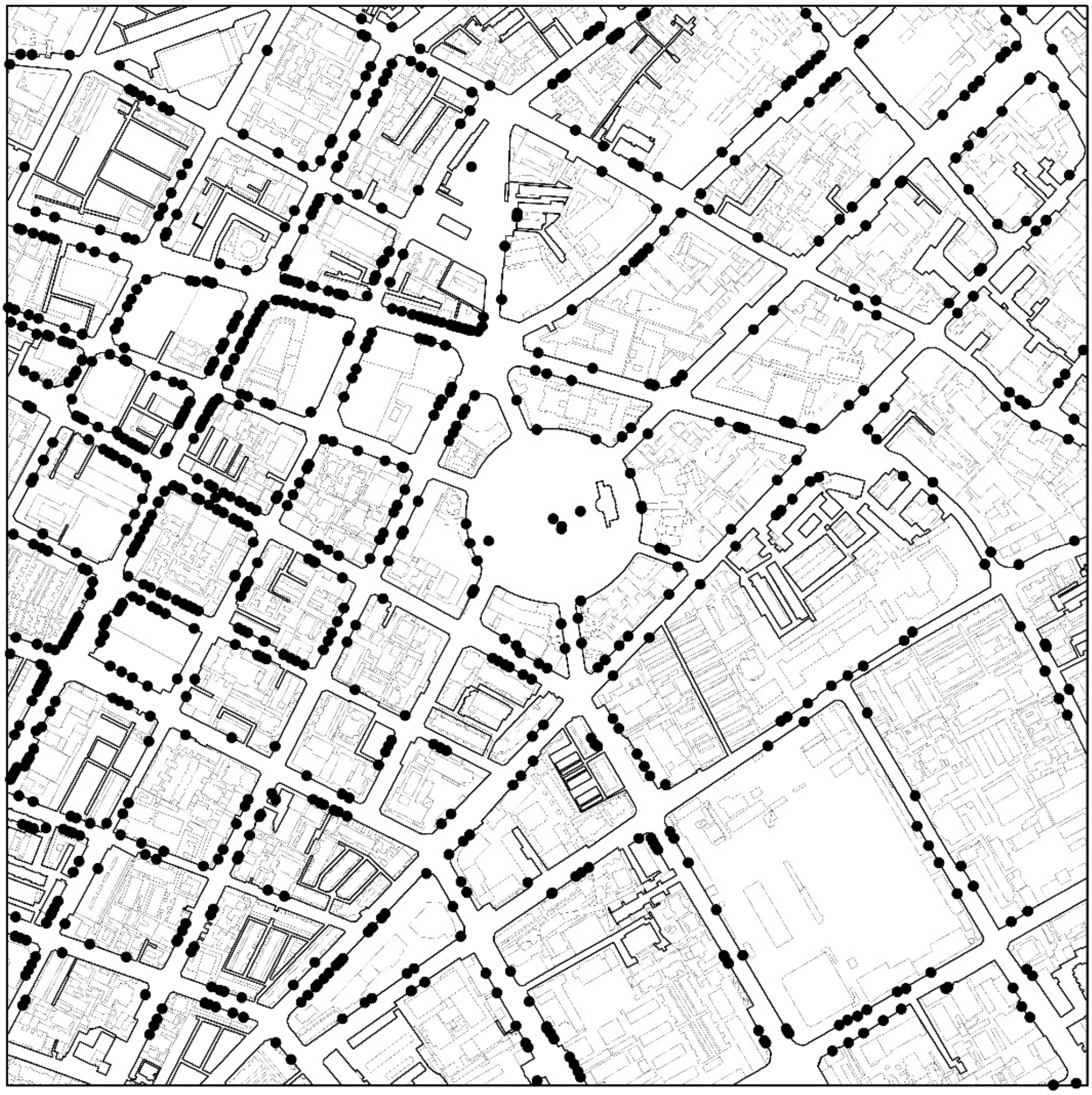


Figure 3-2

The spatial relation among streets, blocks, plots, buildings and points-of-interest (POIs)[6]

[6] A point-of-interest, or POI, refers to a specific point location that someone might find useful or interesting. The dataset of POIs has been argued to be an alternative resource representing fine-resolution land-use (see Liu and Long 2016).

Based on the modified graph representation of the built environment (A), urban street segments are then characterised by various underlying graph properties that capture the connectivity statuses of the spatial network and the land-use system. In such a spatio-functional model (B), there are two categories of numeric connectivity properties, including the spatial and functional centrality measures, respectively, and one membership feature - the function region structure - identifying the communities dominated by one or several specific functions through streets. The former two classes of accessibility measures capture the continuous centrality structures according to the numeric variations, whereas the latter graph membership index defines the spatially-discontinuous boundaries maximising the perceived configurational difference. All these three types of measures are adopted for unfolding the dynamic urban transformation process (C) with the historical road network data and POIs. This application will be discussed in Chapter 04 to identify the changing relationship between form and function. In Chapter 05 and 6, the numeric indices of centrality are adopted as the locational variables in the model for predicting the spatial variation of house price (D) and social co-presence (E). All these applications of the method are demonstrated with the help of the examples in Central Shanghai. The detailed discussion will be represented in the main analytical chapters.

2.2 Case study location

This empirical research in this thesis focuses on the Central Shanghai in the Shanghai Metropolitan Area (SMA) as the setting, in which the empirical study is conducted (Figure 3-3). Shanghai is the economic centre and one of the biggest municipalities in China, along with Beijing, Tianjin, and Chongqing. Given its geographical location, Shanghai was one of the cities that experienced the earliest modernisation in China after the Second Opium War in 1860. Since the *Open Door Policy*[7] was implemented in 1979, Shanghai which used to be a semi-colonial city, has grown significantly to be transformed into a mega-city in China. At present, the city has 23 million residents living in a 6,340 km^2 wide administrative area. It is widely evident that Shanghai offers a rich context for social and configurational complexities. This research does not plan to examine the entire metropolitan area so that the existing rural-urban difference can be properly controlled; instead, it focuses on the spatial configuration at the intra-urban scale within the central area, where census units are considerably smaller and highly urbanised. The central area in SMA serves as an important case study for this article because of the complexity of its built environment and the representativeness of the cities within the process of the rapid urban growth.

[7] The Open Door Policy, in China's modern economic history, denotes the new policy implemented by Chinese government in December 1978 to open the door to foreign businesses.

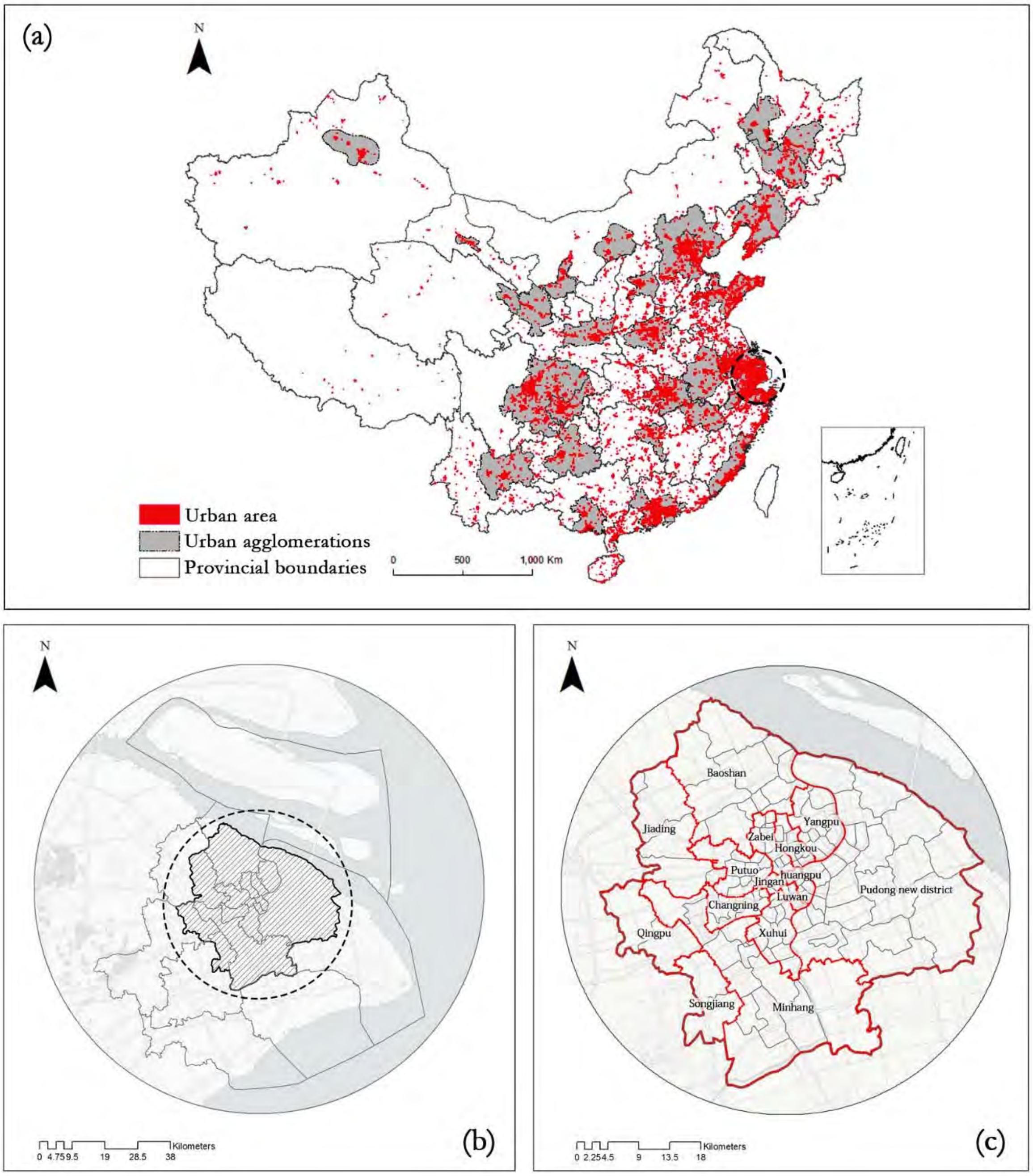


Figure 3-3

Study areas in the Shanghai Metropolitan Area (SMA): (a) the location of Shanghai City in the Chinese city system; (b) the location of the study area in the SMA; (c) the census distribution of the central area

2.3 Data and method specification

The designated three analytical chapters address the different issues on the conditionality of spatial configuration to the shifting urban centrality structures at different scales and the performance. The specific methods and data in various analytical chapters would vary to fit the particular requirements for uncovering different issues (Table 3-1). To examine the shifting relationship between the spatial and functional centrality structures in Central Shanghai (chapter 04), the historical road network data and the POIs data, which remains by far the most detailed source of historical urban spatial grids and the land-use locations in China, are used. The historical land-use maps are obtained from the business atlases and fine-resolution historical maps. By computing the spatial and functional accessibility indices as the variables, the analysis uses unary linear regression models (ULR) to investigate the extent to which the change of spatial or functional centralities are explained by each other across the city. And a discriminant analysis is adopted to evaluate the explanatory power of spatio-functional centrality measures on the changing land-use region structures in the process of urbanisation.

Table 3-1

Data and method organisation in the analytical chapters

Analytical chapters	Data	Analytical method	Variables	
			Independent variables	Dependent variables
Chapter 04: Analysis on dynamic urban transformation process	Road network data (1860s, 1930s, 1980s, 2010s); POIs data (1880s, 1930s, 1980s, 2010s)	Unary linear regression (ULR)/Discriminant analysis	Spatial accessibility measures; Functional accessibility measures	Spatial accessibility measures; Functional accessibility measures; Function regions
Chapter 05: Spatio-functional interaction and the economic performance	Road network data (2015); POIs data (2015); Social media check-in data (2015); House price data (2015)	Network-based mixed-scale geographically weighted regression (NMGWR)/Clustering analysis	House price	Spatial accessibility measures; Functional accessibility measures; Housing structural factors
Chapter 06: Spatio-functional interaction and the social performance	Road network data (2015); POIs data (2015); Social media check-in data (2015); Social media mobility data (2015)	Multivariable linear regression (MLR)/Multi-nominal logistic regression	Co-presence measures	Spatial accessibility measures; Functional accessibility measures; Function regions

In chapter 05, mixed-scale hedonic models are employed not only to unravel the spatial variation of house prices, but also to uncover how the underlying price effects of location factors matter in submarket formation process. The asking house price data was gathered from the online platform for property sales. The dataset consists of average housing price of each house/flat and its structural properties. Street-based geographically weighted regression is implemented to produce the house price effects landscape which is further used in a clustering analysis to identify the submarket boundaries. The research focus is shifted on unrevealing the role that the spatial configuration play on facilitating the spatiotemporal co-presence between different social groups in chapter 06. The mobility data gathered through the social media check-in records in Central Shanghai is used to estimate the spatiotemporal face-to face co-presence pattern between locals and non-locals in streets - the dependent variable in the multivariable linear regression (MLR) models where spatial and functional accessibility measures are defined as the independent variables. A nominal logistic regression model is used to assess of the impacts of the spatial and functional centrality metrics on distinguishing the detected co-presence modes, defined by the spatiotemporal co-presence density and cognitive distance on typical working days. The detailed introduction regarding the analytical methods are placed in the following chapters in due course.

3 SPACE SYNTAX CENTRALITY– SPATIAL ACCESSIBILITY MEASURES

3.1 Basic models and concepts

The space syntax theory origins from the observations that the spatiality of society and the sociality of the urban space simultaneously occur in the cities and address the overarching question that how space and society are in an intrinsic relationship. From a spatial configuration view, it particularly focuses on describing the spatial system as the continuous network in which various spatial parts are interconnected as a whole (Hillier and Hanson 1984; Hillier 1996). In Hillier's argument, the social meanings of urban spaces are theorised and redefined as the social ordering that would be captured by the interaction between spaces and be further reflected and measured by the geometric properties of continuous space network. In the space syntax model, measuring the relatedness in this spatial network is applied as an approach to inform the social and cultural significance (Hillier and Vaughan 2007). Figure 3-4 shows how the way, by which the urban spaces are connected, creates different related social orders. By building up the justified graph (Hillier and Hanson 1984), the spatial shallowness/depth from one root space to other accessible spaces can be unfolded via the length of the edges connecting them.

In the space syntax model, there are four typical methods to describe the space and construct the continuous spatial network for the analysis: the *axial line* (Hillier and Hanson 1984), the *segmental line* (Turner 2001a, 2004; Dalton 2001, 2003; Hiller and Iida 2005), the *convex space* (Hillier and Hanson 1984) and the *isovist* (Turner and Penn 1999) (Figure 3-5). These segmented spaces, therefore, do not only present the individual spaces in the built environment but also indicate the connectivity between their adjoining spaces. This well-defined spatial system is named as the spatial configuration, in which the shallowness of a space is defined by relatedness of the associating adjusted graph roots from the space. Theoretically, the most shallowness appears when all spaces are directly connected with the original space, whereas the deepest spaces are connected end to end in a non-linear sequence from the root space.

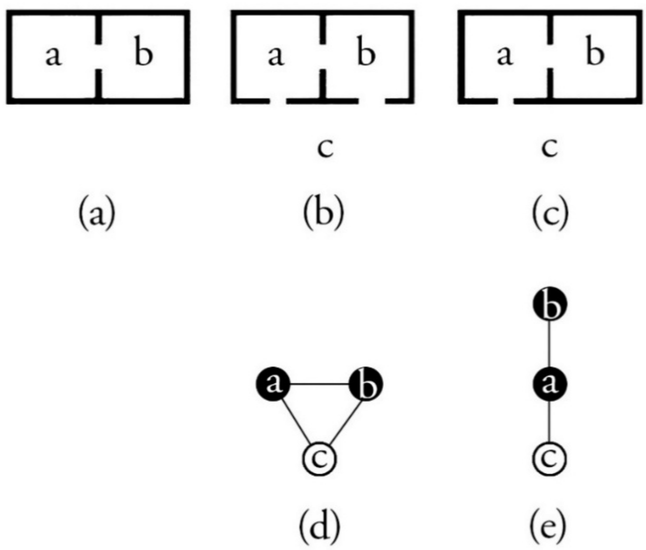


Figure 3-4

A simple diagram of generating the configurational network from spatial layouts. (a), (b) and (c): three spaces are connected in different scenarios. (d) and (e): The associating justified graphs for scenario (b) and (c). (Hillier 1996)

Another import concept in space syntax analysis of the spatial graph is the scale of analysis, since the adjusted graphs vary according to the definitions and variations of the scales. In the axial model, *step depth* - the topological turns - is used as the definition of the radius of identifying the buffer zone. The local scale in the axial analysis is at the given radius 3 steps, and the infinite radius is the global scale. In the segmental model, the radius can be defined on the basis of *metric distance* (total length of the shortest route), *topological distance* (sum of the turns along the fewest turn route), and *angular distance* (accumulative angular change along the least angular change route). The metric radius in the empirical studies has been suggested to be more effective than other formats of the radius in the segmental analysis as it can reflect the interplay between the energy costs and the cognitive efforts required for the traversal along the spatial network. Additionally, the metric definition of the radius is in line with the transport models in which travelling distance is the core of humans' mobility pattern, which reflects the travelling models (Hillier 2009). Consequently, the distinctions between spatial scales in the segmental model are made according to the length of travel: in general, the radii below 2, 500m are more local and more pedestrian-related or biking-related, while the radii bigger than 10, 000m are more likely to be global and be related to vehicular-oriented travels.

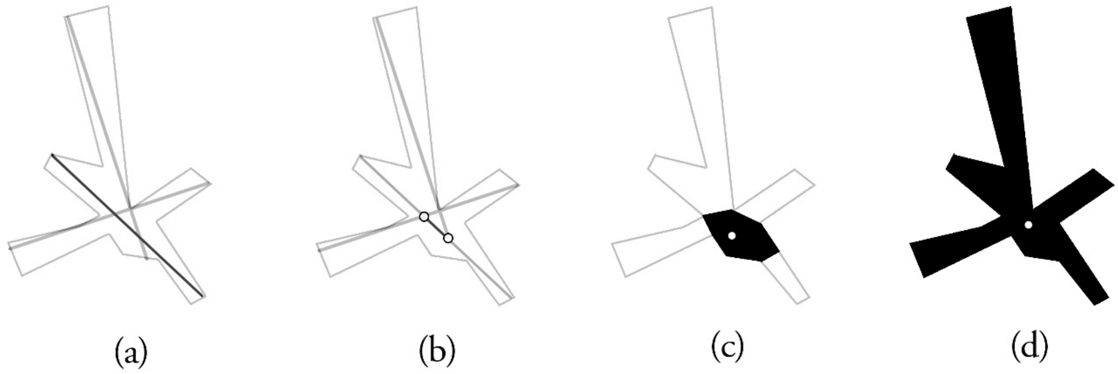


Figure 3-5

Methods of segmenting urban space in the space syntax theory: (a) axial line; (b) segmental line; (c) convex space; (d) isovist.

3.2 Basic measures in the segmental model

Angular integration (INT)

There are two basic measures in the space syntax theory: *integration* and *choice*, indicating different types of centrality in the spatial network analysis. The integration variable – also known as the *angular closeness* –measures the degree that a space is geometrically close to all the reachable spaces at a given radius. Formally, it can be understood as the reciprocal of total angular depth required to reach all the segments at the given radius. The mathematic expression is represented as the follows.

$$INT_{(i,r)} = \frac{(N_i - 1)}{\sum_{j=1}^{J} Dep_{(i,j)}}, \{dis_{(i,j)} \leq r\} \quad (3.1)$$

In this equation, the angular integration ($INT_{(i,r)}$) at the radius *r* is represented as the mean angular depth ($Dep_{(i,j)}$) from segment *i* to all the reachable segments within the buffer zone defined by the pre-identified network distance *r*.

Angular choice (CHO)

The *angular choice* measurement in space syntax is similar to the concept of betweenness centrality in graph analysis but using the angular change at each road intersection as the expenditure to find the angular shortest path (Turner 2001a). It can be defined as the number of times (n_{jk}) that the focused segment *i* has been passed through on the angularly shortest paths from segment j to k within the buffer area defined by the fixed radius r. From a mathematical perspective, this definition can be defined as:

$$CHO_{(i,r)} = \sum_{k=1}^{K} n_{jk}, \{dis_{(i,j)} \leq r;\ dis_{(i,k)} \leq r\} \quad (3.2)$$

In space syntax models, the *radius* refers to the metric distance thresholds applied to select the set of functions from the entire system to be analysed from the root segments. In this work, the distance of the radius is measured along the street segments. Four radius thresholds are specified to represent the spatial scales of the analysis, namely, 500 meters (super local scale), 1,000 meters (local scale), 2,500 meters (lower mesoscale), 5,000 meters (higher mesoscale) and 10,000 meters (global scale). These spatial levels are simultaneously in accordance with the travelling modes, e,g., the radius of 500 meters corresponds to the pedestrian travels, the 1,000 meters could be considered as the distance for biking travels, and the network distance of 10,000 are more likely to be related to vehicular flows.

3.3 Result examples and frequency statistics

Angular integration and choice measures suggest different aspects of the network proximity. In the space syntax theory, they are conceptualised as the *to-movement* and *through-movement* that describe the destination-oriented and the pass-by behaviours separately (Hillier 1999). In other words, integration reflects the selection of the destinations; the choice, on the other hand, reflects the selection the routes to those destinations. Figure 3-6 and Figure 3-7 illustrate the map examples of angular integration at 1,000 meters and choice at 10,000 meters in Central Shanghai for every street segment respectively. The integration map highlights the areas that are more geometrically shallow at 1,000 meters compared with other places. The captured urban core with the highest integration values at this scale is observed at the area around the most famous commercial street – Nanjing Road in current Shanghai, which was the easiest colonial area in Shanghai. Integration centrality structure is relatively patch-like in the angular analysis since the urban spatial attractions tend to be clustered metrically and geometrically at the same time to shape the sense of the core. By contrast, the choice centrality structure is more grid-like, as the way-finding process is moderately discrete. Which specific segment would be selected in the way-finding process depends on the angular connectivity from the original segment to other adjacent segments, so the geometrical continuity will be a crucial factor in influencing the choice centrality structure. As shown in Figure 3-7, foreground spatial network, the routes that are far more likely to be passed through at 10,000 meters, are highlighted. The arterial roads, and the global and local high streets are captured with higher choice values, illustrating their importance of interlinking urban places. These two types of network centrality measures complement and supplement one another whereby a comprehensive understanding of spatial network is shaped.

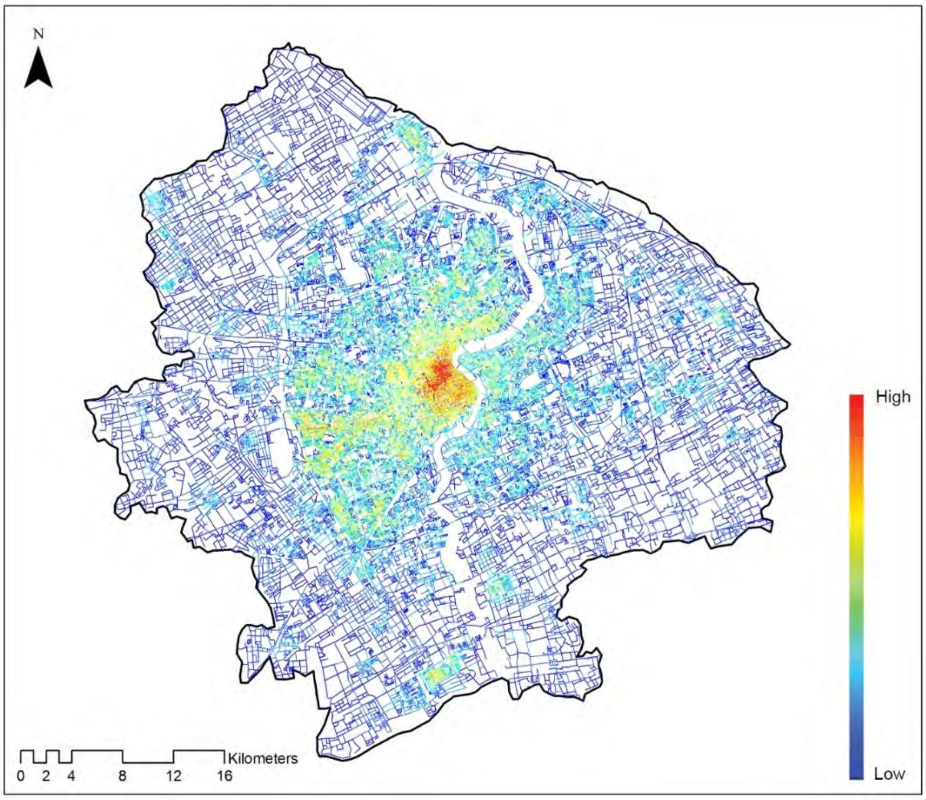


Figure 3-6

Integration (INT) map at 1, 000m network radius in Central Shanghai

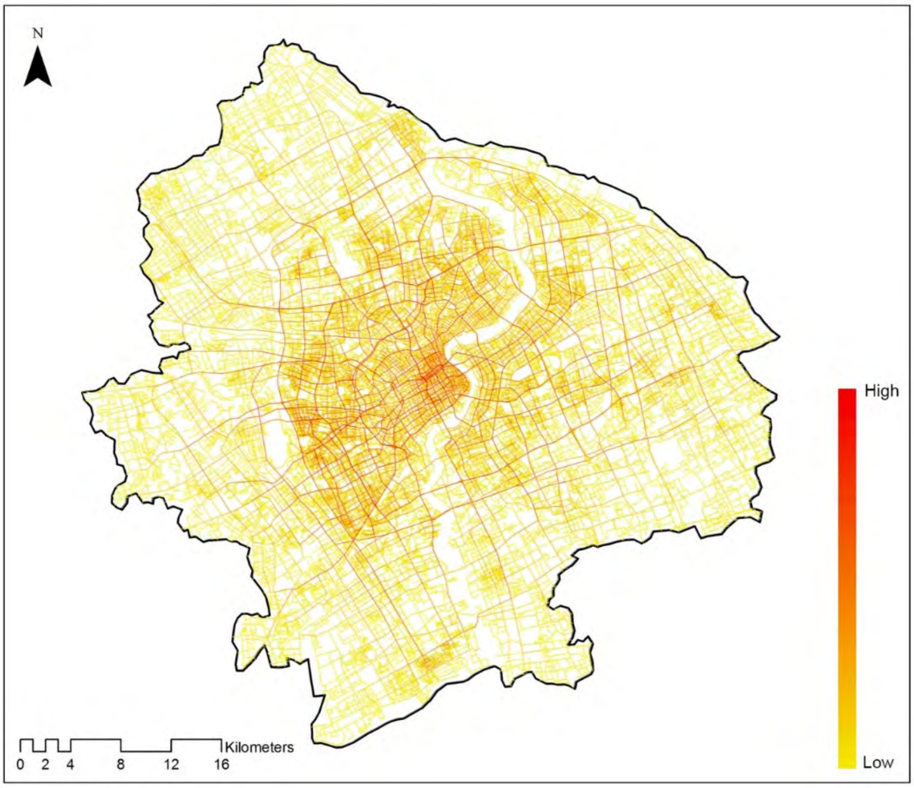


Figure 3-7

Choice (CHO) map at 1, 000m network radius in Central Shanghai

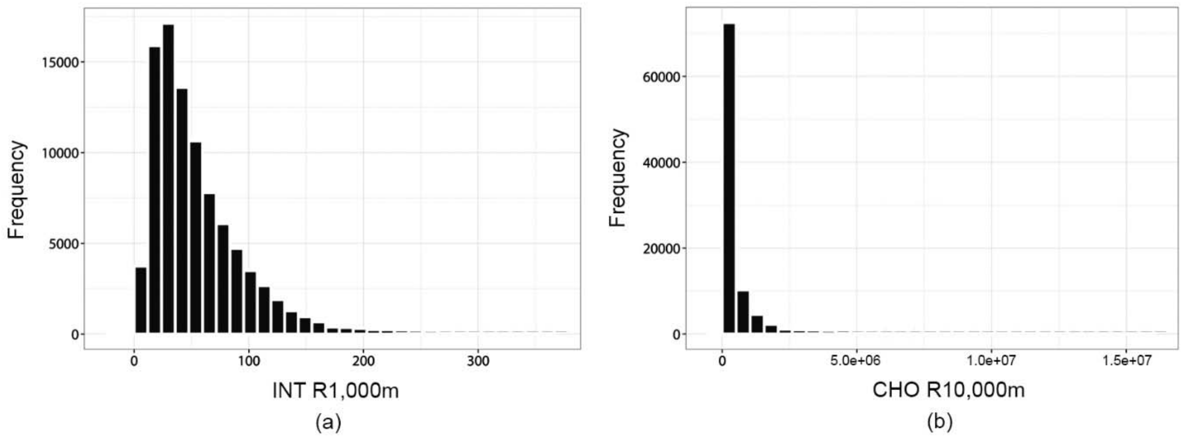


Figure 3-8

Frequency distributions of angular integration (a) at 1,000m and choice (b) at 10,000m in Central Shanghai (N=92,920)

In Figure 3-8, the frequency distributions of angular integration and choice in Central Shanghai are shown. In general, the frequency pattern of integration follows a skewed normal distribution whereas the pattern of choice follows a heavy tail trend. The observed left-skew and the long tail both indicate that spatial centrality measures are not uniformly distributed, and there are far more segments with lower spatial centrality values than the ones with higher values. These centres with higher values are geographically clustered in a few segments following distinct spatial trends - the patch-like and the grid-like, respectively.

4 FUNCTIONAL ACCESSIBILITY: URBAN FUNCTION CONNECTIVITY

4.1 Preliminary definition

In this study, *urban function connectivity (UFC)* is defined as the relatedness information between land-uses through the street networks, representing the sense of function potentials from every street's midpoint to all the reachable land-use points. This particular form of connectivity, therefore, is constructed on the basis of the street network where urban land-uses are assigned spatially. An *urban function region (UFR)* is identified as a group of places where the properties of function connectivity for different active land-uses are similar. Apart from the conventional definitions of functional regions for comparing economic development in regional studies (Antikainen 2005; Williams 2007), the UFRs in this study refer to the clusters of streets within which urban functions operate similarly. Given this definition, this research introduces an alternative approach to partition urban space from the bottom up by considering the spatio-functional relationships in a specified land-use system.

The land-use system in this study is conceptualised as a *path-point model* (PPM), or as a '*network interface model*' (NIM) to abstract the co-existential relationship between urban function points and the visual paths as graphs. In such a model, scored urban function locations (points) are assigned to the nearest paths based on their spatial inter-linkage which is identified as the interface between buildings and public spaces (Alexander et al. 1977; Hillier and Hanson 1984). By converting the spatial relationship between the main elements in PPM/NIM to edges and nodes, the land-use system can be transformed to an interface graph/network. The land-use locations and the directly visible street segments are defined as 'function nodes' and 'segment nodes', respectively, whereas the interfaces (the directly physical relationship) between nodes – including the entrances from the street to the locations and the intersections between the roads - are identified as 'entrance edges' and 'intersection edges'.

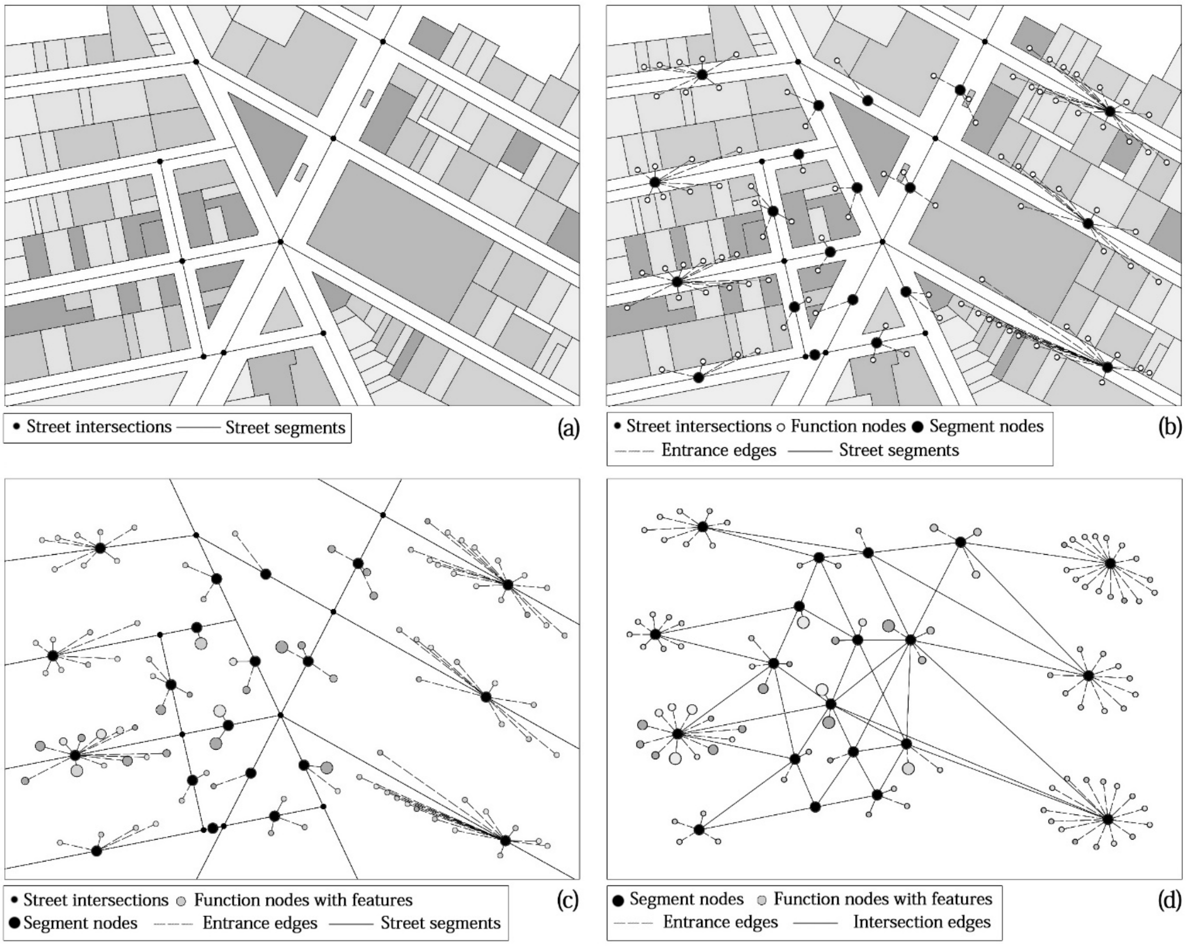


Figure 3-9

The Path-Point Model (or Network Interface Map): (a) road network and land-use distribution; (b) the interface map of street network featured by land-uses; (c) the interface map of street network and POIs and their popularity estimated by other data, for instance, the location-based social media data; (d) the dual graph of the interface network as a public space network and POIs. (The greyscale of POIs refers to the typology of activities, and the size of the points shows the place significance.)

Figure 3-9 illustrates the basic conceptual method used to construct an interface graph step-by-step. The necessary data maps including the road network and land-use pattern should processed so that these entities can be transformed into function and segment nodes with the entrance edges in an interface map on the basis of their interface connections. In the following stages, the dual graph of the interface network is created by converting the street junctions to the intersection edges that connect the segment nodes and assigning the cognitive cost at every junction to the graph as the weights of those intersection edges[8]. The

[8] In this work, from one origin, functions located on the same segment maintain the same cumulative cognitive cost given by the street network connecting them by neglecting the cognitive cost on the entrance edges, while they obtain different metric proximities according to the precise walking distance along the shortest paths.

cognitive cost for the intersection edges is specified as the angular change at each junction according to space syntax theory (Turner 2001a; Dalton. 2000, 2001; Kim and Penn 2003; Haq 2003; Hillier and Iida 2005) and earlier evidence in the field of cognitive neuroscience and way-finding (e.g., Bailenson et al. 1998, 2000; Crowe et al. 2000, Montello 1991). Using angular-weighted adjusted graphs in a simple land-use system, this thesis represents the manner in which the angle change through a journey along the shortest path is calculated (Figure3-10). As the current evidence suggests that humans are not sensitive to very slight directional change (Figueiredo 2009), a cut-off angle is used to filter the imperceptible angular deviations (α) from straight lines to enable a more appropriate approximation of the real movement decision making. Urban streets are the basic spatial units for the function connectivity model, as they are the real conduits for human movement.

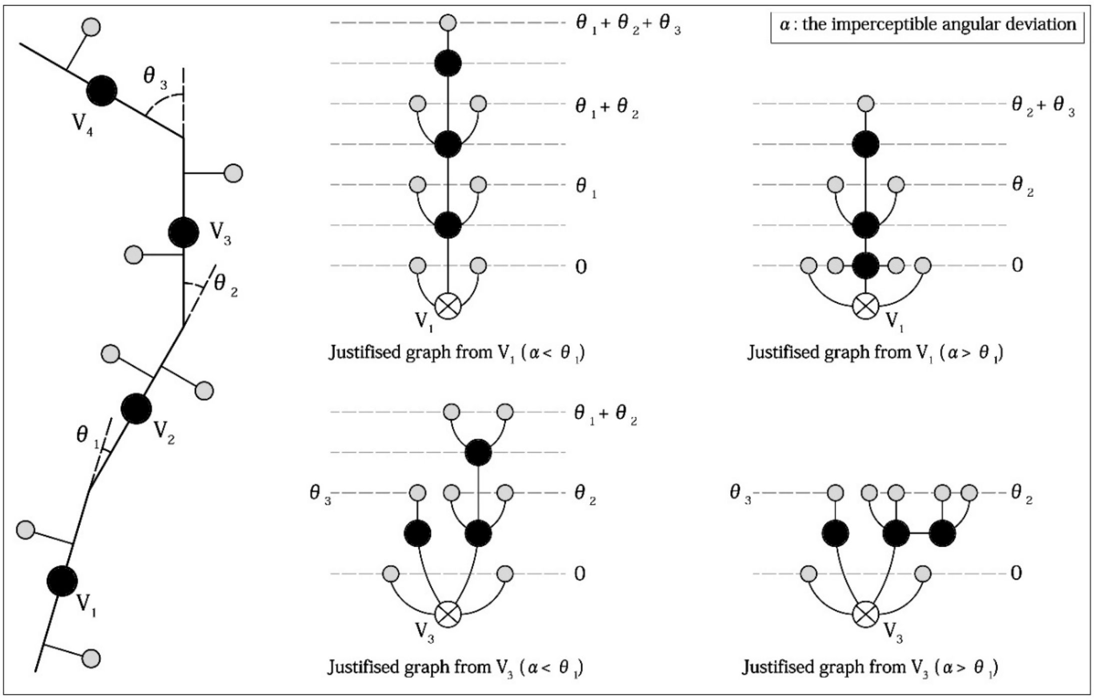


Figure 3-10

The shortest path through a network and its associated angular justified graphs from different segment nodes (V1 and V3) with different settings for cut-off angles ((α<θ1) and (α>θ1))

Notably, scores or any other information can be used to weight the function nodes to capture the various levels of the significance of urban functions. For instance, check-ins and POIs derived from social media service providers can be adopted to present the diverse types of urban activity locations and the proxies for the relative preferences of people in urban destinations. By adding weights for the function nodes, many aspects of function connectivity can be addressed to develop a comprehensive and robust methodology.

4.2 The analytical procedures

A stepwise framework is proposed to identify the various dimensions of UFC and UFRs, which contains several main modules, including data preparation, interface graph formation, function connectivity computation and function regional characterisation (Figure 3-11).

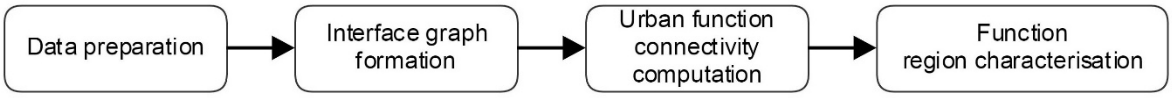


Figure 3-11

Stepwise framework for identifying urban function connectivity (UFC) and urban function regions (UFRs)

4.2.1 Data preparation

In the first module, the dataset is processed using a standard GIS procedure. The initial road network dataset should be cleared and readjusted to an angular segmental map that corresponds better to reality based on visibility and walkability. An important part of this process is to transform the road network to an 'axial model', which will then be segmented to create the segment model needed for this study. In previous space syntax studies, the segment models created from an axial model has been shown an efficient method of capturing the movement and navigation in cities. The road network data are first simplified and then split at the real road intersections. In order to avoid the large curves of the road network, they are transformed to straight segments according to the degree of their curviness (Figure 3-12), following a segmentation method suggested by Liu and Jiang (2012) to convert street central lines to axial segments. Specifically, this study uses the deviating distance from the base line that links the two endpoints of all segments to the farthest vertex in the segment lines to reflect the curviness of segments. The curved segments will be cut at the farthest vertex for calculating deviating distance if their deviating distance are longer than the average (Jiang and Liu 2010). This process will be repeated until all curves are transformed. In so doing, an objective description of the *angular segmental map* is formed based on the notion of visibility.

The POI dataset is collected and geocoded with the street network. The POIs are then reclassified as the required main types of urban activities. The social media check-in data are then linked with the POIs based on the tags and coordinates after filtering the fake points, including the check-in locations placed outside of the study area and the locations that have misfits between the coordinates of the check-in point and cell phone GPS for generating clean data, which reflects all real usage of the land-use locations.

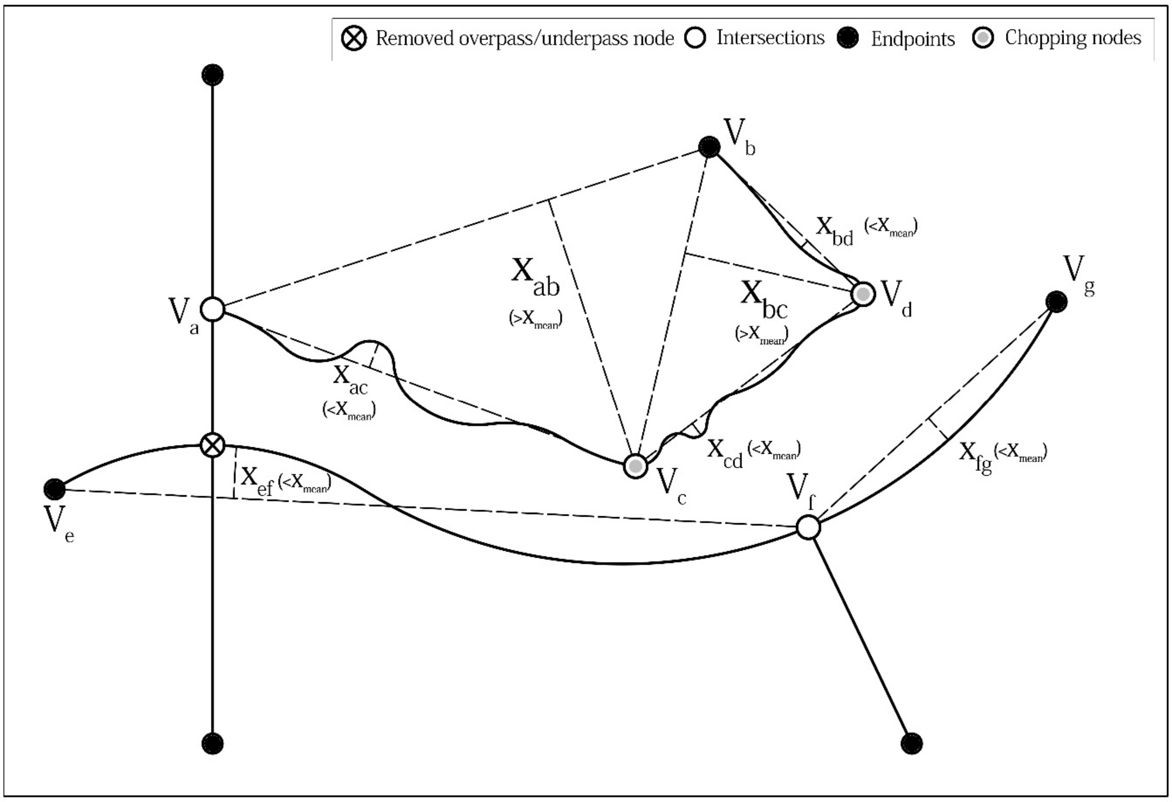


Figure 3-12

Re-definition of the road central line data to angular segment map (X is a deviating distance for an included curve/segment. The segments with a deviating distance greater than the mean value are cut at the farthest vertices in the segments, and the divided segments are re-evaluated in terms of their curves and further cut until their deviating distance are smaller than the mean value.)

4.2.2 Interface graph formation

To draw the interface graph and perform the related computation, this work combines spatially the segment map and the social media check-in data on the GIS (Geographic Information System) platform (Figure 3-13). The POIs are inferred with their check-ins features and snapped to the most proximal segments, whereby the interface relationship can then be appropriately modelled. The current study has used 15 degrees as the cut-off angle for defining the perceptible angular change and calculate the effective accumulated angular change to a reachable destination as a numeral variable to reflect the cognitive cost between a place and the functions accordingly. Given that humans can only easily recognise significant differences between two turns, angular step depth - a discrete description of the angular change - would be more appropriate for describing a sensible angular change for humans. This research defines the angular depth at every angular intersection as an integer that rounds up to the quotient, in which the numeric angular change is divided by a designated interval. In this study, it is assumed that 45° is the projected interval for defining the angular depth. For instance, if the angular change at intersection A and B is 35° and 95° respectively, the angular depth for these two angular transits will be 1 and 2.

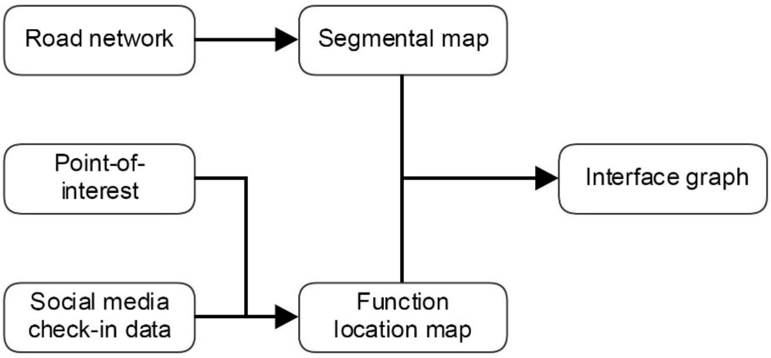


Figure 3-13

Formation of interface graph based on processed datasets

4.2.3 Urban Function Connectivity (UFC) computation

This study considers the urban funciton connectivity based on three principal dimensions including accessible function density, diversity and cognitive distance (Figure 3-14). These three aspects are very essential for the reshape of urban spatial strcuctures, rooted deeply in the location theory. Density and diversity capture the concentration of land-use actvities, indicating the scale and variaty of urban services (Robic 1982). Cognitve distance, on the other hand, represents the cost for approching these amenties, reflecting the cost-saving process. In the analysis of human behavirours, it was widely accepted that the frequncy of travel recudes with the increase of trip length (Fotheringham 1981). And people select urban service accoring to his/her affordable distance. These three aspects can be treated as different types of centrality measures; however, their interaction is more improtant as urban structures are simultaneously characterised by the densification, diversification and distance efficiency optimisation (Fujita et al. 1999). Meanwhile, In attempting to achieve a comprehensive understanding of the interplay among these three aspects, this research packages them as an integrated index to balance the methodological complexity and the simplicity of result interpretation.

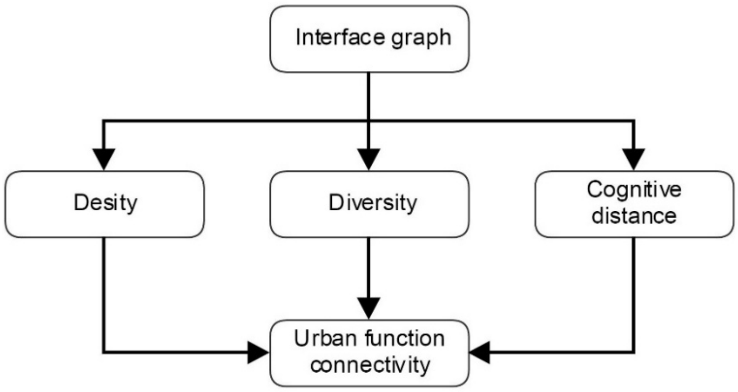


Figure 3-14

Urban functional connecvity and its three principal dimensions

Active land-uses in this study are defined as the complementary land-uses that are more likely to be linked to road network and thereby contribute to emergent movement patterns. Unlike mixed-use developments, which seek a balance of all land-uses, the active uses in this study are based on function complementarity between non-residential land-uses (Hess et al. 2001). Complementary land-uses (active land-uses in this work) include *retail, catering, hotel, office, school, social services, hospital, recreation, culture, park and transport* according to the main activity types that are distinguished in the social media. Although the overall effects of the mixture of complementary land-uses through streets are of great concern, the check-in behaviour for different active land-uses will exhibit different frequencies. Consequently, the way in which activities are classified will influence the weighting results for those functions thereby impacting the final results of function connectivity. Therefore, the classifications of POIs should consider the internal similarity of check-in behaviours for different types of land-uses in order to score the specific function appropriately. For example, retail and catering are two distinct categories because the probability that various shops are checked in is approximately 18%, whereas the same check-in likelihood for restaurants of different types is generally about 48%. It is noted that there is a necessity for distinguishing the culture land-use from recreation as an independent type due to the fact that about 5% of culture amenities are scored, whereas 37.5% of other recreation facilities are featured in social media. In so doing, this research uses the variation of check-in behaviours as the critical criteria to optimise the classification list of active land-uses and to improve the data reliability properly.

Table 3-2

Classification of active land-uses in Central Shanghai according to the social media behaviour

Type	Abbreviation	POIs count	Check-in POIs rate	Check-ins per POI	Check-in users per POI
Retail	RET	81,312	18.355%	16.936	11.531
Catering	CAT	72,351	48.407%	43,632	36.593
Hotel	HOT	27,313	16.918%	24.473	17.297
Office	OFF	54,388	31.447%	22.917	11.361
Education	EDU	9,139	67.261%	112.755	44.654
Public service	PUB	10,762	80.002%	16.239	10.237
Hospital	HOS	3,518	90.421%	149.723	82.204
Recreation	REC	35,080	37.434%	36.751	26.288
Culture	CUL	20,068	4.739%	24.695	17.671
Park	PAR	4,250	68.894%	83.691	57.549
Transport	TRA	6,611	82.665%	190.469	127.654

Accessible Density (DEN)

The DEN index measures the accumulation of scored urban activities from each street within a defined radius through the reachable shortest paths. Assuming there are K types of active land-uses, the accessible function density for the segment node *i* at radius *r* would be aggregated as $DEN_{(i,r)}$:

$$DEN_{(i,r)} = \sum_{k=1}^{K} \sum_{j=1}^{J} O_{(j,k)} \times W_{(j,k)}, \quad \{dist(i,j) < r\} \qquad (3.3)$$

This summation considers the function nodes that are assigned to street segment edges and weighted based on the social media check-in scores. In the equation above, *r* is the defined radius, $O_{(j,k)}$ is the number of the opportunities in type k that the node j can provide and $W_{(j,k)}$ is the specified weight for the function node *j* in type *k*. The scores for the function nodes are relativised according to the list of defined land-use types including retail, catering, hotel, etc., and measured as the normalised check-ins which can be presented as $W_{(j,k)} = \frac{\log C_{(j,k)}}{\log C_k^{max}}$, where $\log C_{(j,k)}$ represents the log-normalised check-ins for the specific function node *j* in type *k,* and $\log C_k^{max}$ denotes the log-normalised value of the maximum check-ins for all the function nodes in the built graph. In the absence of the opportunity information of every POI, this study concentrates on the demand side of the land-use system which is directly related to cumulative check-ins in various types of land-use, the opportunity number for each function node is assumed to be the same as 1.

Accessible Diversity (DIV)

The DIV index measures the balance degree of all reachable weighted urban activities from the original street within a given radius. Diversity can be measured in several ways, but the most popular methods include the dissimilarity index (Cervero and Kockelman 1997) and the entropy method (Chuvieco 1999). In this study, information entropy is applied to measure the diversity of urban function nodes from segment node i at the radius r, and represented as $DIV_{i,r}$ ($DIV_{i,r}$ = [0, 1]). Further, a normalisation process has been applied to enable the different types of activities to be comparable. A direct way to apply such a process is to convert the absolute density to a relative density by dividing the accessible weighted density in type k for each segment node by the maximum value of the accessible density of land-use of the same type at the same radius for all the segment nodes within the study area ($NaDEN_{(i,k,r)} = \frac{DEN_{(i,k,r)}}{DEN_{(k,r)}^{max}}$). The computation of accessible diversity can be formally represented as follows.

$$DIV_{(i,r)} = \frac{-\sum_{k=1}^{K} P_{(i,k,r)} \times \ln\left(P_{(i,k,r)}\right)}{\ln(K)}, \quad \{dist(i,j) < r\} \quad (3.4)$$

$$P_{(i,k,r)} = \frac{NaDEN_{(i,k,r)}}{\sum_{k=1}^{K} NaDEN_{(i,k,r)}} \quad (3.5)$$

The presence probability ($P_{(i,k,r)}$) of the function nodes in type k at radius r for segment nodes i is measured by its empirically observed frequency of normalised density ($NaDEN_{(i,k,r)}$) among all K types of land-uses.

Cognitive distance (DIS)

The cognitive distance index (DIS) measures the mean angular step depth to all the reachable urban activities from the original street within a given radius through the shortest paths. It reveals the cognitive efforts required to reach all accessible functions from the original street segments beyond the same energy expenditure that is measured in the light of the metric length of the streets. This index can be formally expressed by the following equation.

$$DIS_{(i,r)} = \frac{\sum_{k=1}^{K} \sum_{j=1}^{J} Dep_{(i,j,k)}}{N_{(i,r)}}, \{dis_{(i,j)} < r\} \quad (3.6)$$

In the equation above, $Dep_{(i,j,k)}$ shows the angular step depth from segment node i to function node j in type k within the buffer area defined by the radius r, and $N_{(i,r)}$ is the summation of the accessible functions at the same radius.

Urban function connectivity (UFC)

The urban function connectivity index is a composite index that measures the degree to which the dense and diverse urban activities are accessible with less angular step depth within a given radius. Here, density and diversity are treated as the benefit, and cognitive distance is used as the cost, following the cost/benefit models in geography. The final urban function connectivity index ($UFC_{(i,r)}$) which can be calculated formally as follows:

$$UFC_{(i,r)} = \frac{{DEN_{(i,r)}}^{DIV_{(i,r)}}}{DIS_{(i,r)}}, \{dist(i.j) < r\} \qquad (3.7)$$

Here, the impact of the interplay between density and diversity on function connectivity is quantified by a power function, which recently has been applied as an elasticity parameter in measuring job accessibility with job density and variety (Cheng and Bertolini 2013). In the light of foregoing, the product of these two factors (${DEN_{(i,r)}}^{DIV_{(i,r)}}$) will be 1, when $DIV_{(i,r)}$ is equal to 0, and will be $DEN_{(i,r)}$ if $DIV_{(i,r)}$ is 1.

4.2.4 Urban function regions (UFRs) characterisation

Urban streets are connected to different types of functions; in turn, urban streets are characterised by the function connectivity in different land-use types. In this section, urban functional connectivity measures are employed to detect the urban function region structure. There are two steps to detect the urban function regions: firstly, function angular closeness, is proposed to index streets with functional centrality to a certain type of land-use; and then, a k-means clustering analysis is utilised to partition and annotate each region (Figure 3-15).

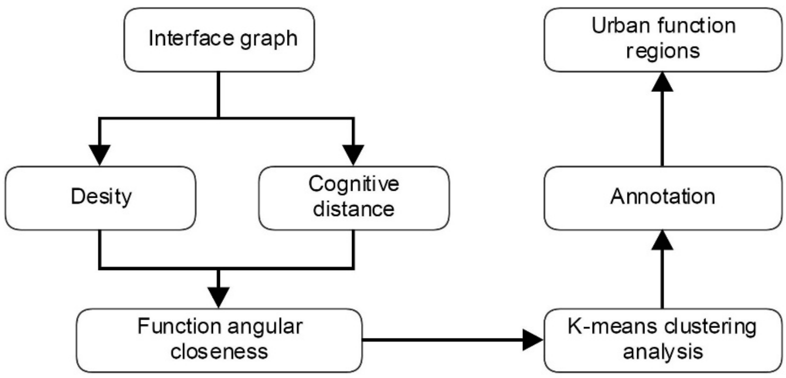


Figure 3-15

Steps to detect urban function region structures

Function angular closeness (FAC)

The FAC index is a particular form of the function connectivity with the focus on the specified type of land-use, and it measures the angular agglomeration of the urban function of a certain type through the shortest reachable urban paths within a given radius. The computation logic of this index follows the idea of establishing angular closeness which is computed as the quotient in which node counts are divided by the mean angular step depth in the space syntax model. Mathematically, this metric can be identified in a straightforward way as follows.

$$FAC_{(i,k,r)} = \frac{DEN_{(i,k,r)}}{DIS_{(i,k,r)}}, \ \{dist(i,j) < r\} \quad (3.8)$$

In the equation above, $DEN_{(i,k,r)}$ refers to accessible density of function nodes in type k from segment node i at the radius r, and $DIS_{(i,k,r)}$ captures the angular cognitive distance to these functions.

Urban function region (UFR)

Within the family of statistical data mining approaches, many algorithms can be used to address the question of grouping multi-dimensional data as clusters. These algorithms include hierarchical clustering, two-step clustering, the self-organisation map (SOM), etc. In this study, k-means clustering is employed by using the FACs of each street as the vectors' dimensions due to its efficiency in handling large-sized numerical datasets (Bishop 2006). In this method, streets maintaining similar function connectivity in all the defined types will be redistricted to several function regions. As its name implies, k-means clustering intends to group objects into predefined k clusters where every object in the same cluster will have the nearest mean. Consequently, the objective of k-means clustering in this study is to minimise the total intra-cluster variance, which is measured by the squared errors. As a type of iterative descent clustering algorithm, k-means clustering can be summarised as follows:

$$J_{(c,r)} = \min_{C} \sum_{l=1}^{L} \sum_{C(i)=l} dist(V_i, \bar{V}_l), \{dist(i,j) < r\} \quad (3.9)$$

where $J_{(c,r)}$ is an objective function for a given cluster assignment C at a radius r, $C(i)$ refers to the label that the observations have, $\bar{V}_l$ is the mean vector for the l th cluster, and V_i is a multi-dimensional vector illustrating the co-presence of function accessibility of various land-uses ($V_i \in (FAC_{(i,1,r)}, FAC_{(i,2,r)}, \dots \dots, FAC_{(i,K,r)})$). This process will be repeated iteratively until the grouping results are stable with a minimised sum of squares.

One well-known problem of k-means clustering is the problem of cluster validity. In other words, the results should be assessed so that the optimised number of clusters could be picked, which can hardly be decided before the analysis (Halkidi et al. 2001). Some metrics have been developed in previous studies for validating cluster numbers, such as, Dunn's Index (Dunn 1973), Davies-Bouldin index (Davies and Bouldin 1979), Silhouette Index (Rousseeuw 1987), Xie and Beni's Index (Xie and Beni 1991) and others. In this paper, Dunn's Index and Silhouette Index are used as the validation indices to evaluate the most proper number of clusters. Because the former index emphasises maximising the inter-cluster distances and minimising the intra-cluster distances, whereas the latter index focuses on the clustering strength of each observation by measuring the mean compactness and separation of clusters.

In this study, the radii used in the analysis of urban function connectivity structures are the same to the ones adopted in space syntax analysis to reflect the modes of urban movements. The selection of radius here seems to be arbitrary to some extents, but it is still reliable since it balances the methodological robustness and the representativeness of the radius selection. In previous studies on the large scale urban systems, it is found that the basic centrality structure can be summarised in several typical modes of variation at different scales (Serra and Pinho 2013). As a validation of the radius selected stated in section an investigation though principal component analysis (PCA)[9] is conducted here to find the most typical radii according to the inherent statistical correlation between centrality indices across scales. It is shown that the centrality at any selected radius can represent a certain effective interval of centrality patterns at close radii by using 0.75 as the threshold. The effective intervals for all the five selected radii can almost cover the whole spectrum. This indicates that the selected network distances are critically distinguishable as components describing the street-based centrality structure at different spatial levels in the case of Central Shanghai (Figure 3-16).

4.3 Result examples and frequency statistics

In this section, to demonstrate how the methodology works, the performance of urban function connectivity measures is explored on the local spatial level, using the 1,000m network distance as the radius. Figure 3-17 illustrates the accessible function density structure in Central Shanghai, which is more polycentric than the angular integration pattern (Figure 3-6), though the positions of the most highlighted cores are consistent around the Nanjing road. Figure 3-18 shows that accessible land-use mixture can also roughly identify the boundaries of the urbanised areas indicated in the density map, but the detailed pattern of the accessible function diversity is not spatially identical with the density in the urban areas. It demonstrates that the interplay between urban density and diversity is formulated in a complex manner.

[9] From a statistical perspective, principal component analysis is a dimension reduction method. It is a statistical procedure to convert a set of possibly correlated variables to a set of linearly uncorrelated variables called principal components.

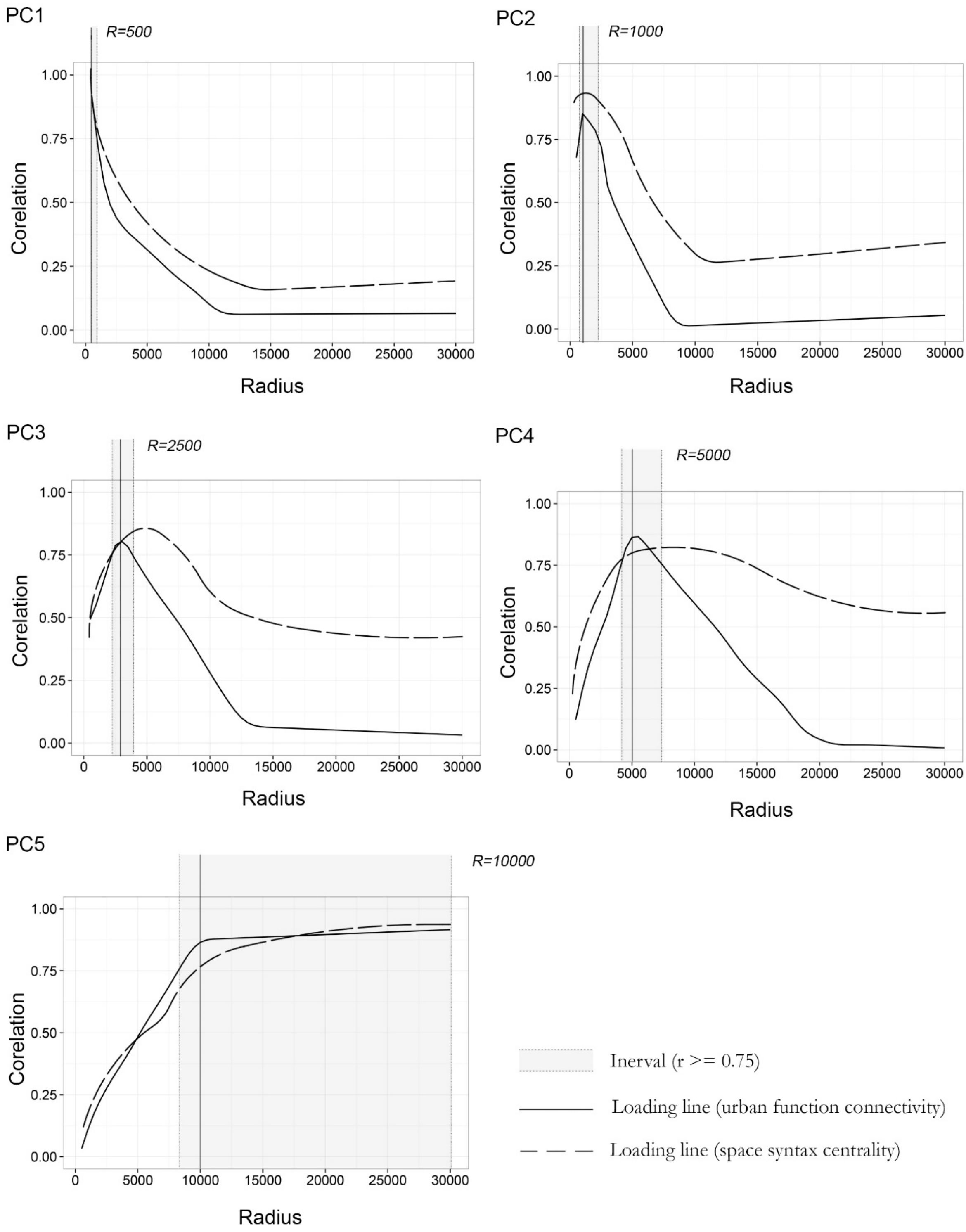


Figure 3-16

The loadings of the selected 5 principal scales of urban function connectivity and space syntax centrality measures in a principal component analysis (PC1: super local scale; PC2: local scale; PC3: lower mesoscale; PC4: higher mesoscale; PC5: global scale)

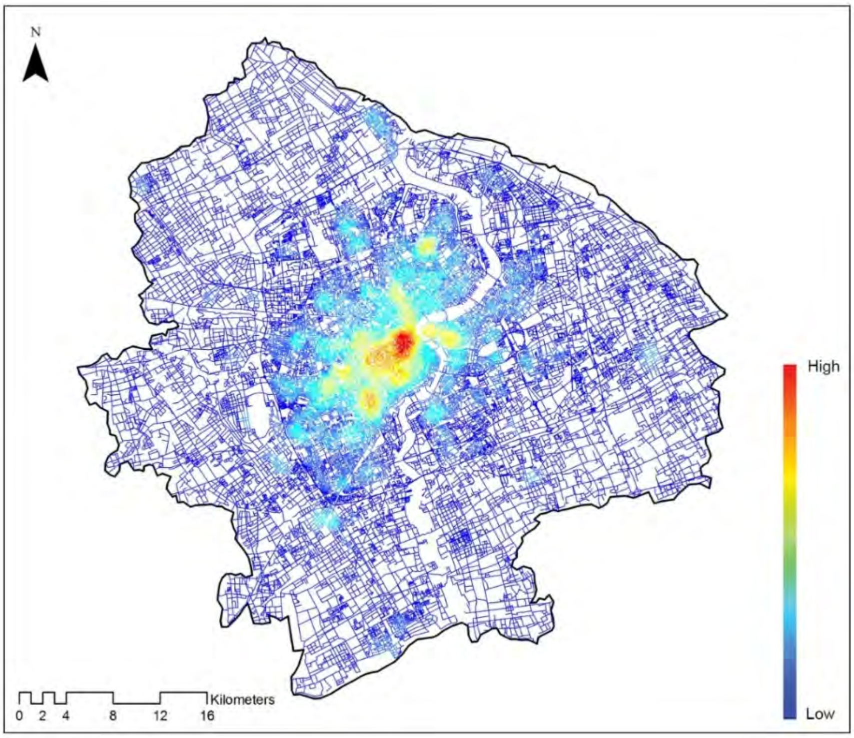


Figure 3-17

Accessible function density (DEN) map at a 1,000 m network distance radius in Central Shanghai

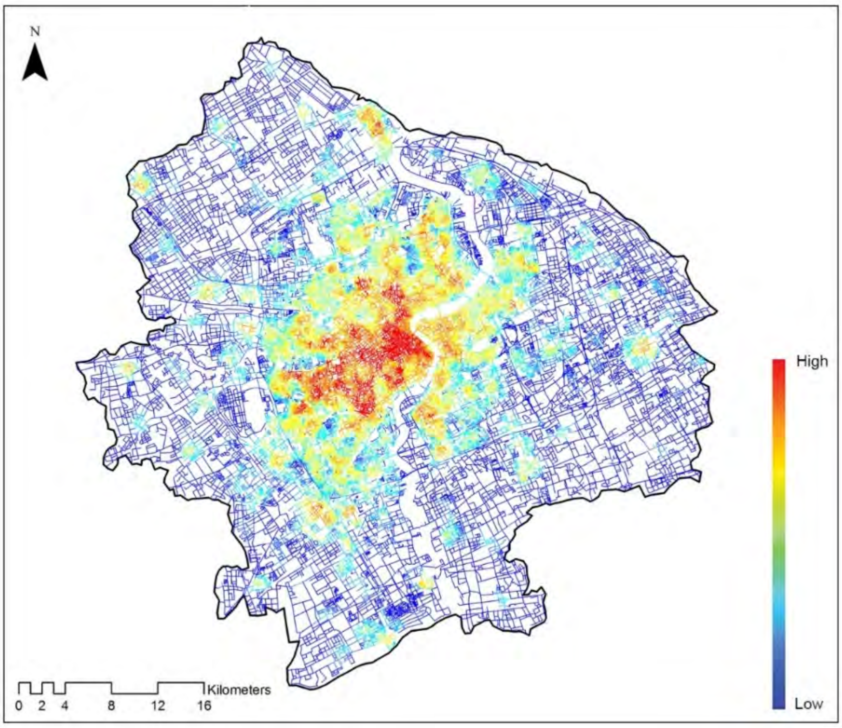


Figure 3-18

Accessible function diversity (DIV) map at a 1,000 m network distance radius in Central Shanghai

In Figure 3-19, the distribution of the cognitive cost to nearby land-uses at 1,000 network distance is represented. It is shown that the highly urbanised areas generally maintain the higher values in the cognitive distance whereas the suburban areas that are interconnected through grid-like motorways have lower cognitive cost. This is not surprising since the highly urbanised streets are relatively historic and self-organised, so the spatial layouts of the city centres would have a deeper spatial structure for shaping the social culture (Hillier 1999, Karimi 1998). The spreading grid-like roads network in the suburban, on the other hand, are for interconnecting suburban centres with much fewer attractions along the roads. Therefore, the cognitive distance (to land-uses) structure has its importance of describing the roles that the streets play in their context by considering the interaction between the attractions and the spatial network.

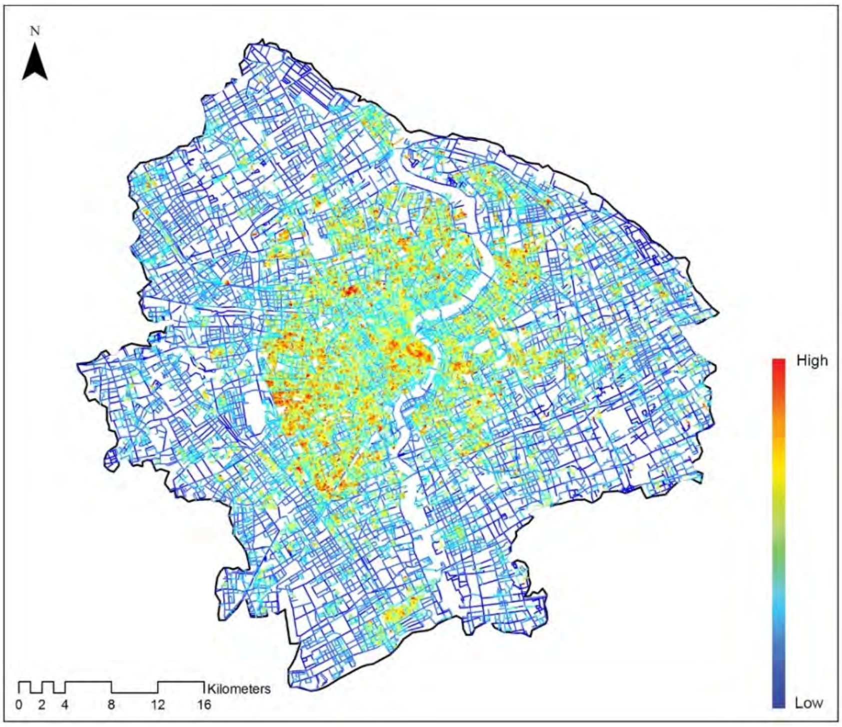


Figure 3-19

Cognitive distance (DIS) to land-uses map at a 1,000 m network distance radius in Central Shanghai

All these three centrality patterns capture the centre-to-edge relationship but represent the differentiable detailed distributions reflecting the underlying spatial mechanisms. A comprehensive summary of these three function centrality measures is shown in Figure 3-20 where the streets centres with high land-use density and diversity but less angular connecting distance are symbolised. This map suggests that, as what space syntax model has suggested, urban land-use centres are not only formed in a metrical way based on energy consumption but more importantly, they are connected to their context in a configurationally effective way with less mean depth thereby maintaining higher composite scores of function centralities. That is to say, the cognitive distance is also essential in the interaction between land-uses.

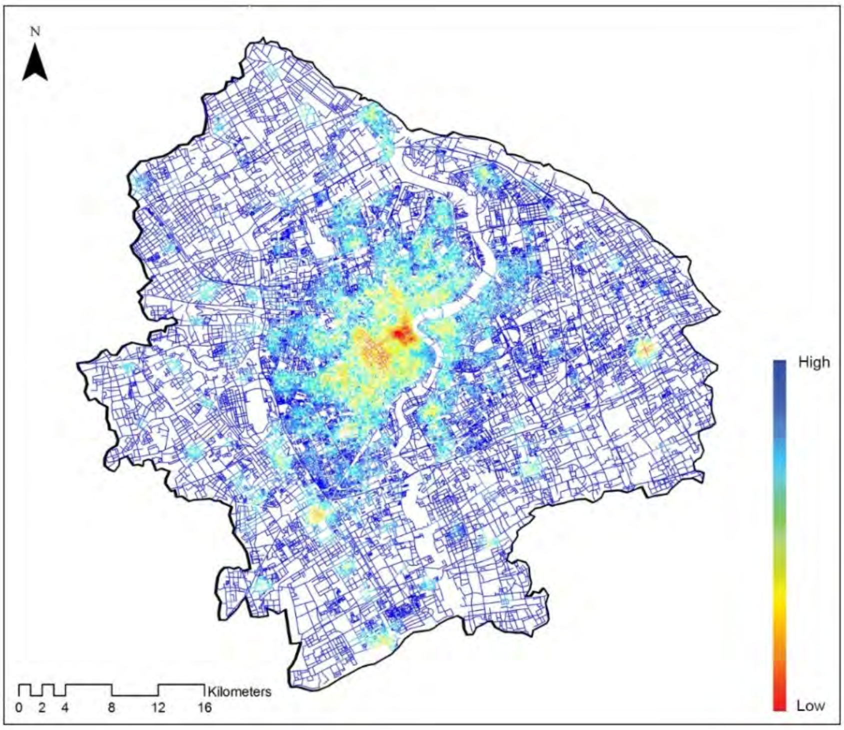


Figure 3-20

Urban function connectivity (UFC) map at a 1,000 m network distance radius in Central Shanghai

The inherent difference among these three principal dimensions of the urban function connectivity can also be discovered by scrutinising their frequency distributions (Figure 3-21). The pattern of accessible function density follows a heavy tail distribution, indicating that the variation between centres in terms of activity intensity is very significant (Figure 3-21 (a)), and a large amount of movements is concentrated in some limited number of streets and the movements at other places are much less. The accessible diversity is right-skewed distributed in terms of its frequency (Figure 3-21 (b)). It suggests that the urbanised areas with higher road segment density gain more land-use mixture than the less urbanised districts. Figure 3-21 (c) illustrates the frequency pattern of the mean cognitive distance. It is a left-skewed normal distribution with two peaks at the left and the right ends, which are the segments with very fewer functions along the streets and the ones without any accessible activity, respectively. After combining these three function connectivity measures, the frequency distribution of the composite values represents a steeper long tail trend compared with the density frequency distribution, which demonstrates that the requirement for obtaining high composite function connectivity scores is more rigours than that for density only (Figure 3-21 (d)). Due to adding the influence of urban diversity and cognitive cost, this map emphasises the role that the spatial network plays in connecting land-uses from street to street, which is more close to the geometrically perceivable urban reality.

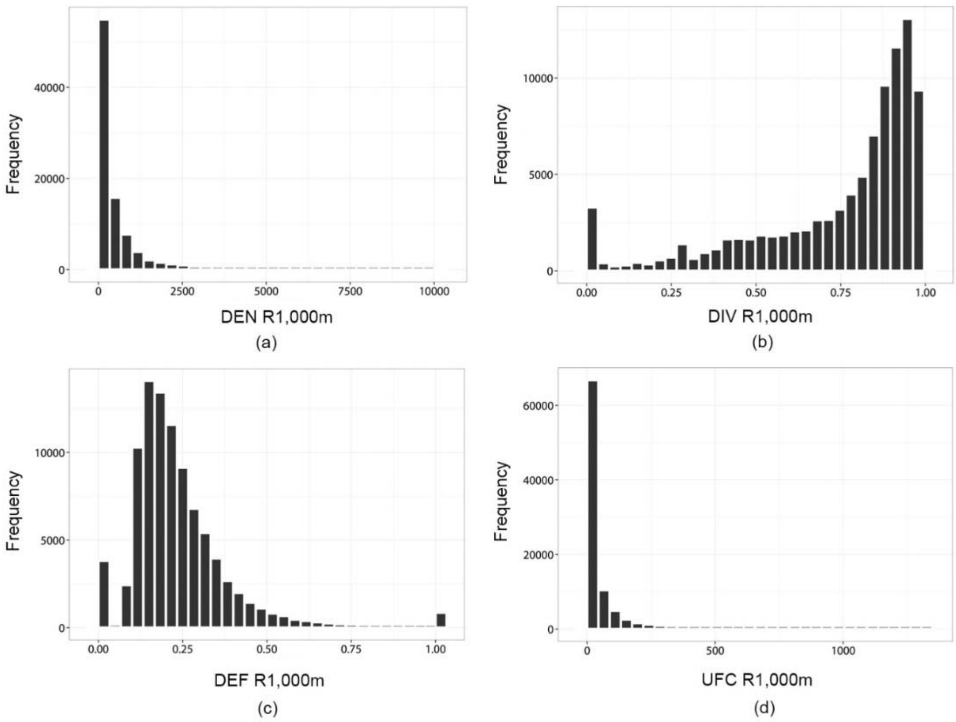


Figure 3-21

Frequency distributions of accessible function density (a), diversity (b), cognitive distance (c) and urban function connectivity (d) at 1,000 m network distance in Central Shanghai (N=92,920)

The patterns function angular closeness to each type of active land-uses in Central Shanghai at 1,000 meters are illustrated in Figure 3-22 and Figure 3-23. Those suggest a fundamental trend that the urban functions are more clustered in the urbanised areas, but the detailed clustering logics for various land-uses can vary significantly. Some public facilities are relatively more evenly distributed for maximising their service buffers with larger coverage. Related examples include the educational functions, hospitals, parks, transport facilities and the public service sites. The commercial-related services, including shops, caterings, offices, cultural amenities, and recreation places, on the other hand, are more clustered in the city centres. These maps demonstrate that the inner-group interaction between urban function in the same type and the inter-group interaction between complementary urban functions coexist, forming a complex overall land-use system.

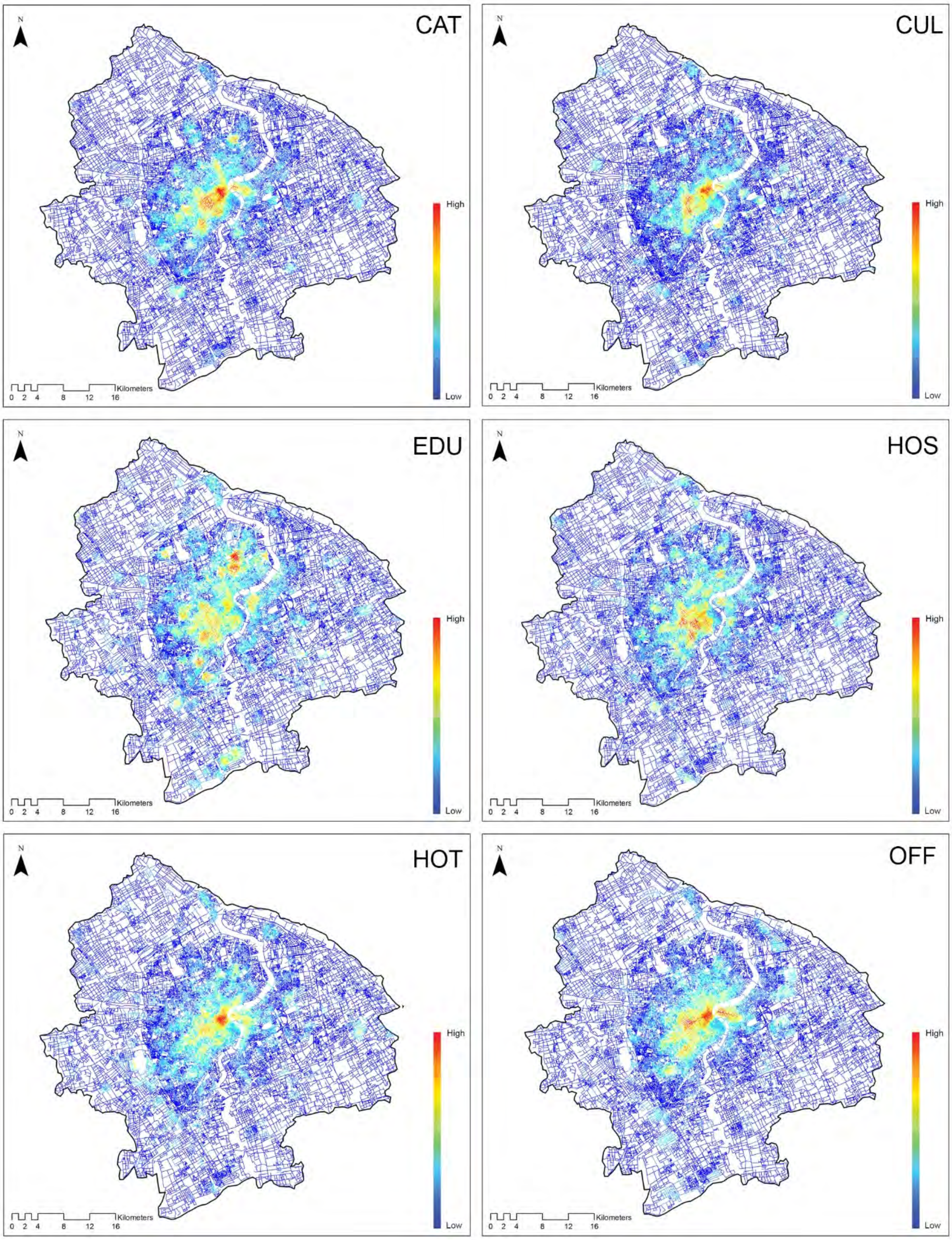


Figure 3-22

Function angular closeness (FAC) maps of different active land-uses at a 1,000 m network distance radius in Central Shanghai (CAT: Catering; CUL: Cultural; EDU: Education; HOS: Hospital; HOT: Hotel; OFF: Office)

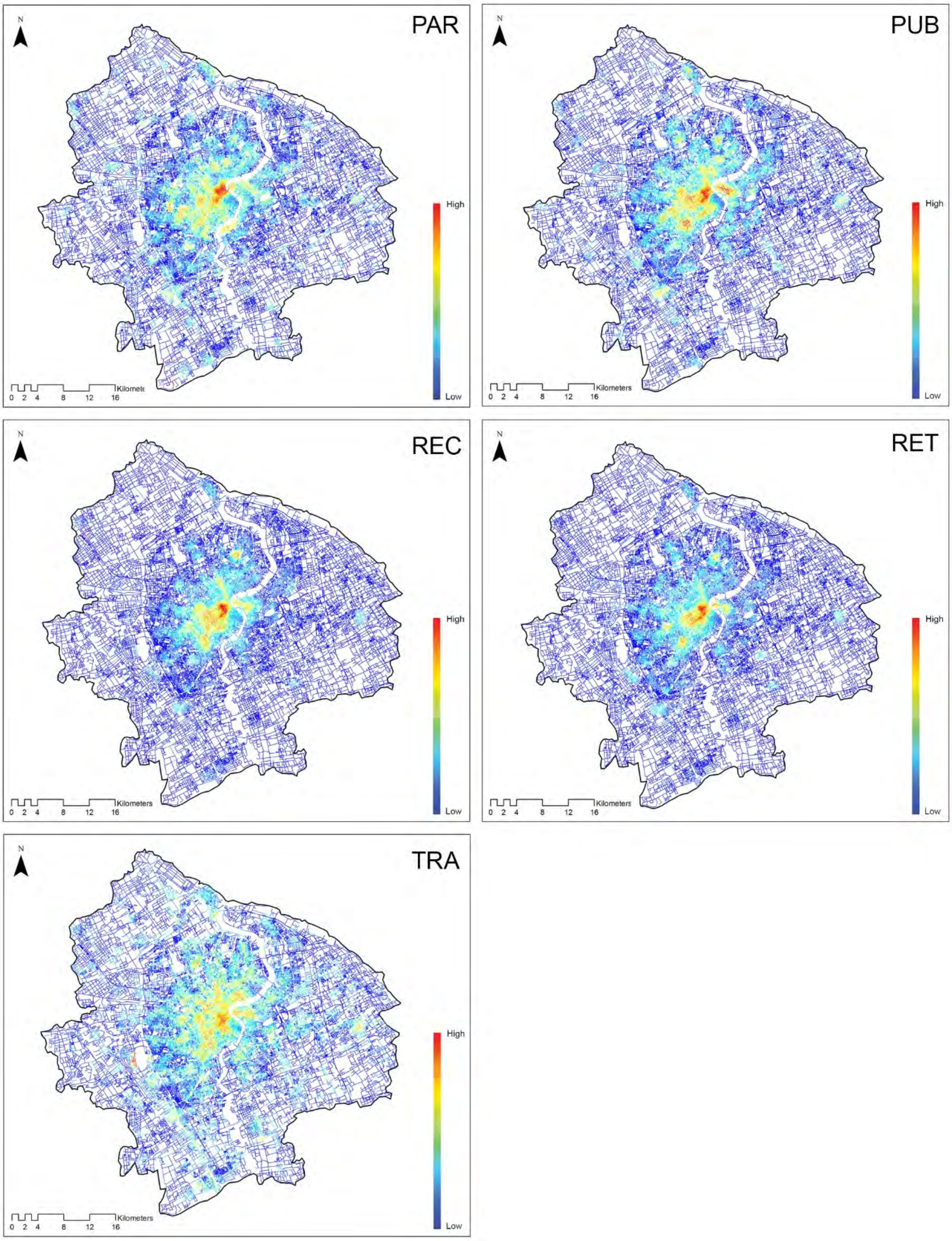


Figure 3-23

Function angular closeness (FAC) maps of different active land-uses at a 1,000 m network distance radius in Central Shanghai (PAR: Park; PUB: Public service; REC: Recreation; RET: Retail; TRA: Transport)

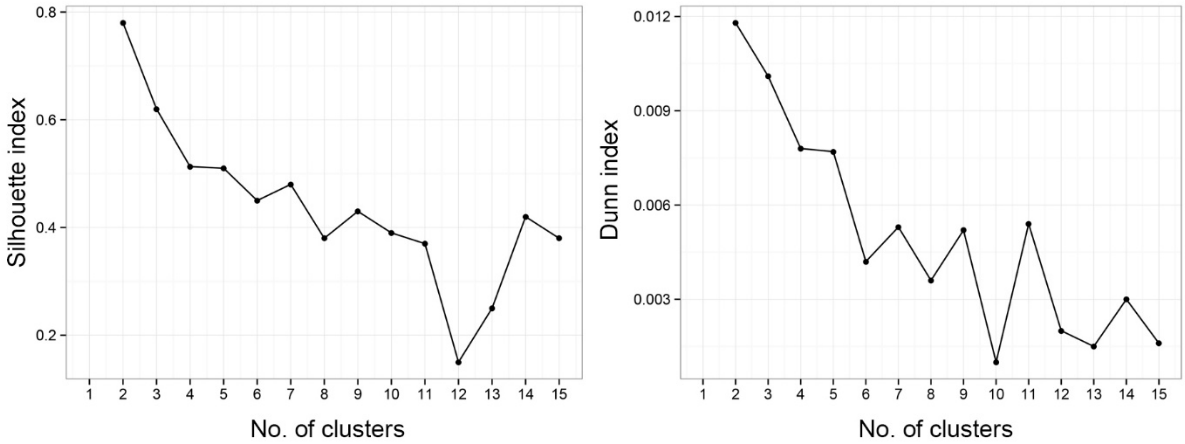


Figure 3-24

The Silhouette index and Dunn index patterns against the number of clusters for defining the optimal amount of the function regions at a 1,000 m network distance radius in Central Shanghai

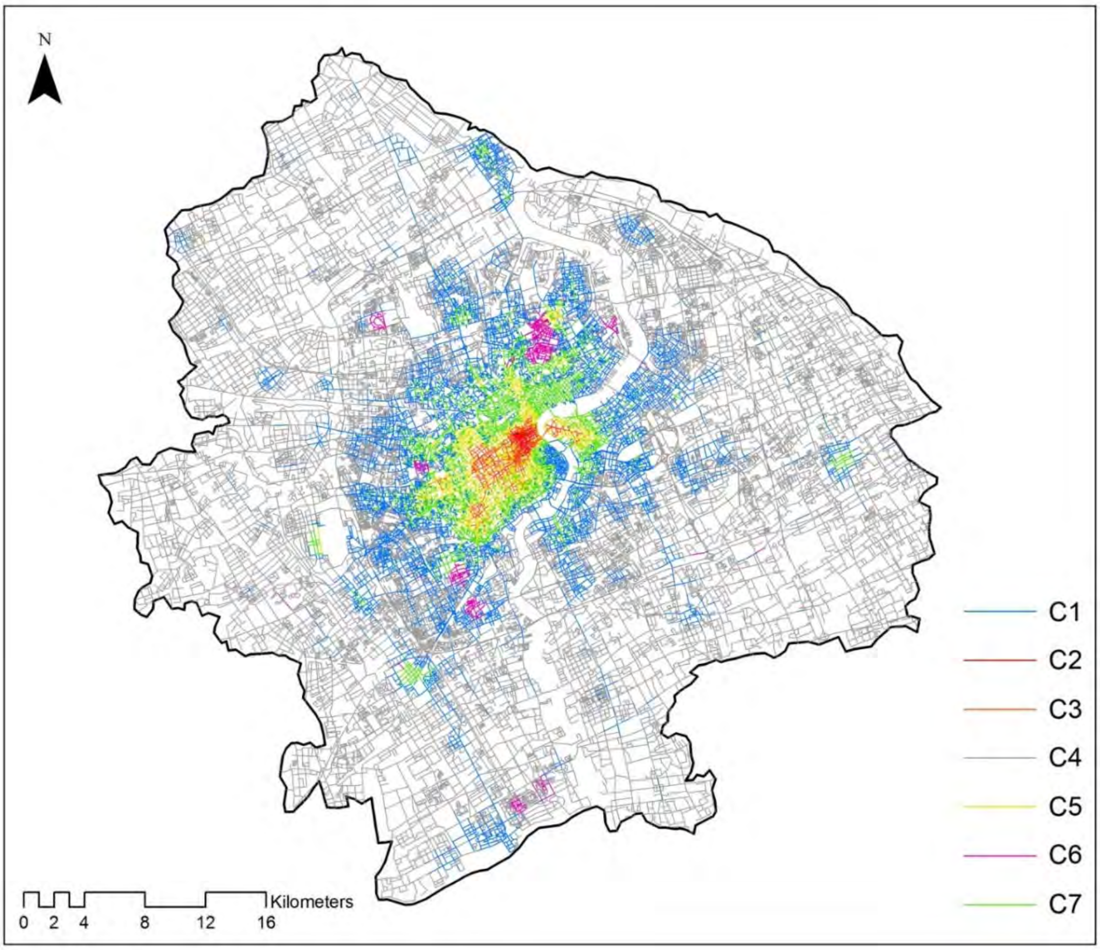


Figure 3-25

Urban function regions (UFR) map at a 1,000 m network distance radius in Central Shanghai

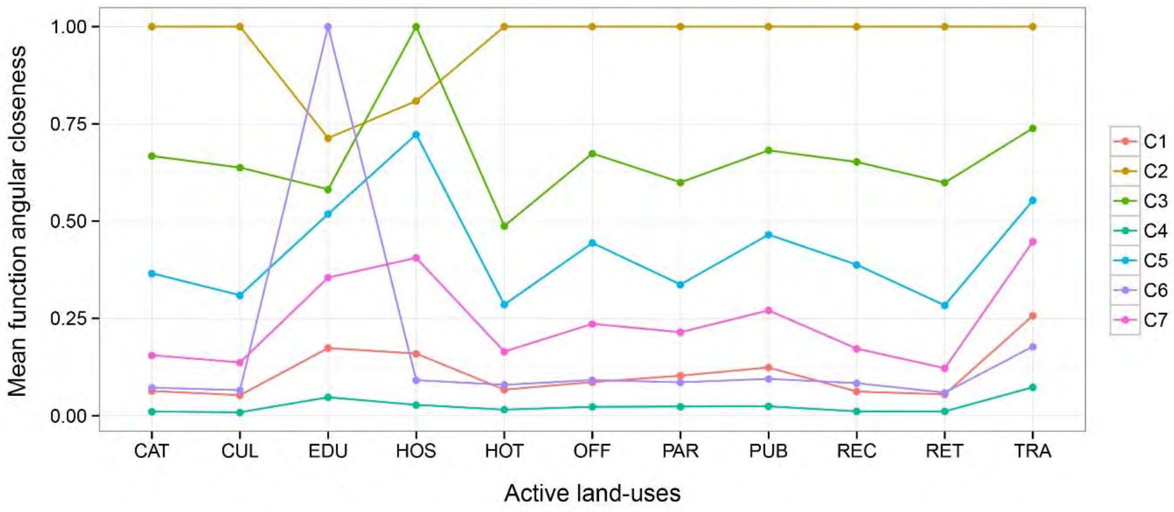


Figure 3-26

Annotation of urban function regions (UFR) at a 1,000 m network distance radius in Central Shanghai

Aiming for obtaining a clear and comprehensive understanding of the interaction between various urban activities, this work uses clustering analysis to detect the spatial boundaries of function regions that are reported in Figure 3-25. The clustering validation implies that seven clusters will be the optimised number of function regions for the study area (Figure 3-24). According to Figure 3-26, cluster 4 (C4) is captured as the non-central region with the lowest values of angular closeness to all types of land-uses. Cluster 6 (C6) is defined as the education region with highest mean angular closeness to educational amenities and lower accessibility to other land-uses. Cluster 2 (C2) is the central business region with the highest accessibility to all active land-uses with the exception of education services and hospitals. Custer 2, 5 and 7 (C2, C5, C7) are all business regions with decreasing levels to the active urban functions.

The defined regions can be further validated through being compared with the named areas in the real built environment. The streets in the education region (C6) for example, are all the campuses of the universities in Central Shanghai, and the central business region (C2) are the traditional Central Business District around Nanjing Road. These facts empirically confirm the effectiveness of the proposed method of delineating street-based urban regions. Moreover, in the comparison between spatial and functional centralities patterns, it suggests that the captured centrality structures are not spatially or statistically identical at the same scale. This observation of functional centrality patterns of various types of land-uses in Central Shanghai preliminarily verifies the complementarity between these two types of accessibility for spatial network analysis. By accounting for the spatial effects of the diverse exogenous location characteristics proposed in this chapter including the spatial conditionality of spatial network and land-uses as well as the place significance measured by social media check-ins, the spatio-functional interaction model shows a great potential to be capable of providing the multi-dimensional perspective on urban morphologies.

5 LIMITATIONS

The application of the research framework and the delivered methods are productive in the way of providing a multi-dimensional method to model land-use patterns from a network perspective. In fact, this study introduces a framework to analyse the land-use network, which is extendable and scalable to fit for any specific requirements. Consequently, many further steps that can be taken to improve them in future with more available data and efforts to maximise their potential in different research scenarios. Yet, it is also noteworthy that the operationalisation, easiness of interpretation and communicability of a method might be reduced due to the increase of methodological complexity. Thus, any further amendment on the methodological improvement should be carefully conducted with more datasets based on rigorous verification and validation.

5.1 Other effects on the demand and supply sides

This study focuses on the morphological properties of the land-use pattern by assuming other effects on the supply side of land-use distribution are spatially even. In the urban reality, the supply side might also have significant impacts on the perceived land-use accessibility. The social media check-in records are the estimation of the clustering of the people’s place preference. The floor area of function is also important indicating a kind of potential about accommodating how many people, which is related to the land-use or facility planning. If the data about the business areas for POIs are available, its influence should be addressed in the following methodological development. Furthermore, it is also notable that some factors on the demand side could also be considered in the method. The demographic features of citizens, as the critical elements for defining social groups, could be added into the proposed method to evaluate the land-use accessibility maps for a particular group of people according to their daily travelling demands.

Ideally, all the crucial factors on the supply and demand sides could be added into the method for making the result more accurate. However, there are some risk that it would increase the methodological complexity and impede the result interpretation. Thus, in this study, the essential components have been properly addressed with clear definitions under the goal of developing a comprehensive but dexterously constructed framework. Meanwhile, adding the elements on the demand side into the model is ideal for evaluating the satisfaction of service supply, but is very likely to be inappropriate for morphological analysis, since the primary concern of the latter is the design establishments of the built environment which are more static than the change of urban demographic patterns. Therefore, it is argued that the spatio-functional interaction model proposed in this research is a reasonable tool for analysing the spatial configuration. Additional efforts on the interaction between the demand and supply sides will possibly enhance and extend the potential applications of the spatio-functional interaction model to other related studies in future.

5.2 Distance decay

The measures introduced in this chapters are radius-based for defining the reachable area where the energy costs for approaching all the accessible functions are the same. While the concept of graph-radius is plausible for its mathematical innovations in space syntax research, the contour method is criticised for its simplification of the impact of distance (Geurs and Von Wee 2004). The usual way of addressing the metric distance effect is to use a distance decay function to reflect the declining trend of spatial interaction with the increase of the distance. In configurational studies, the distance decay function is also considered as an effective way to remove the size effects in spatial network analysis, because all the nodes are always taken into account (Dalton 2007). Though there are some specifications of the impedance functions in the existing studies, e.g., the logistic or power functions, which is a distance decay function, is controlled by a cost sensitivity parameter which has a significant influence on the generated results. The typical way of choosing the appropriate decay parameter is conducting the calibration work based on the empirical datasets. Adopting distance decay function can reduce the arbitrary of radius selection and the size effect in the proposed method, and make the method comparable to other existing measures in the field of transport geography.

5.3 Bias of social media data

This study uses a huge amount of social media data which has been argued to be biased riskily in literature (Goodchild 2013). The data generated by social media users are normally limited to a subset of the population, they, therefore, may not be representative of the overall patterns of population (Gorman 2013). Using these datasets might obscure rather than reveal the complexity of social and spatial processes (Graham and Shelton 2013). In order to have a reliable description of urban reality, researchers need to grasp the opportunities by taking the challenges of data bias (Kitchin 2013). Potential solutions include combining social media data with other surveyed datasets (e.g., census data), using simulation technologies to validate the statistical characteristics of social media data, or employing machine learning methods to fit the raw data into the training data. Future developments eliminating the bias of social media data will make relevant spatial analysis more robust than before.

CHAPTER 04

URBAN EVOLUTION AS A SPATIO-FUNCTIONAL INTERACTION PROCESS

1 INTRODUCTION

Accurately identifying the shifting urban spatial structures produced by urban forms and functions contributes to an advanced understanding of urban morphological dynamics and related planning practices. Although evolutionary city structures have been widely discussed, comprehensive research focusing on the dynamic interactions between spatial and functional systems is still lacking. This chapter investigates the transformation of urban centrality structures as captured by the shifting interdependence between centrality indices (angular integration and choice) and delivered urban function connectivity metrics (accessible function density, diversity and cognitive distance), generated in tandem by spatial network and land-use patterns. By reconceptualising urban evolution as a centrality process in which spatial and functional centrality processes co-exist and co-evolve, this study constructs a systematic connection between these two types of centrality structures during identical transition periods in Shanghai's history of modernisation. Four critical snapshots of street networks and Points-of-Interest (POIs) in history of urbanisation are selected as a spatiotemporal description of the urban transformation of Central Shanghai.

The research in this chapter follows three objectives. The first is to examine the extent to which the functional centrality structures indexed by urban function connectivity metrics differ from the spatial centrality structures as defined by space syntax centrality measures in the history of urbanisation. The second is to explore the extent to which these two types of centrality structures correlate with each other over time. The final aim is to investigate the extent to which this spatio-functional relationship performs differently from one location to another for segmenting urban function regions. By computing and mapping the spatial and functional centrality structures, this chapter conducts descriptive statistics, inter-scale/inter-centrality correlations and raster-basedcentrality change with the aim of capturing the differentiated performance of these two types of urban centrality processes quantitatively and qualitatively. A canonical discriminant analysis is then conducted to quantitatively identify their predictive accuracy in various scenarios to delineate the detected urban function regions. This chapter ends with a discussion regarding the possible valuable insights that could shed light on the morphological evolution process of cities as indicated by the configurational interplay between form and function and into an explicit identification of urban change.

2 BACKGROUND

Depicting urban spatial structures is one vital prerequisite to uncovering the process by which urban morphologies evolve. An urban spatial structure is a summary of the various ways in which people interact through perceivable urban forms (Anas et al. 1998). A centrality structure reflecting the sense of ‘a centre’ usually refers to the concentration of urban activities in a prominent location (Horton and Reynolds 1971; Hillier 1999). In this sense, an urban structure generally contains the functional elements representing the interactions between form and function that, in turn, illustrate the spatial conditions facilitating the morphological agglomeration of land-uses. Revealing the links between the spatial and functional elements of the urbanisation process is vital for any urban revitalisation programme, as it contributes to sustaining the long-term prosperity of city centres (Burger and Meijers 2012; Tallon 2013).

In traditional typo-morphological research, the built environment is analogised to an architectural biosphere, and urban spatial elements – buildings, blocks, streets, etc. – are considered ‘species’ with distinguishable characteristics. Thus, tracing the transformation of the spatial typologies of urban form has historically been the main approach to understanding hidden spatio-social transformations (e.g., Moudon 1997; Pinchemel 1983; Darin 1998; Cataldi et al. 2002; Pinho and Oliveira 2009). With their emphasis on the structural properties of spatial configurations, configurational studies focus on the formulation and reproduction of hierarchical urban centres as driven by the spatial interactions of spatial elements at various scales (e.g., Hillier 1999). Numerous studies have demonstrated that changes in spatial centrality generated by the urban grid dramatically influence the distributed commercial amenities (e.g., Hillier 1999; Porta et al., 2009; Porta et al., 2012; Scoppa and Peponis, 2015). The land-use patterns identified in configurational studies and space syntax studies, in particular, are considered to be the products of spatial centrality, which drives the economic process (Hillier 1996). This argument reclaims the theoretical and practical positions of urban design in the land-use allocation process. However, the inherent structures of the land-use patterns are over-simplified, thereby constraining the further exploration of how land-use locations react to the spatial advantages provided by the spatial network.

A land-use system is not simply a layer that corresponds to the spatial network. Rather, it has its own logic by which it formulates observable patterns. It can be impacted by the bid price from the central area to the periphery (Alonso 1960), competition or market sharing (Hotelling 1990; Christaller 1996), complementary interaction (e.g., Eppli and Shilling 1996), gravity interaction (e.g., Wilson 1998), investment in the transport system (Wegener 2004; Waddell 2002), and the geometrical accessibility to other land-uses (Stahle et al. 2005; Sevtsuk 2010; Agryzkov et al. 2016). Conventional methods of identifying the shapes of urban centres are based on the analysis of land-use agglomeration with reviews of informed opinion (e.g., Batty et al., 1997; Wheaton 1974). In contrast to how space syntax theory explains the process of urban evolution, geographical studies generally consider urban evolution to be a process of accessibility change at larger scales, driven by a series of land-use changes resulting from underlying socioeconomic transformation; however, these studies neglect the role of urban geometrical structure (Geurs and Von Wee 2004; Batty 2009). Recent efforts have aimed to describe land-use interaction through high-resolution morphological analyses of the built environment. For example, using spatially lagged logistic regression methods, Sevtsuk (2014) has found that the locational decisions of particular types of retailers in buildings along street networks are related to the accessibility of other types of commercial amenities. On the basis of the social media data gathered from Foursquare and Twitter, Agryzkov et al. (2016) visualised city as a complex network, and adopted the PageRank algorithm to measure its node centrality with the aim of assessing the successfulness of public space.

To summarize, spatial and functional centrality structures are both vital dimensions of the definition of an urban centre and its hierarchical nature. Nevertheless, existing studies have failed to apply a novel, systematic approach to measuring and comparing them from a syntactic/structural perspective on the urban evolutionary process.

3 THE FRAMEWORK AND DATA

3.1 Research framework

The research framework for this chapter is illustrated in Figure 4-1. There are four main modules in the research in this chapter. The first one is data processing (a) aiming to convert all the obtained historical information to the geocoded datasets. The street networks in historical maps are digitised as the spatial layers of segmental maps, and the locational information regarding the land-uses in the local atlases and the local planning chronicles are gathered and geocoded along the street segments where they are located. In the following two steps (b and c), the urban evolution is defined as a spatial centrality process and a functional centrality process, respectively. Measures computation, centrality structure mapping, correlation analysis and raster calculation are the four sub-steps in these two modules. By conducting these analyses, this research progressively explores the descriptive statistics, inter-scale/inter-centrality correlations and the raster-based centrality change for measuring the differentiated performance between the two classes of urban centrality process quantitatively and qualitatively. In the last module (d: spatio-functional centrality process), the correlational relationship between the spatial and function centrality measures is examined at the first step, and then the canonical discriminant analysis is conducted for identifying quantitatively the predicting accuracy of the space syntax centrality and the urban function connectivity variables in various scenarios for delineating the detected urban function regions.

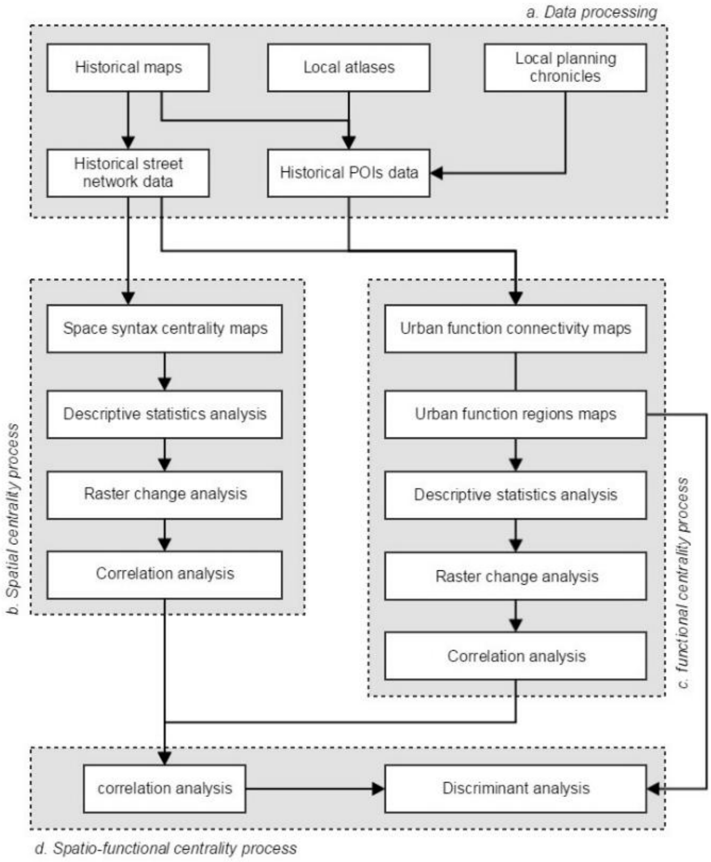


Figure 4-1

Proposed framework for analysing urban transformation

3.2 Centrality computation

Two groups of network centrality measures are used in this study: the spatial accessibility measures that serve as the space syntax centrality indices, including integration and choice, and the urban function connectivity indices, including density, diversity and cognitive distance. Typical radii, including 500 m, 1,000 m, 2,500 m, 5,000 m, and 10,000 m, are used to represent spatial and functional accessibilities across scales in each case in history. This chapter also uses spatial clustering to detect the change of function regions in history as a useful supplement to the shift of the functional centrality structures. The radius for identifying the functional region is the walking distance of 1,000 m since the land-uses are basically understood by pedestrians more than the mobile flows (Liu and Long 2016).

3.3 Data

3.3.1 Study area

This analysis focuses on the spatial structures of Shanghai in history within the administrative boundary of current Central Shanghai in the Shanghai Metropolitan Area (SMA) as the setting for our empirical study (Figure 4-2). Shanghai has been China's economic centre since 1949 and is currently one of the country's largest municipalities, along with Beijing, Tianjin, and Chongqing. Because of its geographical location, Shanghai was the first city in China to undergo modernisation after the Second Opium War when Shanghai was a semi-colonial city. Since the Open Door Policy was implemented in 1979, Shanghai has been significantly growing and has been transformed into a mega-city. The rapid urban expansion and regeneration in Shanghai make it as a valuable case for investigating the transforming spatial and functional complexity.

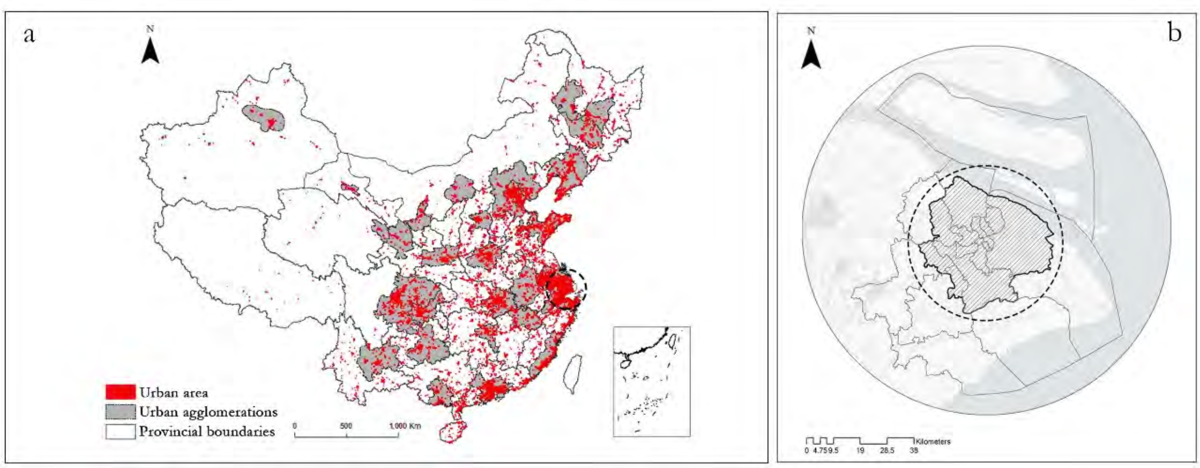


Figure 4-2

Study areas in the Shanghai Metropolitan Area (SMA): (a) the location of Shanghai City in the Chinese city system; (b) the location of the study area in the SMA

3.3.2 Street network – spatial network

The street network datasets applied in this chapter are redrawn according to the historical maps. To produce accurate segmental maps, the street network data are generated by converting the axial maps to the segmental maps. Unlike those produced directly by the central road lines, the segmental maps in this study are produced by controlling the axiality of segments (see section 4-2 in Chapter 03), which reflects the minimal cognitive cost to people travelling from one segment to another. The final datasets are shown in Figure 4-3.

3.3.3 Historical POIs – land-use patterns

Land-use data can be represented and summarised in many ways with various settings, which can lead to different observations. POI datasets are the fine-grained land-use patterns with identical relations to the spatial network. In this study, the land-use locations on the historical maps, and in local atlases and local planning chronicles (Sun et al. 1999; Chen and Wu 2004; Shanghai Institute of Surveying and Mapping 1989), have been digitised, labelled, geocoded, and assigned to the street segments where they were historically located. To maintain consistent classification of any two land-use distributions during different periods, all historical POIs have been relabelled and categorised into 11 main types of active land-use that are complementary to each other (Table 4-1). Although the significance of various types of land-use might vary historically, a generalised classification of urban functions is a prerequisite for conducting an objective comparison of different snapshots of historical urbanisation.

Table 4-1

Historical POI classification and numbers in Central Shanghai

Type	Abbreviation	POIs count			
		1880s	1940s	1980s	2010s
Retail	RET	841¶	38,002	12,180	81,312
Catering	CAT		1,284	1,276	72,351
Hotel	HOT	4	333	1,302	27,313
Office	OFF	61	4,621	6,096	54,388
Education	EDU	8	489	2,777	9,139
Public service	PUB	43	1,855	1,949	10,762
Hospital	HOS	12	748	438	3,518
Recreation	REC	5	147	220	35,080
Culture	CUL	123	236	94	20,068
Park	PAR	7	75	77	4,250
Transport	TRA	63	989	153	6,611
		1,167	48,779	27,562	324,792
	Weighted by check-in records	N	N	N	Y

¶: Due to the absence of detailed information regarding retail and catering amenities, both types of amenities are merged into one group called commercial establishments (COM) and estimated according to the length of the high streets reported in the historical literature.

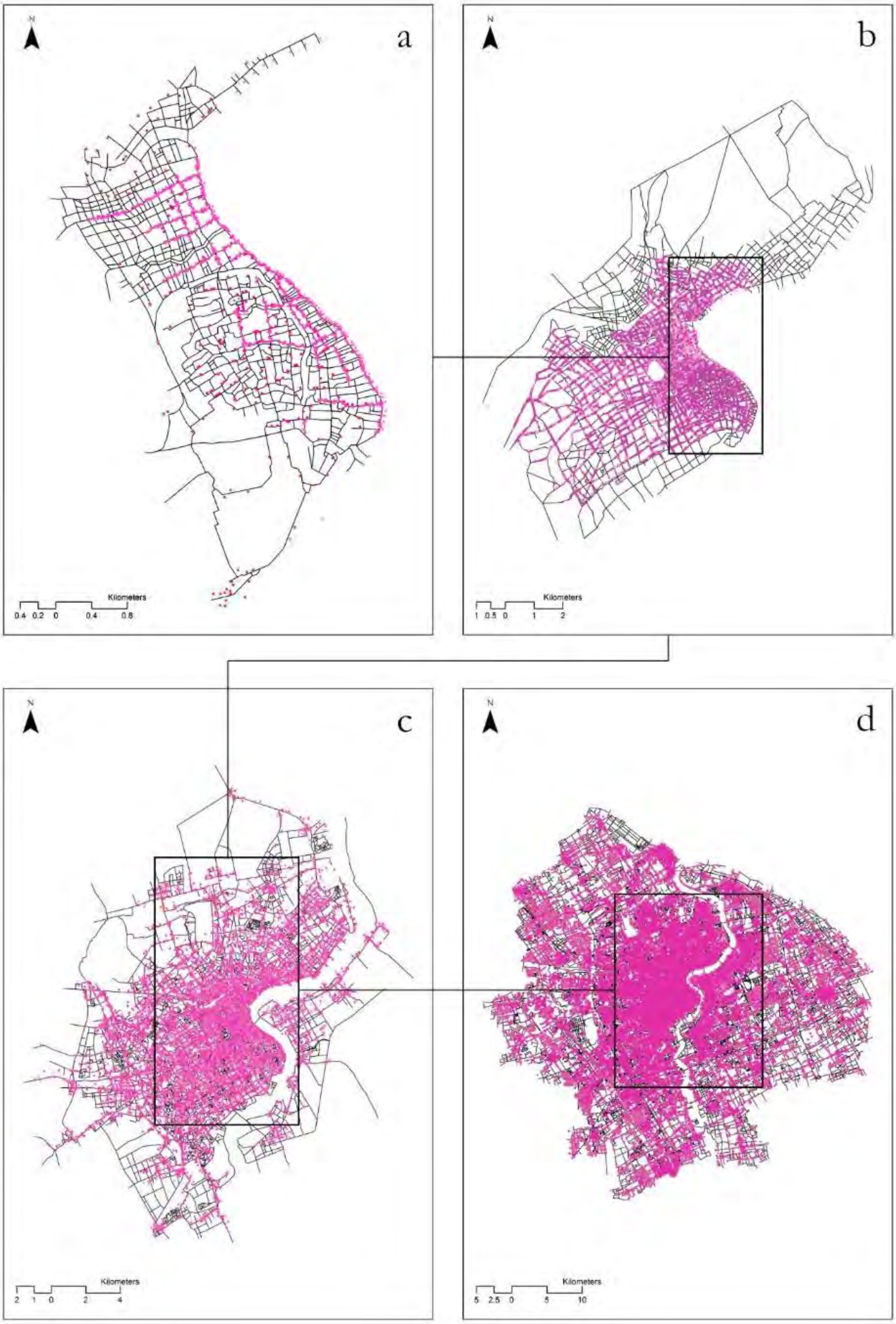


Figure 4-3

Geocoded historical POIs and associated street networks during the 1880s (a), 1940s (b), 1980s (c), and 2010s (d)

The sizes of the POI datasets have become increasingly larger with urban development. However, the POI dataset from the 1940s is larger than the dataset of POIs in the 1980s due to the map resolution used by its cartographers. There are also some data missing from the current POI datasets proposed for use in this study. The detailed data on retail and catering activities in Central Shanghai in the 1880s are not available in this dataset. Therefore, they have been merged into a new category of land-use named commercial establishment (COM). Their densities are estimated using the lengths of the frontages of the high streets reported in the local planning chronicles. Social media check-in features in the POI data are used as the weights for each amenity in the 2010s, whereas the variation in the locational popularity of individual land-use locations is assumed to be equal during other periods because of the absence of relevant data in the historic land-use maps; the agglomeration of land-uses around a certain location is used to estimate that location's significance.

3.4 Identification of urban transformation in Central Shanghai

Shanghai City is used for the empirical studies in this article not only because it is typical of Chinese cities but also because it was one of the first modern cities in China to undergo significant spatial transformation. To clearly define the meanings of the selected snapshots of Shanghai's history of urbanisation, spatial features are used to objectively identify the critical steps in the city's urbanisation. Four metrics of urban form – average block size, road network density, total length, and total urban area – are used to capture various aspects of urban growth in relation to population growth. It is clear that, in parallel with rapid urban growth, Shanghai's urban form became less pedestrian-friendly, with larger blocks and lower road network density (Table 4-2). This trend, however, is not as consistent as expected. Between the 1940s and the 1980s, the speed of population growth in Shanghai slowed, as did the growth of the city's urban area, total street length, and block sizes (Figure 4-4). Its street network density, however, grew slightly during the same time interval, which suggests that the densification process of the road network was highly significant. This challenges the traditional definition of the stages of urbanisation, according to which the modern history of Chinese cities is divided into the early modernisation and modernisation periods using the birth of the People's Republic of China in 1949 as the turning point. Based on Shanghai's historical spatial configuration, this study redefines the key stages of the city's urbanisation process as follows: 'early rapid urban growth' is the period from the 1880s to the 1940s when the city grew rapidly due to the connection of the colonial areas to the historic centres; 'steady urban growth' is the period from the 1940s to the 1980s when the urban economy was in a recovery phase; 'modern rapid urban growth' occurred after the implementation of the opening policy in 1978. This definition provides a morphological perspective on Shanghai's urban evolution and provides the basis of the following analysis.

Table 4-2

Descriptive statistics of stages in Central Shanghai's urbanisation process

	1880s	1940s	1980s	2010s
Average block size (km^2)	0.007	0.036	0.053	0.078
Network density (km/km^2)	17.003	8.064	8.521	6.736
Total street length (km)	135.208	648.515	1,713.767	11,591.011
Total urban area (km^2)	7.952	80.425	201.113	1720.759
Population (thousand people)	302.767	6,204.400	9,487.763¶	21,415.329¶

¶: The populations of the study areas during these periods are estimated according to the reported population densities and the total populations. The total populations in the 1980s and the 2010s are 11,859,700 (1982) and 23,019,148 (2010), respectively.

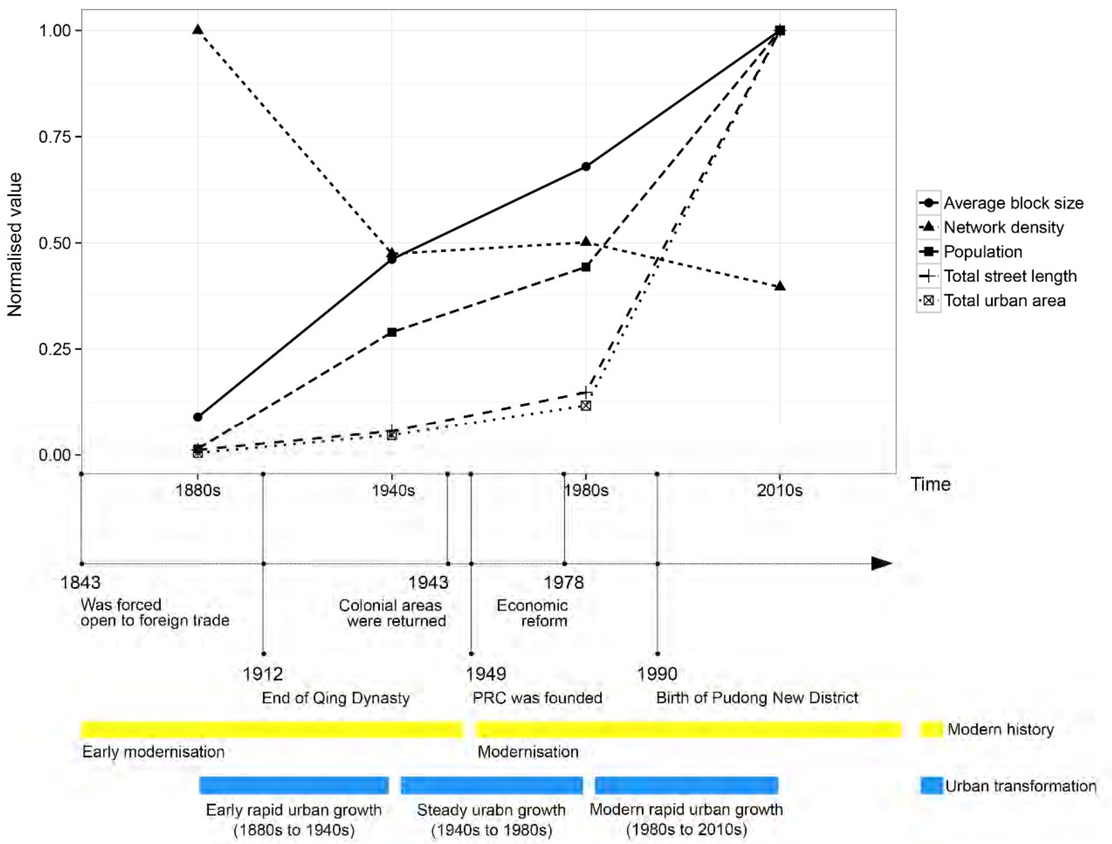


Figure 4-4

Identification of the critical stages in Shanghai's urbanisation process in terms of the observed spatial and social features (PRC: People Republic of China)

4 Empirical results

4.1 The spatial centrality process

4.1.1 Descriptive statistics: the overall spatial transforming trend

The descriptive statistics of the normalised space syntax centrality measures are shown in Table 4-3. The method used to relativise these indices is the approach proposed by Hillier et al. (2012), in which the size effect in the space syntax model is removed at the global scale by taking into account the scaling of the city's size. Therefore, the centrality measure are comparable across the historical periods, regardless of the sizes of the systems. Average road network connectivity increased over the past 130 years, as did the mean and maximised global integration values, suggesting that the spatial network of Central Shanghai has become more interconnected. In contrast, the changing directions of the average and the maximum choice values are opposite. Along with the increase in the extreme value comes the reduction of the average level. This reveals another trend in the urbanisation process: the spatial network turned out to be more hierarchical, and, accordingly, the differentiation among various levels was more significant than before. It is also noteworthy that the growth in average connectivity, the overall integration level and the maximum choice value were interrupted during the period of steady urban growth from the 1940s to the 1980s. The reason for this might be that the self-organisation process dominated temporal urban evolution, which led to the internal growth of the spatial network and a decrease in its hierarchical heterogeneity with the decelerated spatial expansion. The preliminary results indicate that shifts in the spatial centrality structures of cities can provide additional information regarding the stages of urbanisation.

Table 4-3

Shifting statistical performance of spatial centralities across periods

	1880s	1940s	1980s	2010s
Mean connectivity	4.077	4.441	3.831	4.752
Mean normalised Integration (R10000)	0.839	1.213	0.943	1.305
Maximum normalised Integration (R10000)	1.165	1.786	1.392	1.994
Mean normalised Choice (R10000)	0.965	0.994	0.892	0.501
Maximum normalised Choice (R10000)	1.505	1.555	1.497	1.635

4.1.2 Space syntax centrality maps: spatial centrality structures

The space syntax centrality maps present the detailed distributions of street network centralities across scales. The integration distribution at the local scale in the 1880s shows a separation between the Chinese inner city and the colonial area (Figure 4-5-a), which reflects the political distance between these two areas. The local centre, which was formed later, combined these two areas and further shaped the current urban centre at the pedestrian level (Figure 4-5). With regards to the global integration centrality distribution (Figure 4-6), the streets along the river, which formed the central business area in Shanghai, are highlighted. This area was well known for its national dominance in the import and export trading economy. With the urban spatial expansion, the spatial centre at the global scale shifted to the colonial area, which, until the 1980s, was further enhanced and expanded towards the west along the main road passing through the east and the west. In the 2010s, the global centrality structure indicated by the integration shows growth in the west bank towards the south-west and extends across the river to the newly built developing area on the east bank. The choice maps at the local scales represent, over time, the correlation between integration and choice in general (Figure 4-7), which is due to the significant variation in road network density that is the basic source of urban movements. The choice distributions at larger radii, however, extract the main road system from the less-central context (Figure 4-8). The highlighted street systems during different periods are highly overlapped, suggesting the dominance of these strongly active routes in directing the urban transformation process. These core streets that are emphasised by the pass-by flows were relatively organically organised before the 1980s but have tended to be more artificial since the modern planned road systems were emphasized. Therefore, the global choice structures in Central Shanghai capture the shifting skeletons of the urbanisation process; while the integration structures illustrate the dynamic potential locations and shapes of the centres along those skeletons, as well as their related scale-dependency.

4.1.3 Heat map analysis: the spatial centrality change flow

The urban growth patterns reflected by changes in global integration structures are shown in Figure 4-9. The street-based results are rasterised because of the existence of the spatial bias within historical street network data. During the early rapid urban growth process, the spatial advantage of the colonial area increased, whereas that of Shanghai's old town decreased. During the steady urban growth stage in the 1940s, global integration centrality moved to the outskirts, where some centres were emerging, including the area around the railway station and the Xujiahui business areas. The cost of the spill-over of this integration centrality was the decrease of centrality in the colonial area. This observation reveals that the gravity core of the newly emerging city centre moved to the area where the road network densification process occurred. During the modern rapid urban growth process, the city's central area – indicated by higher integration values – became stable, with very few changes in global integration centrality. Nevertheless, this urban expansion resulted in the dramatic growth of spatial advantages on the city's periphery in the 1980s. The new Pudong district, for instance, maintained the grouped enhancement of the network shallowness, which suggests that it could easily facilitate further growth. Another two centres that were planned in the 1980s – the Wujiaochang and Tianlin areas – are also captured. In this case, the steady urban growth process contributed to the expansion of the city's central area and the shift of its gravity core and consolidated the city centre, which maintained its centrality during the process of modern rapid urban growth. These results imply that rapid urban growth might not naturally lead to an immediate shift in the centrality structure, but the steady urban growth and spatial densification that follow it will lead to such a shift and thus strengthen the city centre's position in the future.

4.1.4 Correlation matrix analysis: synergy between spatial centralities

The interplay between the integration and the choice centrality measures at various scales across time is further quantitatively scrutinised based on comparing the correlation matrices between them, and the related results are illustrated in Figure 4-10. The most obvious trend that appears in all historic snapshots is the intera-scale correlation for a certain type of spatial syntax centrality. The angular integration values at various radii are highly correlated; the choice metrics at different levels are also strongly interrelated, with the exception that the interdependence between local choice and global choice is significantly weaker. The correlation between different centrality measures, however, varies according to the different development stages of Shanghai's urbanisation. The synergy between the spatial centrality indices of the spatial network system, indicated by the inter-centrality correlation, became significantly weaker from the 1980s onward, particularly at the higher spatial levels. This is the consequence of the modern road system's invasion of the historical spatial grids, which further intensified the division between the integration and choice structures.

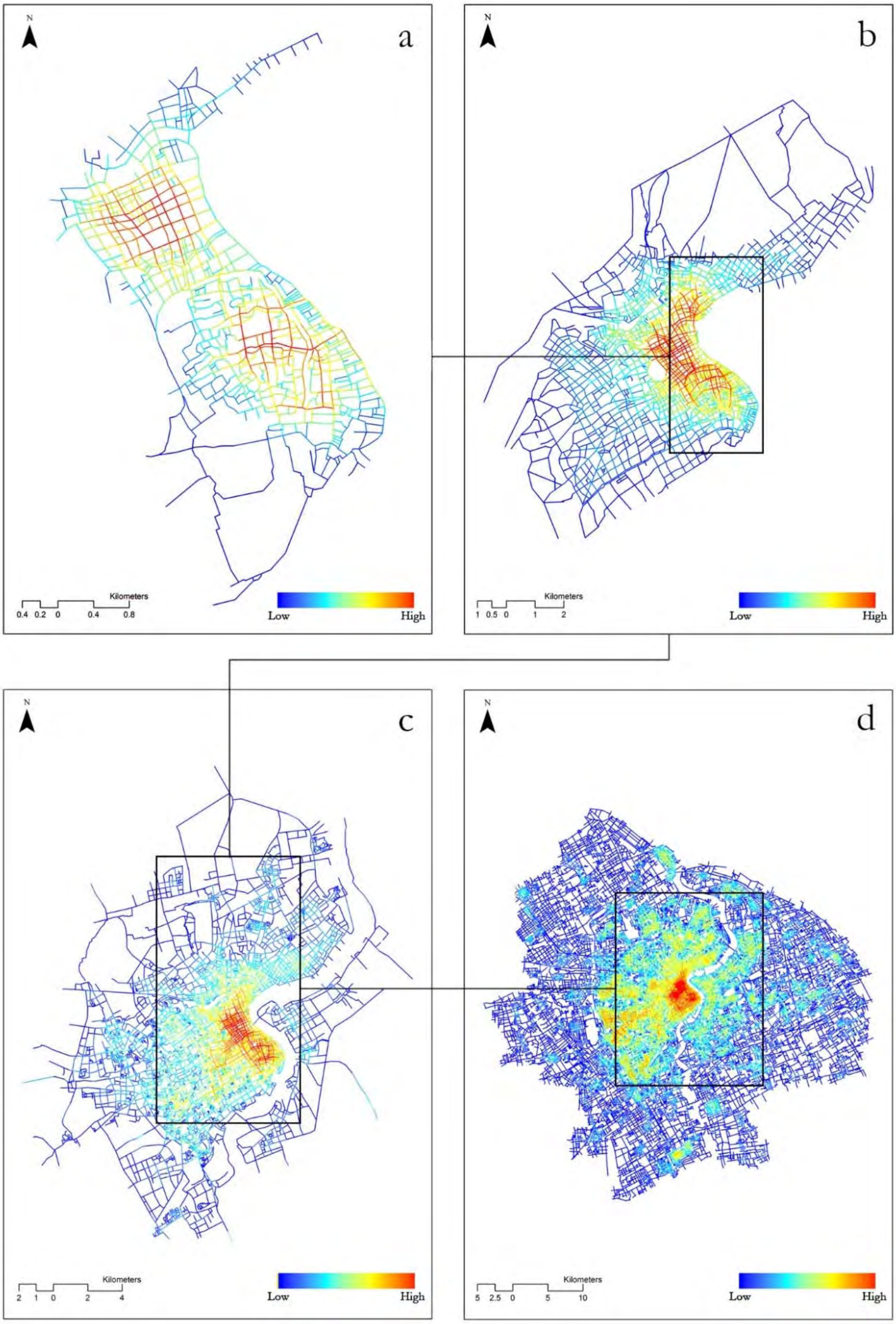


Figure 4-5

Integration maps at 1,000 m across periods ((a) 1880s; (b) 1940s; (c) 1980s; (d) 2010s)

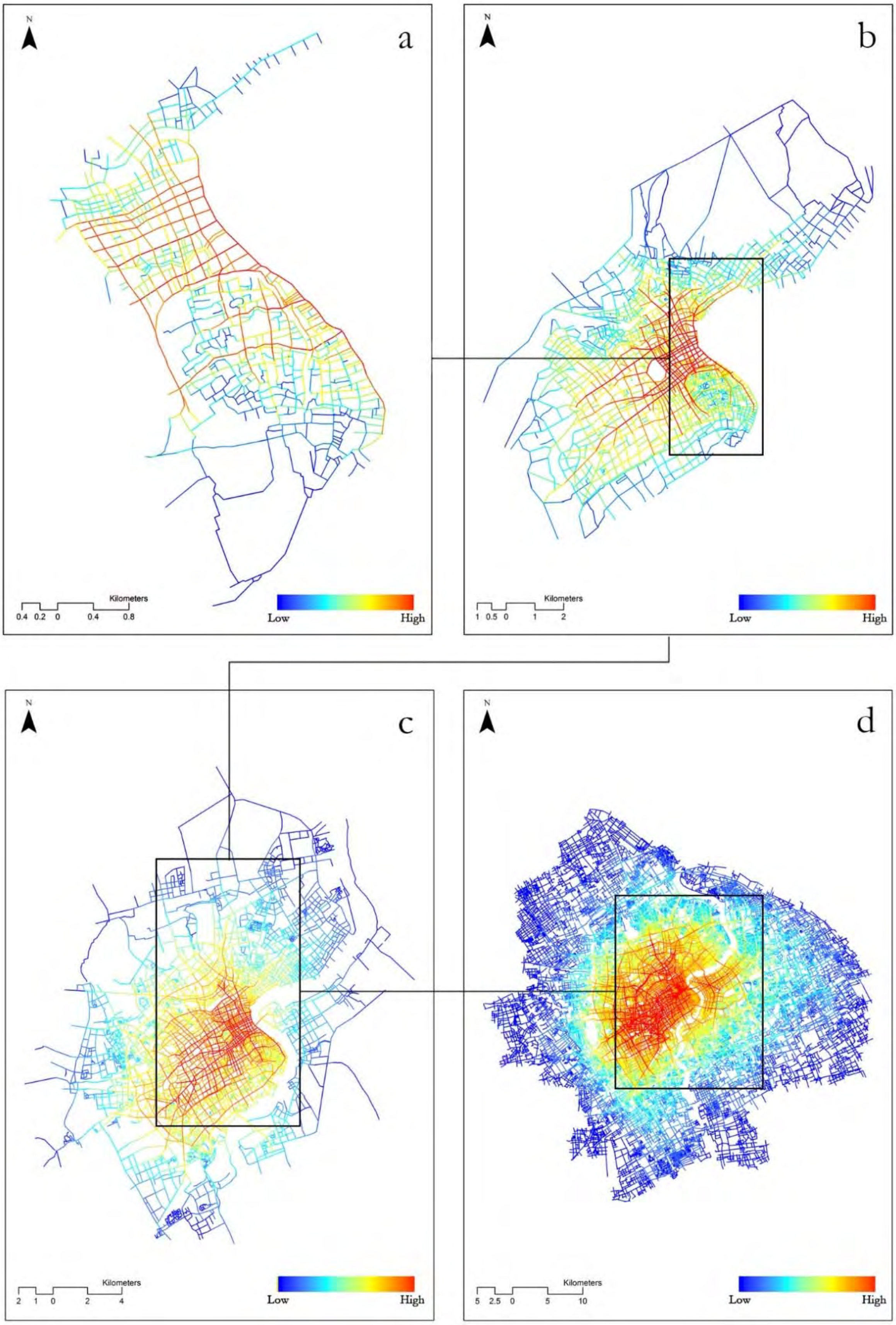


Figure 4-6

Integration maps at 10,000 m across periods ((a) 1880s; (b) 1940s; (c) 1980s; (d) 2010s)

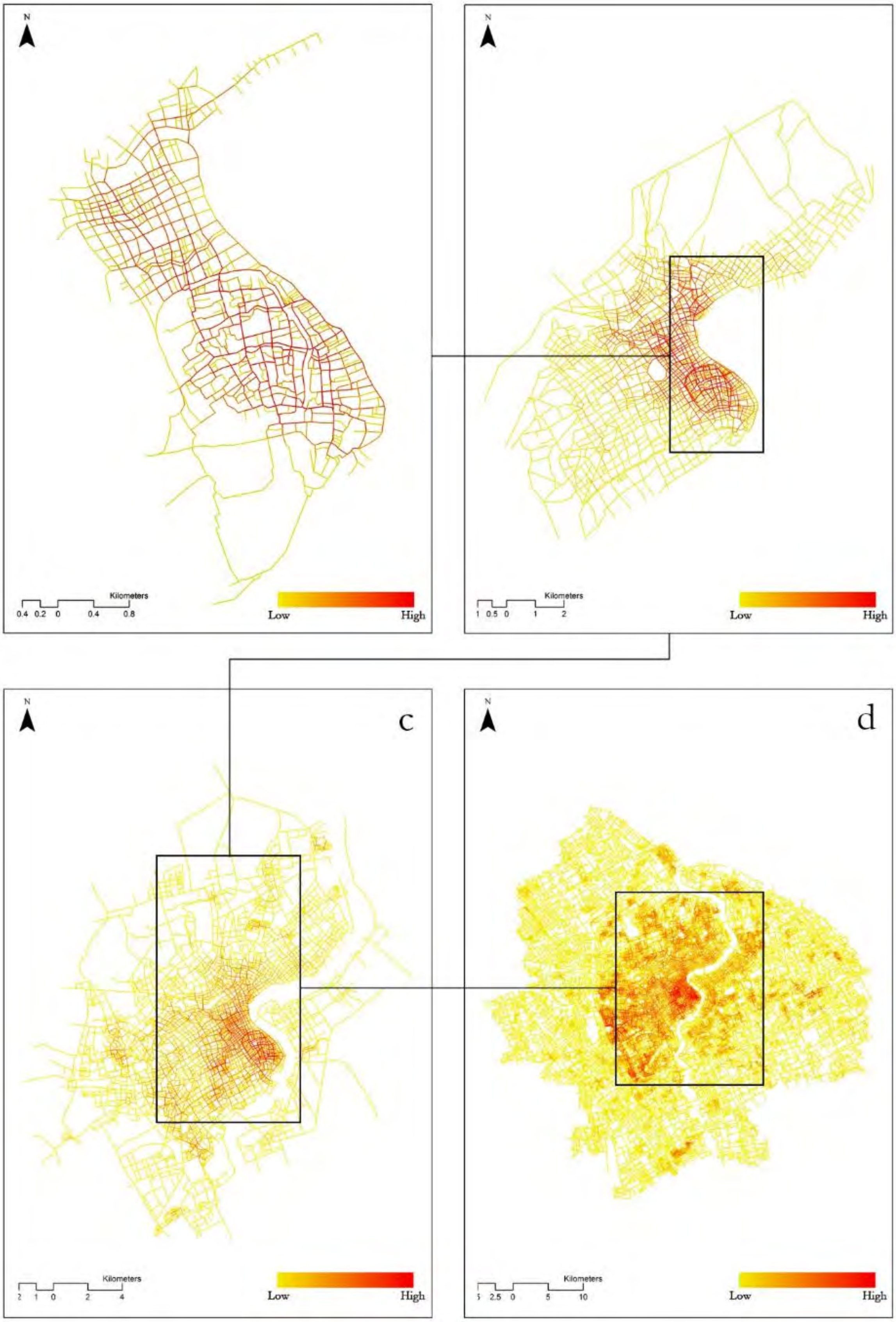


Figure 4-7

Choice maps at 1,000 m across periods ((a) 1880s; (b) 1940s; (c) 1980s; (d) 2010s)

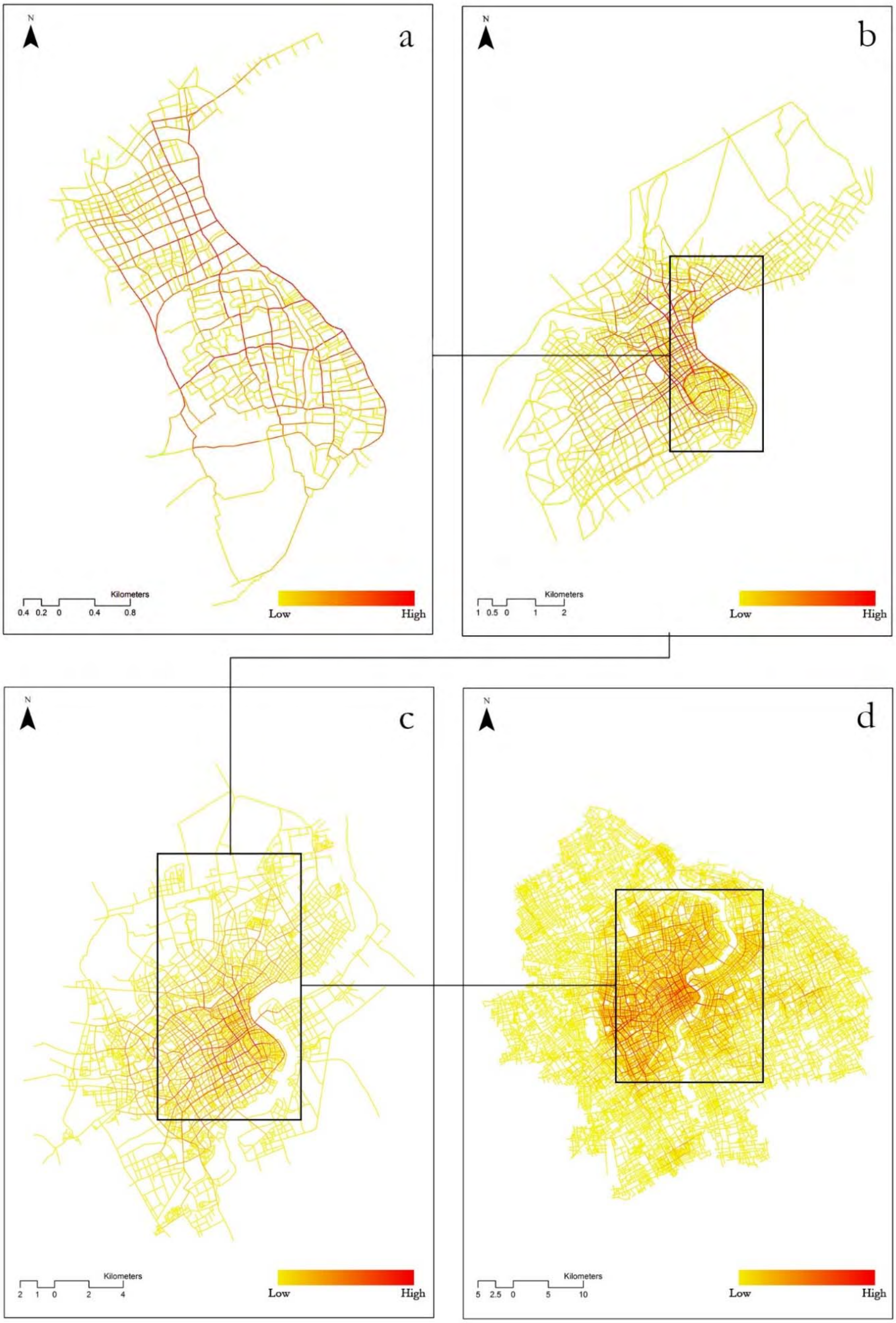


Figure 4-8

Choice maps at 10,000 m across periods ((a) 1880s; (b) 1940s; (c) 1980s; (d) 2010s)

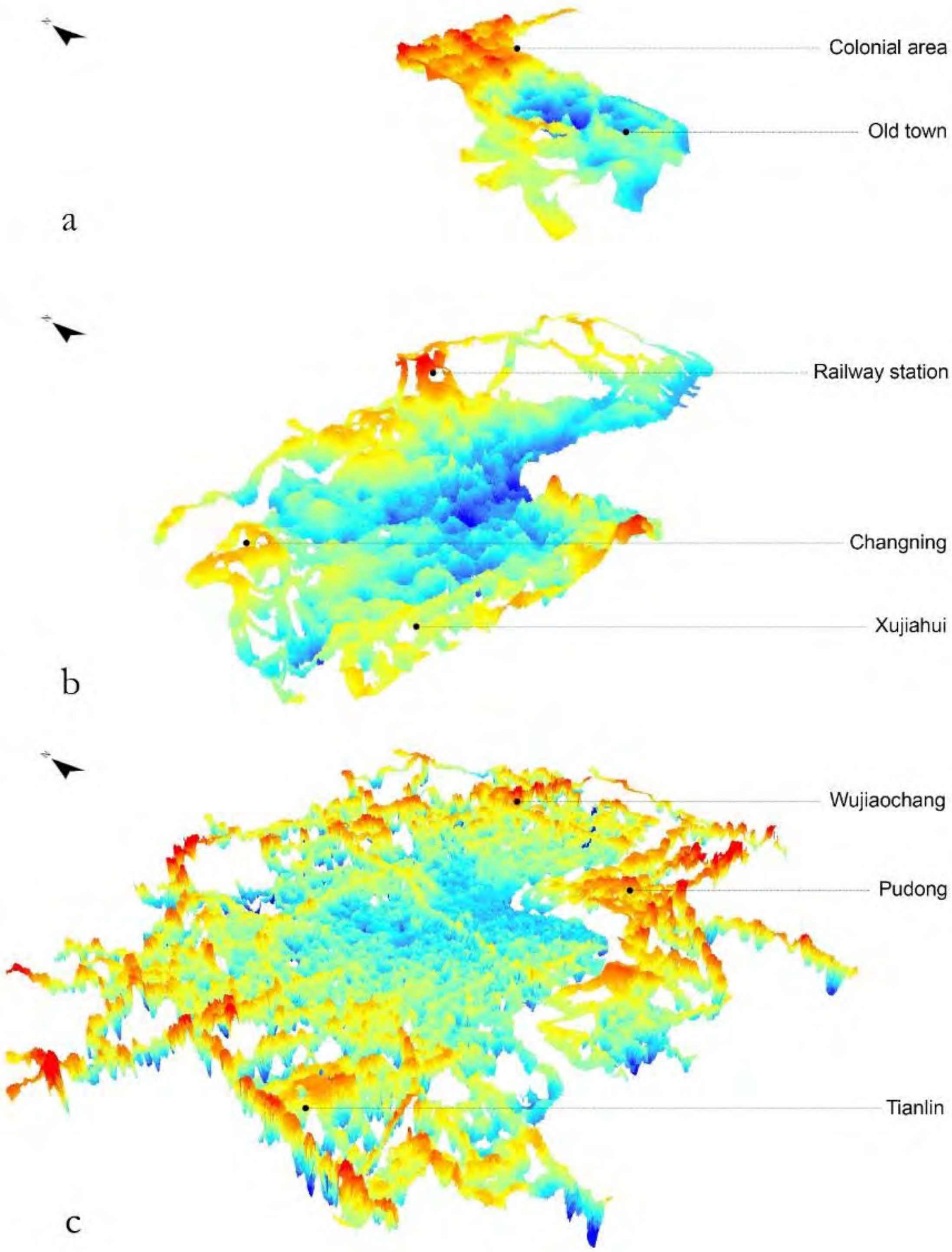


Figure 4-9

Global spatial centrality change: global integration change during the early rapid urban growth stage between the 1880s and the 1940s (a), during the steady urban growth stage between the 1940s and the 1980s (b), and during the modern rapid urban growth stage between the 1980s and the 2010s (c). (Red denotes an increase in centrality whereas blue denotes a decrease)

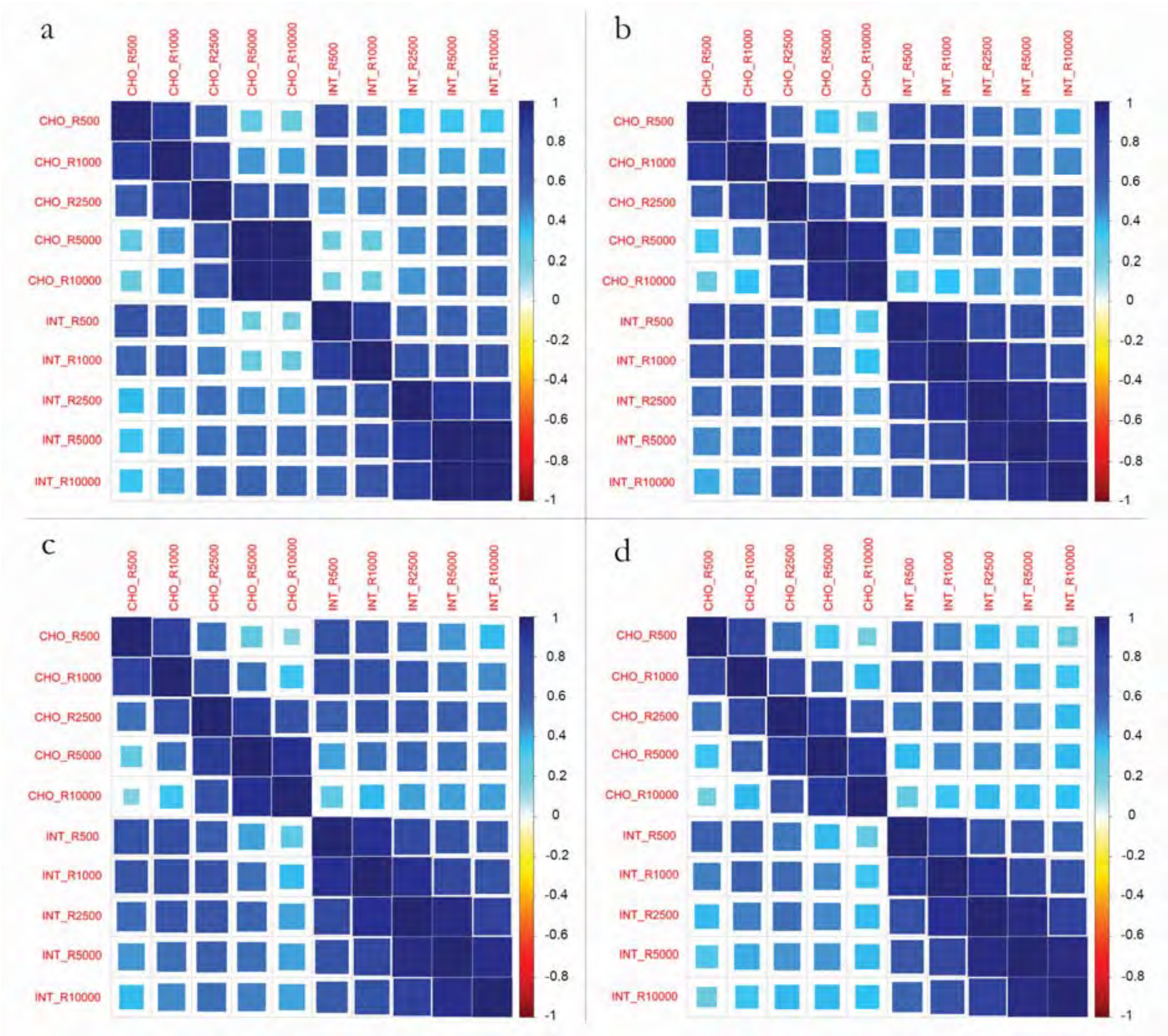


Figure 4-10

Correlation matrices between any two pair of spatial centralities (integration (INT) and choice (CHO)) across various radii during different periods ((a) 1880s; (b) 1940s; (c) 1980s; (d) 2010s

4.2 The functional centrality process

4.2.1 Descriptive statistics: the overall functional transforming trend

During the process of rapid urban growth, the gap between urbanised areas and less-urbanised areas widened; this is supported by evidence of the decline in the mean accessible function density and diversity at all scales, as shown in Table 4-4. The overall trend of shrinking diversity at the smaller scales (at 1,000 m) was reversed during the process of steady urban growth, when a land-use diversification process occurred. The cognitive effort required by the reachable land-uses at the micro and the mesoscales has become less and stable since the 1940s. This tendency suggests that, since the 1940s, urban function patterns have been more configurationally accessible at scales that are relatively local due to the dominance of the superimposed modern grid-like road system. In contrast, the global mean angular distance to land-use increased. Unlike the interpretation of the spatial centrality process, the performance of land-use systems provides more information regarding the processes of densification, diversification and efficiency optimisation (also known as cost-saving), distinguishing the predefined urbanisation periods in the modernisation of Central Shanghai.

Table 4-4

Shifting statistical performance of urban function connectivity measures across periods

	1880s	1940s	1980s	2010s
Mean normalised DEN (R1000)	3.917¶	2.351	2.155	0.691
Maximum normalised DEN (R1000)	8.181¶	7.407	8.152	9.324
Mean normalised DIV (R1000)	0.856	0.781	0.799	0.747
Mean DIS (R1000)	8.209	5.651	5.739	5.985
Max DIS (R1000)	15.602	14.576	20.504	20.797
Mean normalised DEN (R5000)	9.868¶	7.838	5.641	2.307
Maximum normalised DEN (R5000)	9.999¶	10.856	10.513	10.774
Mean normalised DIV (R5000)	0.999	0.964	0.971	0.937
Mean DIS (R5000)	18.289	15.814	14.895	14.471
Max DIS (R5000)	38.458	32.355	42.721	42.034
Mean normalised DEN (R10000)	9.990¶	10.766	8.506	4.027
Maximum normalised DEN (R10000)	9.999¶	10.999	10.962	10.948
Mean normalised DIV (R10000)	0.999	0.997	0.995	0.976
Mean DIS (R10000)	18.413	18.671	23.312	21.474
Max DIS (R10000)	38.724	36.311	48.694	52.615

¶: The maximum value, in theory, for urban function connectivity in the 1880s is 10, whereas the limit for other periods is 11, as a within-group normalised method is applied and the ceiling of the accessible function density is equal to the number of types of active land-uses.

4.2.2 Urban function connectivity maps: functional centrality structures

Figure 4-11 and Figure 4-12 map the integrated urban function connectivity measures at various levels. In the 1880s, the local function centre structures were relatively isolated from each other along the sides of the river; they were located in the Chinese old town and the colonial area, respectively. This local centre, as indicated by local function connectivity, was moved to the north-west of the inner city in the 1940s, and the newly emergent local functional core has been further consolidated and expanded towards the north and the west since the 1980s. In the 2010s, the core of the city's functional centrality structure was anchored in its historical location; simultaneously, the sub-centre structure started to emerge. Some sub-centres have attracted the clustering of various land-uses, thereby forming a polycentric land-use structure at the pedestrian scale. Compared with the spatial centrality structures at the 1,000 m radius during the same period, the functional centrality structures are visually different in terms of their position, shape, and inherent polycentricity. At the global scale, the transformation of the functional structures follows a similar trend that is observed in the shift of spatial centrality through visual judgement. The global functional centre was determined to have been located on the riverside in the 1880s; it was shifted to the concession areas in the 1940s; it grew towards the west in the 1980s; and it became a convex functional core in the geometric centre of the central urban landscape of today's Shanghai.

As a useful complement to the urban functional centrality structure, the detected urban function regions – based on the statistical performance of the multidimensional function connectivity vectors for different types of land-uses – are mapped in Figure 4-13 and Figure 4-14. These emergent land-use communities differ from others according to their composition of access to different land-uses. The increase in the number of function regions from the 1880s to the 2010s suggests that the land-use structures have become more and more complex as urban development has progressed. This complexity is also reflected by the presence of some specific land-use communities that are led by some specific type(s) of land-uses. In the 1880s, the daily active streets (C2), including most of the areas in the Chinese old town and the small area connecting it with the colonial district, were places with better connectivity to cultural amenities, hotels, parks and recreation establishments. This makes sense because during that period the Chinese inner city maintained many temples and destinations for daily entertainment purposes. The colonial area at this time contained the developed business areas (C1), led by modern schools, healthcare and other public services. These two land-use communities were in close proximity to the central business area (C4) on the riverside. The differentiation between the colonial area and the Chinese old inner city provides evidence of the political variation between these two places, illustrating that land-use patterns are also products of the political landscape and confirming that the statistical characteristics of the structure of these urban functional regions have spatial meanings. During the 1940s, the urban functional region structures shifted; two developing areas (C4 and C5) emerged and were led by the newly planned educational facilities but distinguished by being mixed with other land-uses. Urban functional expansion during this period was education-oriented. The central business area (C3) in the 1980s was larger than that in the 1940s because the developed business area of the 1940s was upgraded and merged with it. Other functional regions at this time were distinguished based on the overall degrees of spatial co-presence among the active land-uses, with the exception of two types of developing areas (C2 and C4) with lower overall levels of land-use mixtures, as highlighted by the dominance of their connectivity to transport facilities and community parks. Therefore, after the opening policy was implemented, growth in urban functions was led by transport services and parks in residential communities. In regard to the 2010s, there were seven function regions detected in the clustering analysis. Moreover, the discrimination among them was fundamentally influenced by the presence of ensemble connectivity to various land-uses. However, some patches (C6) emerged in a fragmented manner with the dominance of educational services, i.e., the vast campuses of the universities. The location of the central business district (C2) was anchored in the same place as 30 years ago. The less urbanised areas (C1, C5 and C7) were highlighted by their connectivity to the public urban facilities, such as transport, hospitals and educational institutions, which implies that essential urban services, as vital public goods, were more important than other urban functions in the developing areas. This suggests that requirements for health care and travel convenience have become additional demands of modern society, much like educational functions in the pre-modern society of Central Shanghai. These shifting patterns in the urban function regions create a detailed picture of the dynamic changes in the boundaries and structures of land-use communities; but more importantly, they capture changes in the determination of urban function connectivity.

4.2.3 Heat map analysis: the functional centrality change flow

Normalising global urban function connectivity enables comparisons across cities with different sizes of land-uses to represent the shifting flows of land-use centrality structures (Figure 4-15). During early rapid urban growth, urban functional centrality moved to the colonial area and the south-west from the Chinese old town. When steady urban growth began, the functional centrality in the north (around the railway station and the Changshu Road) significantly increased, and the areas around Xujiahui were also expanded. Most of the hinterland and the Chinese old town were also functionally strengthened. These findings confirm the occurrence of internal growth during this period, as indicated in the discussion above. After the opening policy was allocated nationally, the Pudong district started to obtain political and planning support, and, therefore, it experienced a significant improvement in its global function connectivity. The Tianlin districts also demonstrated an agglomeration of new land-uses. The earliest colonial area, however, lost its accumulated functional centrality due to the shift of the gravity core.

4.2.4 Correlation matrix analysis: synergy between functional centralities

In Figure 4-16, the results of the correlation matrices among the functional centrality measures for the land-use system are reported. A general trend here is that the accessible function density and the integrated urban function connectivity were strongly correlated with a positive sign at all scales, which illustrates the importance of the basic scale effects in measuring the land-use interaction. Furthermore, the function density and diversity exhibit a positive relationship across scales. Historically, the significance of this density-diversity synergy became more and more significant at different scales, and specifically, the local diversity structures have been recognised by the land-use density distributions at the larger scales more successfully since the 1940s (compared to earlier) thereby generating local-global synergy between density and diversity. The mean angular step depth to the nearby functions is positively related to the land-use clustering and mixture degrees at the local levels, but this relationship is reversed when a critical radius is reached. This implies that the urban activities are clustered locally in the urbanised area, requiring more cognitive efforts to interact at the lower scales but less angular step depth to interact at the city-wide scales. The critical scale for the conversion of the relationship between the average angular cost and the reachable land-use density was different across cases during the different historical periods. The critical scale was the radius of 2500 m in the 1880s, 5,000 m in the 1940s, 10,000 m in the 1980s and 150,000 m in the 2010s (not shown in the figure), respectively. The increase in the critical radius across time is the consequence of the increasingly rapid urban expansion that has caused Central Shanghai to continuously grow larger and larger

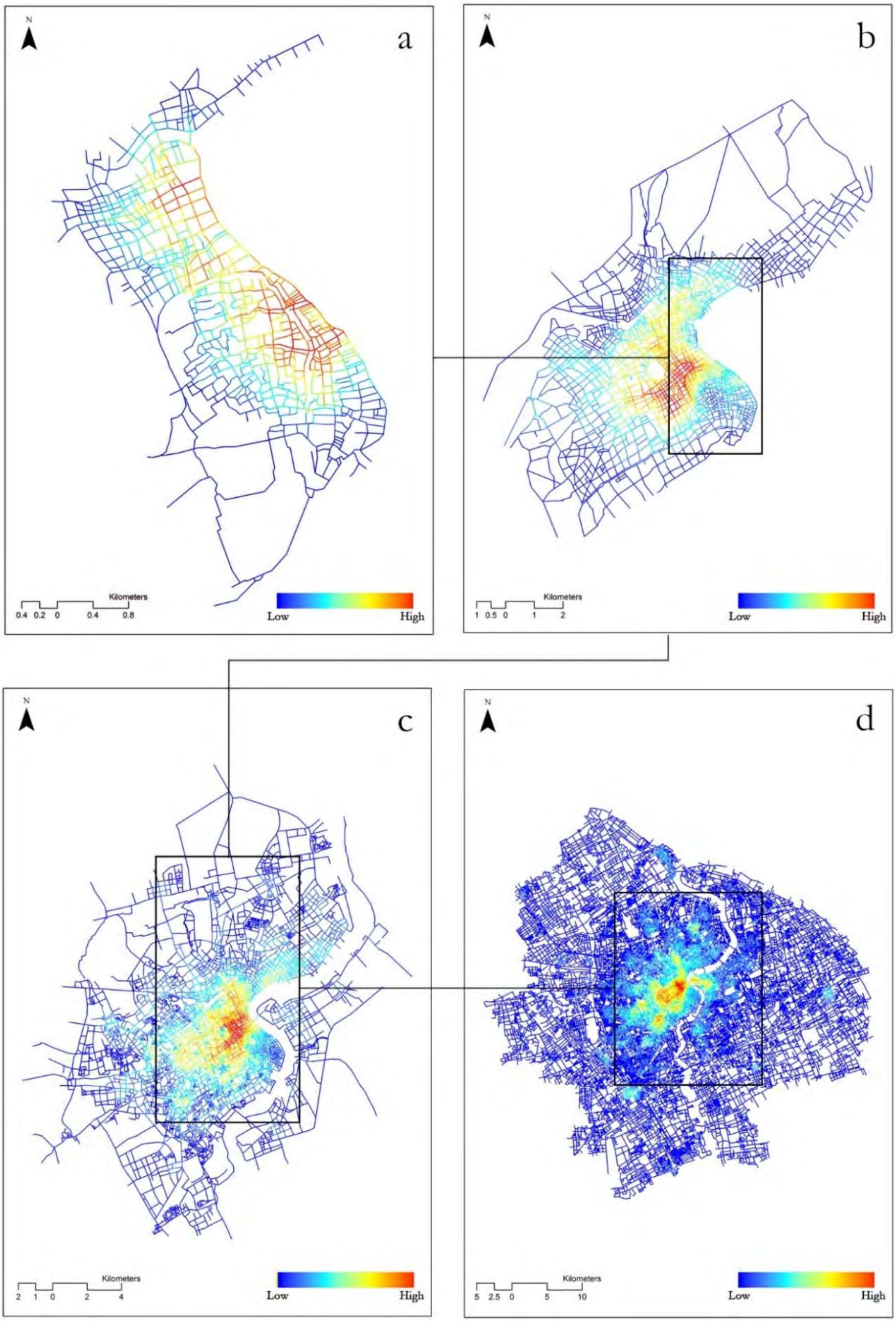


Figure 4-11

Urban function connectivity maps at 1,000 across periods ((a, c) 1880s; (b, f) 1940s; (c, g) 1980s; (d, h) 2010s)

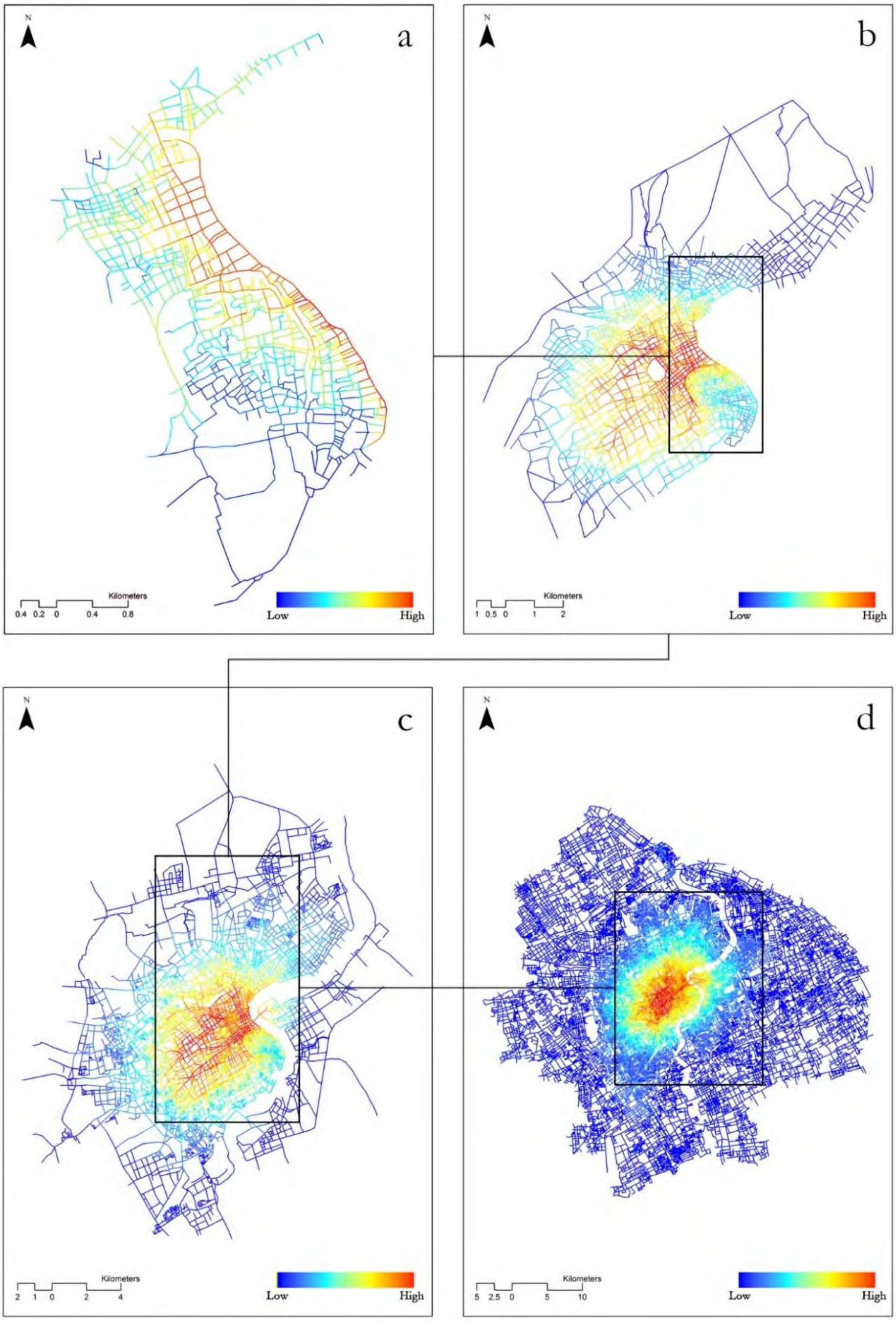


Figure 4-12

Urban function connectivity maps at 10,000 m across periods ((a, c) 1880s; (b, f) 1940s; (c, g) 1980s; (d, h) 2010s)

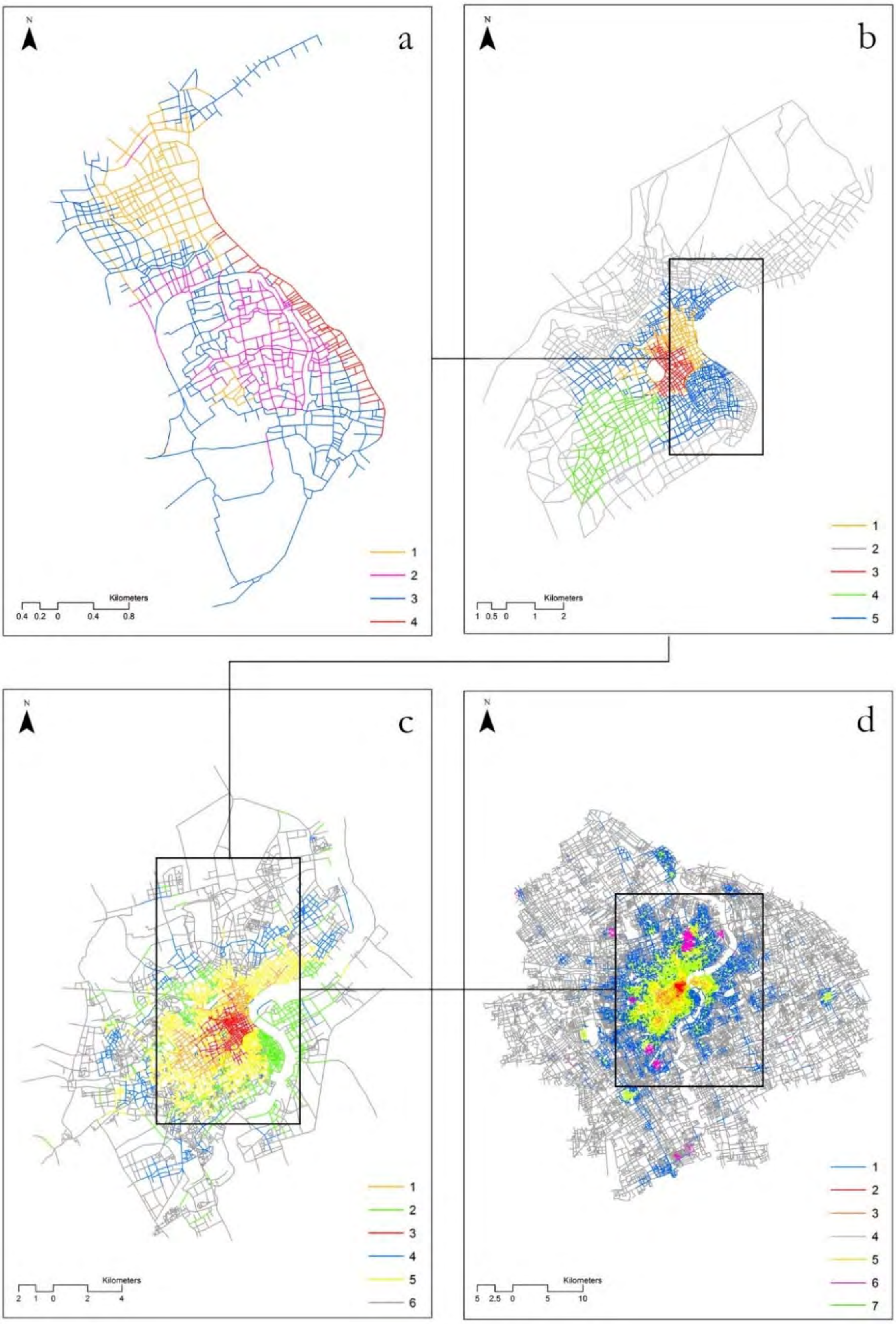


Figure 4-13

Urban function region maps across periods ((a) 1880s (c=4); (b) 1940s (c=5); (c) 1980s (c=6); (d) 2010s (c=7))

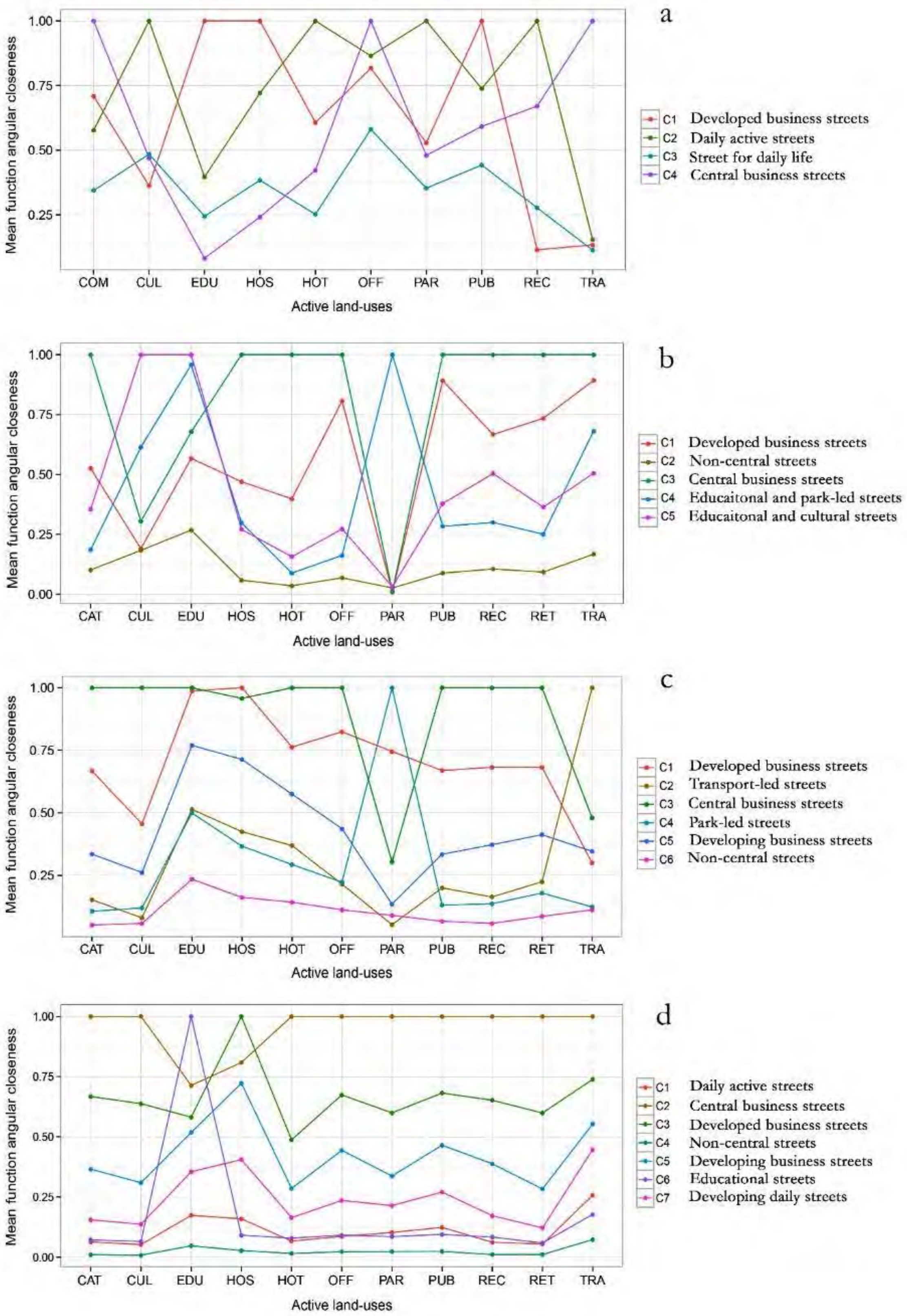


Figure 4-14

The average function angular closeness index for each active land-use in urban function regions across periods ((e) 1880s (c=4); (f) 1940s (c=5); (g) 1980s (c=6); (h) 2010s (c=7))

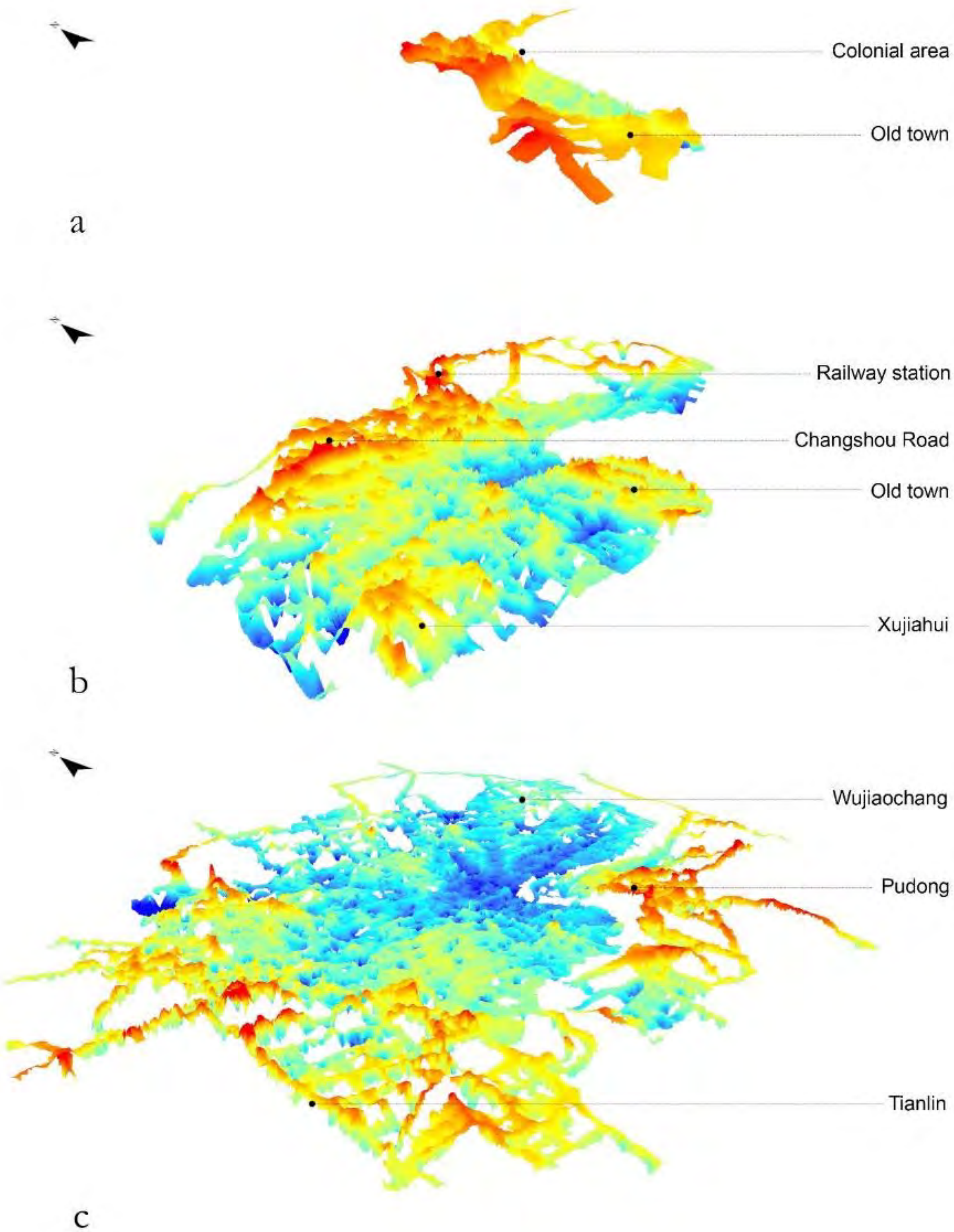


Figure 4-15

Global functional centrality change: global urban function connectivity change during the early rapid urban growth stage between the 1880s and the 1940s (a), during the steady urban growth stage between the 1940s and the 1980s (b), and during the modern rapid urban growth stage between the 1980s and the 2010s (c). (Red denotes an increase in centrality whereas blue denotes a decrease)

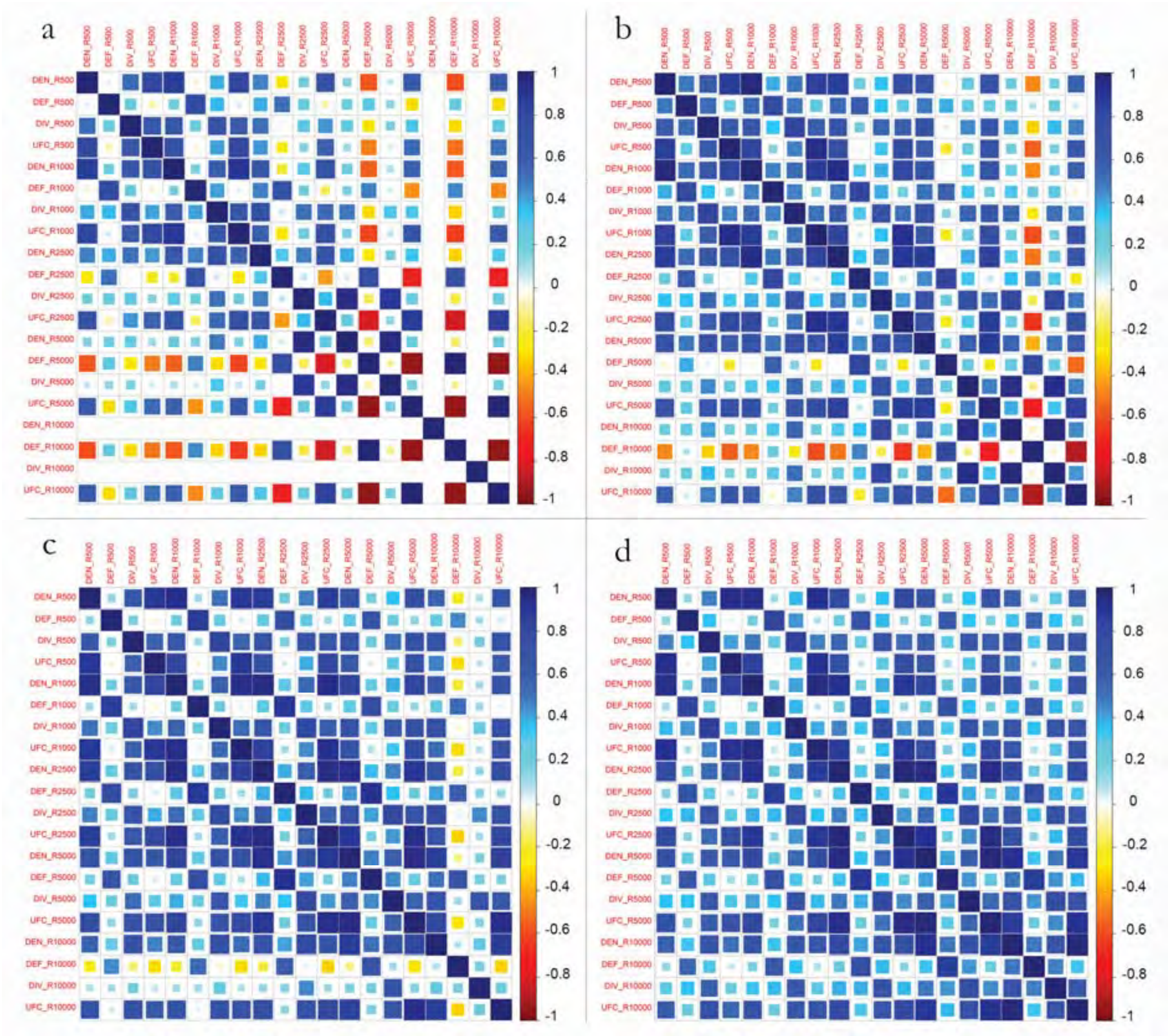


Figure 4-16

Correlation matrices between any two pair of functional centralities (density (DEN), diversity (DIV), mean angular distance (DIS) and the integrated urban function connectivity (UFC)) across various radii during different periods ((a) 1880s; (b) 1940s; (c) 1980s; (d) 2010s). Note: the standard deviation of accessible function density and diversity are 0 for the Central Shanghai in the 1880s

4.3 The spatio-functional interaction process

4.3.1 Comparison between spatial and functional centrality structures

The observed difference between the spatial centrality process and the functional centrality process suggested the complementary relationship between them. First of all, the change of the descriptive statistics of the spatial centrality patterns implies the expansion and the densification of the street network, whereas that of the functional centrality patterns suggest the densification, diversification and cost-saving processes of the land-use system along the streets. These spatio-functional processes characterise the urban developing stages from different perspectives. Moreover, differences emerge between the angular integration and the urban function connectivity maps, particularly at the local scales regarding the locations and shapes of the centrality cores. Additionally, the angular choice maps indicate the trend of the city-wide hierarchisation of the street system and the urban function region structure implies the complex concentration in the land-use change.

Furthermore, the urban growth in the spatial centrality and the functional centrality centres does not coincide. The former, as shown in the heat map analysis, does not lead to the change of the latter which represents the impacts of the existing land-use centralities and the policy allocation or spatial interventions. The historical variation of inter-centrality relationships at multi-scales infers the defined developing stages of Central Shanghai in the past. The two defined rapid urban growth processes are both inferred by the augmented degree of the co-presence between spatial and functional centrality measures, but their unique feature is the performance of the synergy between the angular choice and integration structures, which was stronger in the early rapid urban expansion but much suppressed for the modern rapid urban development due to the increasingly serious differentiation between the modern orthogonal grids and the historically organised form.

Generally, the difference between the form and function centrality structures at the local scales are more obvious than that on the larger levels. In addition, how the spatial network of the city is designed impacts the shifting synergy between form and function thereby shifting the fate of the city. These findings demonstrate that valuable remarks regarding the urban transformation process can be appended to the morphological analysis of urban structure by combing the syntactic analyses of the urban form and its associated land-use pattern.

4.3.2 Correlation matrix analysis: synergy between form and function

Figure 4-17 shows the results of the multi-scale interplay between the spatial and functional centrality measures, generated by the correlation matrices for the Central Shanghai in history. Overall, the influence of the integration centrality structures on the individual metrics of the urban function connectivity is more significant than that of the angular choice centrality patterns because urban land-use distributions are representing the landscape of the destinations for the daily life. The integrated urban function connectivity pattern, summarising the accessible density, diversity and mean angular step depth, is found to be more statistically correspondent to the spatial centralities than any single index. It is evident that the spatial centrality distributions impact the land-use allocation more comprehensively in a complex manner; in other words, the land-use distributions will adjust dynamically for maximising the overall efficiency on the citizens' daily demands. It also empirically proves the effectiveness of the proposed composition measure for capturing the interplay between those three principals explicitly. During the early rapid urban growth process, the spatial centrality structures have been sufficiently recognised by the functional centrality patterns thereby generating the augmented synergy between urban form and function. When the steady urban growth came, this spatio-functional interaction at the higher scales was further enhanced, but then slightly suppressed in the following modern rapid urban growth.

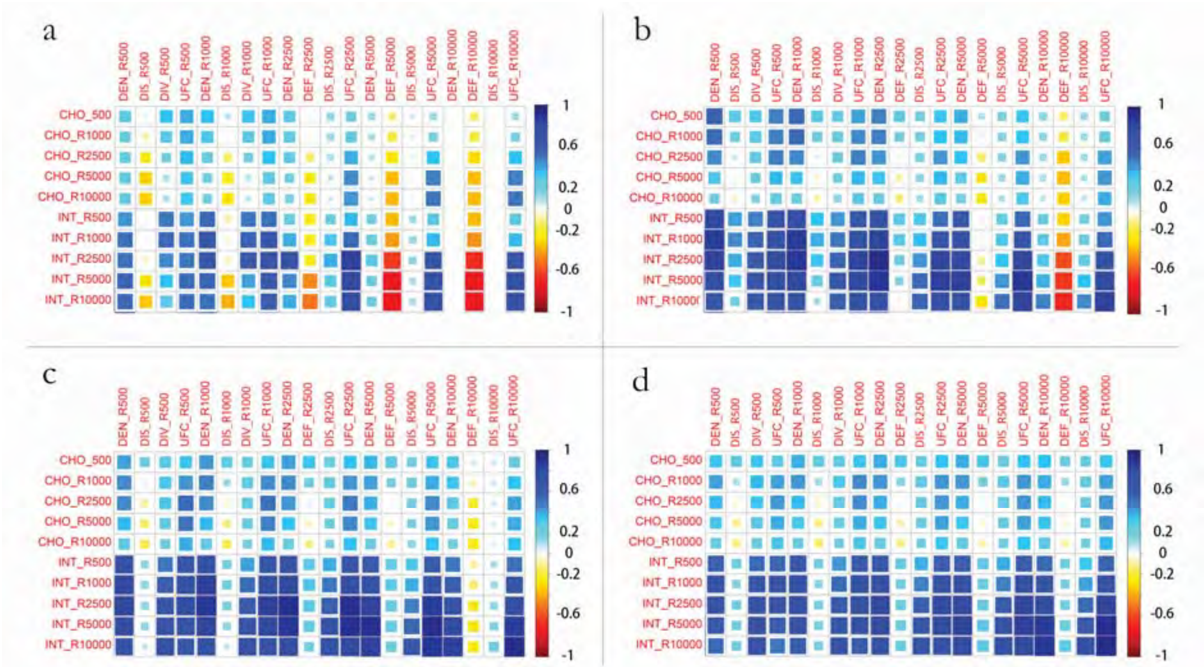


Figure 4-17

Correlation matrices between any two pair of configurational centralities (integration, choice, function density, function diversity and function delivery efficiency) across various radii during different periods ((a) 1880s; (b) 1940s; (c) 1980s; (d) 2010s)

4.3.3 Discriminant analysis: delineating urban function regions

In order to quantify the additional influence of spatial network on the formation of urban function regions that represented in Figure 4-13, a discriminant analysis is conducted that included as predictors most of the centrality measures. In the canonical discriminant analysis, the number of the discriminant functions is N-1, in which N refers to the total amount of the memberships in the sample. The first three functions in the outputs together can explain over 95% of the variance in all cases (Figure 4-18), and the first two are the main determinants with more than 75% information from the original variables. Although the specification of the significant variables for the functions in different cases varies, there is still some fair similarity between them in terms of the scales where the centrality measures rely on.

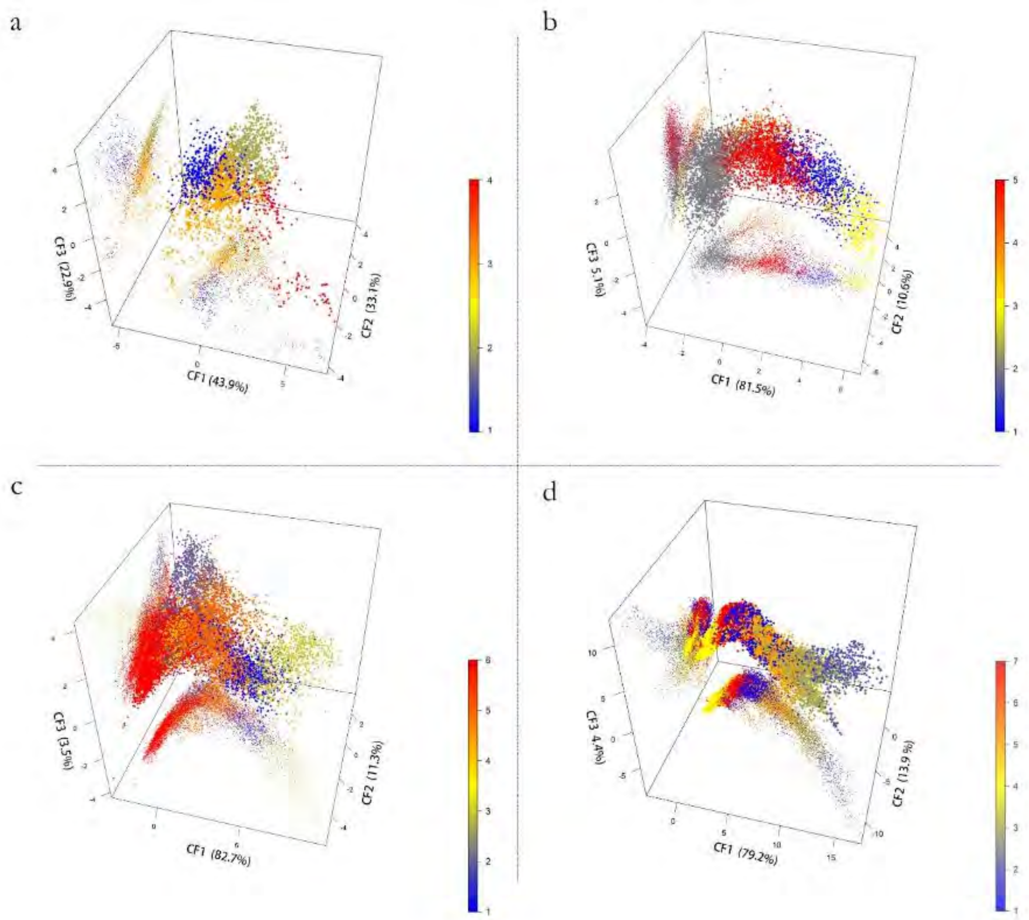


Figure 4-18

3D scatter plot diagrams of the first three canonical discriminant functions across periods ((a) 1880s; (b) 1940s; (c) 1980s; (d) 2010s) at 1000

The first two canonical discriminating functions in all the samples can be classified into two types: the optimum and the sub-optimum spatio-functional synergy, represented by the different degrees of co-presence between spatial and functional centralities across scales. The meanings of each predictor function are explained by recording the significant loadings of the centrality measures (Table 4-5). Function 1 is the optimum spatio-functional centrality, mostly defined by the most significant co-presence between centralities across scales, which is visually close to the global centrality structure; while function 2 is the sub-optimum spatio-functional interaction with a lower degree of centrality co-presence. Figure 4-19 plots the detected urban function regions against the two core functions. Notably, the urban regions can be successfully discriminated by the two principal functions. With urban development, the range of the two functions becomes wider, which indicates that the urban centrality structures have been historically polarised. Although the picture clearly shows shifts in the urban function regions' centroids over time, some similarities can be easily identified. The central business streets and the developed business streets score high on optimum spatio-functional centrality but low on sub-optimum spatio-functional interaction. The non-central streets, as expected, are scored negatively in both cases. The streets dominated by a specific type(s) of land-use(s) are highlighted with positive scores on function 2 but negative or minuscule positive values for function 1. The developing business streets, or the daily active streets, are placed in the second quadrant, where both functions are scored positively. The consistency of the relative positions of different function regions in the scatter diagrams reveals that the complex spatio-functional interaction is the main factor impacting the streets' typology in terms of the land-use patterns.

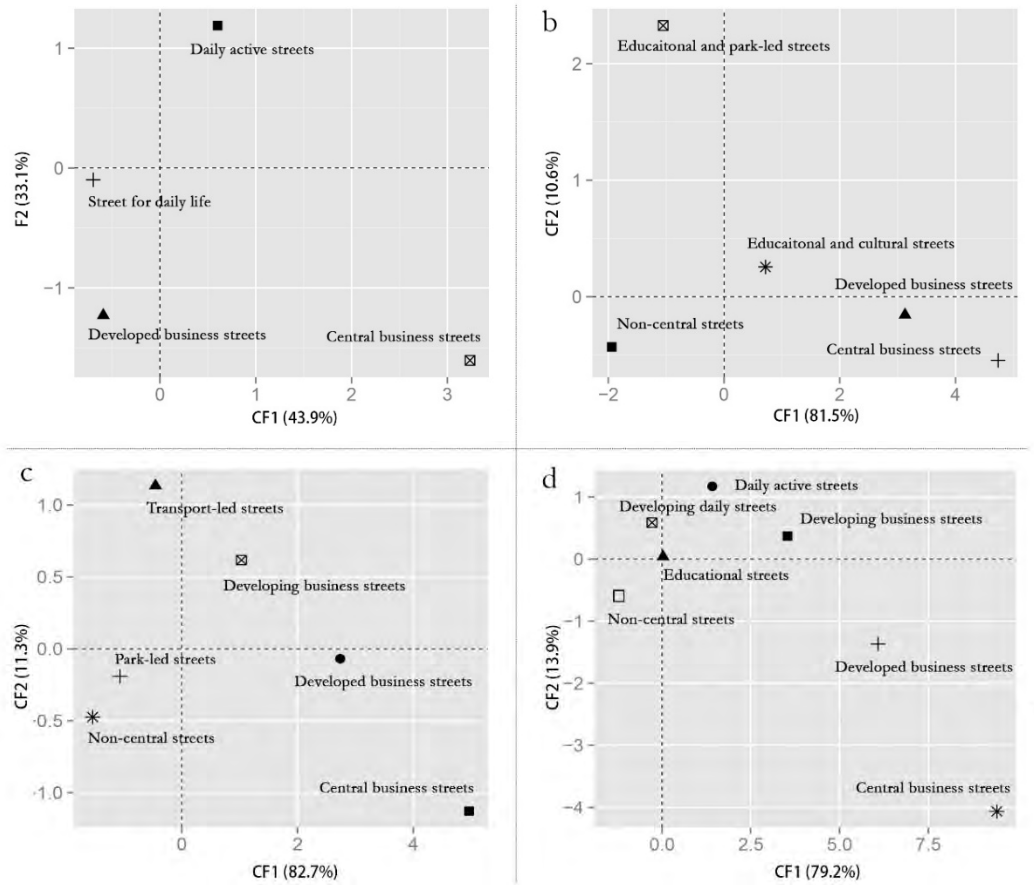


Figure 4-19

Canonical discriminant functions at urban function region centroids ((a) 1880s; (b) 1940s; (c) 1980s; (d) 2010s)

Table 4-5

Structure matrix table in Central Shanghai during various periods ((a) 1880s; (b) 1940s; (c) 1980s; (d) 2010s)

	1880s		1940s		1980s		2010s	
	CF1	CF2	CF1	CF2	CF1	CF2	CF1	CF2
Space syntax variables								
INT_R500			0.429		0.418	0.232	0.352	
INT_R1000	0.221	0.262	0.606		0.576	0.291	0.483	0.116
INT_R2500	0.448	0.144	0.763		0.708	0.313	0.541	0.261
INT_R5000	0.466		0.639	0.302	0.677	0.391	0.516	0.426
INT_R10000	0.453		0.511	0.390			0.449	0.578
CHO_R500			0.229		0.173	0.220	0.143	
CHO_R1000	0.184	0.357	0.241		0.236	0.154	0.203	
CHO_R2500	0.272	0.151	0.255		0.275		0.209	
CHO_R5000	0.412	-0.177	0.203		0.246		0.188	
CHO_R10000	0.417	-0.199			0.188		0.150	0.115
Urban function connectivity variables								
DEN_R500			0.708		0.775		0.685	-0.341
DEN_R1000			0.788		0.847		0.873	-0.320
DEN_R2500	0.466	0.463	0.703	0.106	0.757	0.230	0.771	
DEN_R5000			0.377	0.270	0.611	0.517	0.677	0.360
DEN_R10000			0.087	0.152	0.359	0.526	0.494	0.563
DIV_R500	0.424	0.265	0.273	0.445	0.377	0.525	0.323	0.560
DIV_R1000	0.324	0.343	0.200	0.298	0.305	0.395	0.240	0.443
DIV_R2500	0.110		0.151	0.233	0.268	0.364	0.254	0.407
DIV_R5000	0.034		0.118	0.213	0.186	0.292	0.280	0.432
DIV_R10000				0.145			0.184	0.375
DIS_R500								
DIS_R1000		0.484		-0.193				
DIS_R2500	-0.107	0.591		-0.287		0.133		
DIS_R5000	-0.609	0.387		-0.208		0.214		
DIS_R10000	-0.634	0.365	-0.442	-0.320	-0.104	0.134		0.067

Note: INT – Integration; CHO – Choice; DEN: – Accessible function density; DIV: Accessible function diversity; DIS: Mean angular distance to functions; CF1: The optimum spatio-functional centrality; CF2: The sub-optimum spatio-functional centrality.

To further evaluate the performance of these two detected functions in predicting the memberships of the urban function regions, the second step of the discriminant analysis is to assess the predictability of the projected variables in terms of segmenting the known region structures based on the prediction accuracy of the detected linear models based on the sample provided. The relevant results are reported in Table 4-6. There are three specifications of models utilised for comparison: the first model is organised with only the spatial centrality variables, the second one only contains the functional centrality factors, and the last one is a mixed model with both families of the structural centralities proposed in this chapter.

The accuracy of the models with only the space syntax variables during different periods is more than half (except for the model of the 1980s) with an overall accuracy of 47.1%. The highest predictability of the spatial centrality variables appeared in the 1940s, when early rapid urban growth occurred. Compared with the performance of the spatial centrality variables, the urban function connectivity variables maintain higher accuracy in all samples. This is consistent with our expectations, as the land-use regions are inevitably impacted by the land-use system in some sense. The detected urban function regions here, however, are treated as the independent classification of the streets because they are defined based on the combined statistical significance of the connectivity for diverse land-uses rather than the urban function connectivity indices for all the land-uses that are used to predict the affiliation of function regions.

Table 4-6

Prediction accuracy of urban function regions using space syntax centrality and urban function connectivity measures across scales

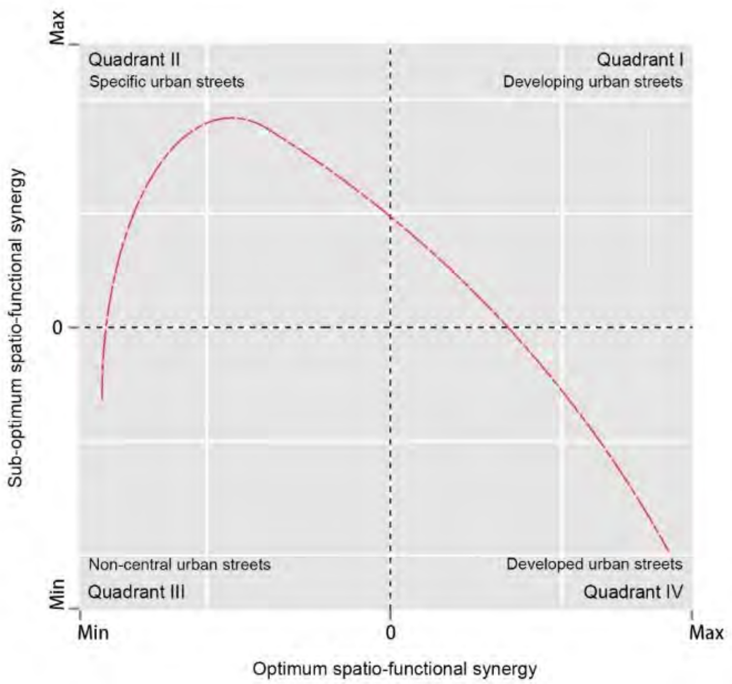
	Prediction accuracy for regions							Overall accuracy
1880s								
Membership	1	2	3	4				
SSX variables	57.6%	63.1%	56.3%	39.9%				57.4%
UFC variables	71.8%	86.4%	76.1%	84.5%				79.4%
SSX and UFC variables	78.2%	90.6%	81.9%	89.1%				86.7%
1940s								
Membership	1	2	3	4	5			
SSX variables	50.6%	75.0%	64.4%	76.2%	67.6%			69.3%
UFC variables	68.3%	83.2%	84.4%	83.9%	63.6%			75.7%
SSX and UFC variables	74.4%	85.2%	86.1%	80.7%	71.7%			80.6%
1980s								
Membership	1	2	3	4	5	6		
SSX variables	54.3%	33.0%	76.9%	38.3%	27.1%	56.0%		47.1%
UFC variables	62.6%	61.3%	74.6%	61.1%	53.1%	51.5%		55.9%
SSX and UFC variables	70.0%	58.5%	74.7%	65.7%	55.5%	55.9%		61.1%
2010s								
Membership	1	2	3	4	5	6	7	
SSX variables	40.9%	80.1%	38.3%	75.4%	28.2%	80.1%	37.6%	59.6%
UFC variables	50.1%	74.3%	62.4%	78.6%	55.3%	74.3%	59.2%	67.5%
SSX and UFC variables	51.6%	74.3%	63.9%	79.5%	56.5%	74.3%	58.2%	72.9%

More importantly, the extent to which the spatial centrality measure will improve the predictive model with only the functional centrality measures is the primary concern of the designed discriminant analysis. The irreplaceable role that urban form plays in discriminating among urban function regions is verified by the observation of the improved model's predictive accuracy when the spatial centrality measures are taken into account in the benchmark models. This also provides evidence that the spatial and functional centrality structures not only preserve their similarities but also sustain a complementary interrelationship, delineating the urban function communities within the urban context. Moreover, it is arguable that other factors might also be strongly influential, particularly during the periods after the implementation of the open policy when the predictability of the spatio-functional interaction is smaller than that during the previous period.

5 SUMMARY AND DISCUSSION

The study in this chapter sheds light on the evolutionary nature of the interaction between urban forms and functions from a syntactic perspective using a series of quantitative measurements of urban centrality structures with historical street network and POIs datasets. By introducing centrality indices for spatial and functional morphologies, namely the space syntax centrality indices and the urban function connectivity metrics, generated by the spatial network and land-use patterns in tandem, this article detects and compares the spatial and functional centrality processes and their interactions at different stages of the urbanisation process. This is one approach to integrating historical spatio-functional information and extracting comprehensive knowledge regarding the urban evolution process. Based on a case study of Central Shanghai, this chapter summarised a general picture of spatio-functional interaction in the urbanisation process, confirming the novelty of taking into account the function centrality structures in configurational studies and verifies the effectiveness of the detailed measurements. The quantitative framework and associated findings presented here can be used as references to more comprehensively and explicitly describe the dynamics of changing urban centre systems, thus enriching our understanding of urban morphological evolution and supporting appropriate planning and design applications.

This empirical study of Central Shanghai's urbanisation history implies that the urban evolution process can be jointly characterised by the spatial and functional centralities of the urban context. There are several aspects of its potential contribution. First, it suggests that urban form interacts with urban function by shaping the interrelated spatial and function centralities. They are not static but rather dynamic, as parts of a complex process. The defined urbanised stages in history can be successfully characterised by the ways in which the spatial and functional elements are interrelated. Furthermore, the proposed functional centrality structures capture various principal aspects of the configurational agglomeration of active land-uses through the street network, such as the densification, diversification and distanciation (cost-saving or spill-over) processes, which are different from those informed by the spatial centre's patterns captured by the space syntax centrality, particularly at the local scales. The current study provides theoretical propositions and methods for modelling the syntactic properties of a land-use system and spatial network in a morphological analysis, and in space syntax studies in particular. Moreover, this research demonstrates that urban spatial centralities influence functional centralities in a complex and comprehensive fashion, which has been captured by the integrated urban function connectivity measure that summarises the interplay among individual functional centrality measures. Additionally, it reveals that rapid spatial expansion does not naturally lead to a change in the structure of urban centres, but functional expansions with spatial consolidation result in the reorganisation of the hierarchy of centres. The results of the discriminant analysis of predicting the membership of the detected urban function regions quantitatively verified the complementarity between urban form and functions.



4

Figure 4-20

A generalised model for the distinction of the street-based land-use community structures based on the integration between the optimum and the sub-optimum spatio-functional synergy functions

This research also illustrates a general rule that governs how urban streets can be classified by the synergy effects simultaneously exerted by the spatial network and land-use patterns (Figure 4-20). In such a model, the co-presence of spatial and functional centralities across scales is first packaged as two types of spatio-functional synergies: the optimum and the sub-optimum spatio-functional synergies. The four quadrants in the rectangular coordinate plane defined by these two categories of spatio-functional synergy indicate four classes of urban function regions in streets: the non-central urban streets are located in the third quadrant; the specific urban streets, highlighted by the dominance of connectivity to certain type(s) of land-use(s), are defined in the second quadrant; the developing urban streets, including the daily active streets and the developing business streets, are captured in quadrant I; and the developed urban centres are in quadrant IV. Notably, the locations of function regions in this plane are not only divided by the quadrants in general but also controlled by a curve from quadrant III to quadrant IV, crossing quadrants II and I in a sequence. This curve also represents a process by which urban function regions transform from one type into another due to shifts in the performance of the spatio-functional synergy functions. At different urbanisation stages, the detailed embodiment of this plane can vary. During the steady urban growth process, the four quadrants of the plane are relatively balanced, as the deviations arising in both are relatively small. During the rapid urban growth process, however, the polarisation of the spatio-functional synergies will be intensified, which will lead to the compression of the quadrants – an indicator of the gap between the urbanised and non-urbanised areas. The robustness of the emergence of relevant phenomena in the empirical study of Central Shanghai is evidence of the representativeness of the proposed ideal model for segmenting streets based on the complex spatio-functional interaction.

This study provides important insights into the syntactic analysis of the dynamic interaction between urban form and land-use patterns using the historical street network and POIs. The proposed approaches and their results provide references for future studies analysing the urban evolution process. Several areas of this research could be further developed in subsequent efforts. First, the proper weights for the historical POIs could be added into a current framework to infer the popularity of individual function locations for function connectivity computation. In this study, only the POIs in the 2010s are weighted by the assigned social media check-in data; other historical POIs are weighted equally due to the absence of data on their significance. Backed by multiple data sources, the explicitness of the delivered functional centrality measures could be enhanced. Second, more empirical experiments could be conducted in the future to validate the generality of our findings and the applicability of our methods across cases. Third, the analysis of the urban evolution process in this work is spatiotemporal with a long time interval. Identifying the evolution of urban functional centrality structures along a fine-grained temporal dimension with emerging geographical location information will be valuable in advancing current knowledge of urban spatial and functional evolution.

CHAPTER 05

SPATIO-FUNCTIONAL INTERACTION AND HOUSE PRICE PATTERNS

1 INTRODUCTION

Urban centrality structures represent the externality of city economic activities, which forms the theoretical proposition for the study in this chapter. The primary goal of this chapter is to further unfold the economic translation process of urban centrality structures in the housing market which is sensitive to the change of its neighbouring spatial and functional conditions. This offers a valuable scope of assessing the contribution of functional centrality structures to a more comprehensive and explicit understanding of economic meanings of the spatial configuration. The spatial heterogeneity of the housing price in the same market is particularly focused in the current analysis to examine the spatial stability of the price effects of the spatio-functional interaction.

By using Central Shanghai as a case for the empirical study, this chapter specifically evaluates how the interactions between the spatial layouts and land-use system at various scales through the street network affect the spatially homogeneous valuation of residential properties and the segmentation of housing markets in a network-based mixed-scale hedonic model (MHM) where the submarkets pattern are determined and annotated by the spatially varying estimates on streets. The scope of this chapter is three-fold: 1) to examine whether spatial accessibility and function connectivity metrics through street network impact the housing price patterns; 2) to investigate whether the effects of spatial accessibility and function connectivity indices perform uniformly across space; 3) to study the contribution of spatio-functional interaction through streets at different scales to forming the rational submarkets distributions. The space syntax centrality and function connectivity metrics through streets are assigned to the property locations as independent variables in the proposed network-based mixed-scale hedonic model with non-Euclidean distance metric. Based on the local coefficients generated from the detected local parameters in the network-based mixed-scale hedonic model instead of raw data, this study uses a network-constrained k-means clustering analysis to identify the housing submarkets. In this respect, the effects of spatio-functional interplay through streets on the spatial heterogeneity and the submarket delineation of the house price patterns can be explicitly revealed. By doing so, this chapter verifies the generic roles of urban functional centrality structures in reshaping local housing submarkets and spatial variation of house price. Relevant policy implications are discussed in the last section.

2 BACKGROUND

As the vital factors reflecting the economic externality, location variables capture the geographical characteristics of city properties. The connotations of location can span from environmental quality, landscape comfort, socioeconomic features, to travelling impedance, etc. In urban studies, accessibility is a critical concept that represents the *potential of opportunities for interaction* in different locations (Hansen 1959). Related research focusing on the regional determinants or the distance factors in the analysis of housing price patterns were typically conducted based on the assumption that built environment is homogeneous across the landscape (Batty 2009). Consequently, the influence of the fine-grained design of built environment upon the housing price variation is over-simplified or overlooked. The absence of the proper consideration of spatial disparity of urban space thereby constraining the possibility of explicitly understanding the socioeconomic impacts of urban design.

In hedonic price theory, the urban property is priced for its inherent utility-bearing characteristics (Lancaster 1966; Rosen 1974) including its structural features, location situations and the neighbourhood effects (Dubin 1988; Bourassa et al. 2007). The existence of spatial heterogeneity of housing price pattern indicates that property value is not self-existent but closely related to its surrounding property values. In this sense, the spatial autocorrelation between property values can hardly be captured by the structural or locational variables; therefore, the neighbourhood effects should be taken into account in the hedonic regression models (e.g., Goodman 1978; Huwang and Thill 2009; Hui et al. 2016). Due to the recent development of the local regression methods, for instance, notably the locally weighted regression (LWR) method (Cleverland and Devlin 1988), geographically weighted regression (GWR) (Brunsdon et al. 1996; Fotheringham et al. 2003), spatial autoregressive models (Kelejian and Prucha 1998), etc., addressing the neighbourhood impacts is suggested to be an effective way of controlling the spatial variation of hedonic price functions, improving the prediction accuracy (e.g., Goodman and Thibodeau 1998) and generating the reasonable submarkets (Bourassa et al. 1999; Bourassa et al. 2007; Helbich et al. 2013). Nevertheless, it was found that not all variables vary geographically, and sometimes only certain parameters influence housing prices based on spatial locations (Wei and Qi 2012). Thus, spatially homogeneous factors and heterogeneous elements should be considered simultaneously so that spatial knowledge of property valuation can be advanced. Moreover, the priority of adopting the landscapes of local estimates in housing submarket segmentation process has been distinguished from conventional ways to define submarkets, for instance, demarcating the submarkets according to the constant marginal prices (Goodman and Thibodeau 2007) or with distinct patterns of observed characteristics (Palm 1978), as its independence of the exogenously predefined units and effectiveness for improving the accuracy of the hedonic models for the defined submarkets (Helbich et al. 2013). Against this background, the mixed-scale hedonic model is recognised as an efficient regression approach to address the neighbourhood effects by combining the standard GWR model and the conventional hedonic model to capture the complex interactions between variables and to define the emergent submarket patterns in a data-driven procedure.

Housing hedonic studies can be conducted with different variables settings on different scales, which might lead to the different conclusions with the modifiable areal unit problems (MAUPs). Conventionally, the mixed-scale hedonic model was employed with the regional indicators and the Euclidean distance metrics beyond the sampling landscape (Fotheringham et al. 2003), which are not particularly suitable for studying the impacts of built environments within non-Euclidean metrics on an intra-city scale (Lu et al. 2011; Lu et al. 2014). Urban streets, the places where the real urban economy occurs (Jacobs 1961; Hillier and Hanson 1984; Hillier and Hanson 1997; Hillier and Vaughan 2007), have been paid very few attention in hedonic regression models. In fact, they are not only the urban elements that deliver spatial and functional convenience but also the proper spatial units for the high-resolution analysis of housing price pattern. Additionally, the network distance along the streets explicitly portrays the actual spatial interactions between properties, and its contribution to optimising the statistical performance of the GWR has been confirmed in recent studies on housing price distribution (Lu et al. 2014; Lu et al. 2016).

Against the background of the spatial heterogeneity of house price patterns, this chapter applies a network-based mixed-scale hedonic model framework in this chapter to explore the role that the fine-scaled spatio-functional interaction in the built environment between the spatial network and land-use system plays in the observed spatial heterogeneity and housing market segmentation of Central Shanghai. This spatially weighted regression models can produce in-depth insights on the spatially varying influence exerted by centrality measures which is normally neglected by the global regression approaches. Ongoing research in this chapter is constructed in the following four sections. The subsequent section presents the research framework and the mixed-scale hedonic model specifications, followed by a brief introduction of the data. The empirical results are interpreted in the fifth section. This chapter concludes with the related discussion, potential implications, and suggestions for the future efforts.

3 THE METHOD

3.1 Research design

The study design in this article is illustrated in Figure 5-1. This framework includes a stepwise research procedure, which generally follow the methods conducted by Bourassa et al. (2007) and Helbich et al. (2013) with different variables settings, definition of spatial relationship, and basic unit for analysis. In the first step (step a), the required data are obtained from websites of two well-known online housing agents through data mining processes. This asking house price data are used as a proper estimation of the real transactions due to the poor availability of the private buying records (Chandler and Disney 2014; Law 2017). This house price sample is randomly split into two parts for cross-validation: one part is the training data for regression analysis and the remaining is the test data for the validation and the annotation of the generated submarkets. In step b and c, spatial and functional network accessibility measures are computed and then assigned to the corresponding residential properties based on their exact locations on roads. In the following step, these location features and structural features are used as the inputs in the proposed mixed-scale hedonic model to generate the street coefficient maps that are interpolated with spatial constraints that are defined by the connecting relationship between road segments. At the last stage, a data-driven community detection method with network connectivity constraints is adopted to group the street network as the submarkets.

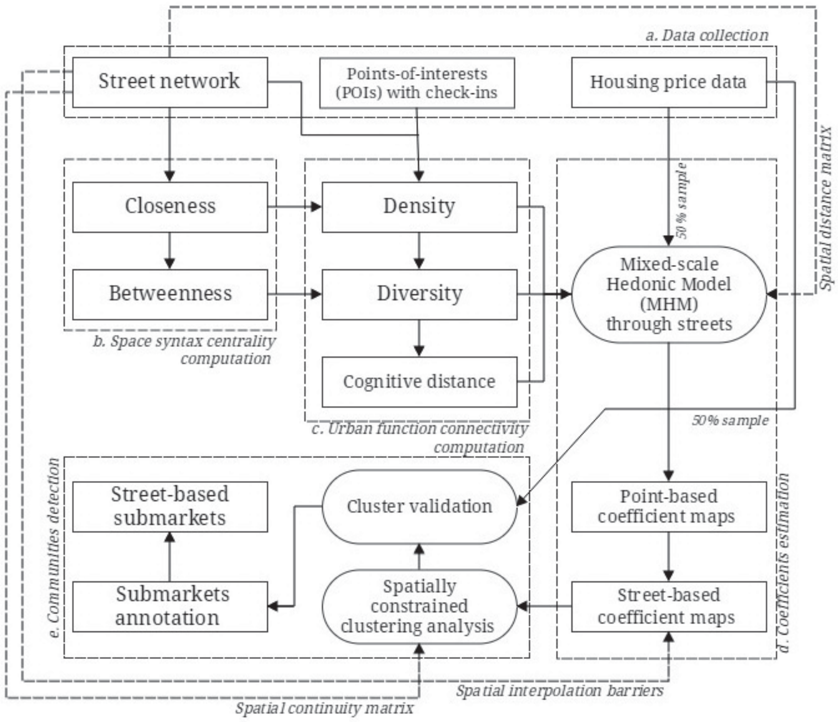


Figure 5-1

The network-based mixed-scale hedonic model for estimating the coefficient maps of local factors and detecting the housing submarkets patterns

3.2 Indexing streets with spatial and functional context

As argued in previous chapters, street centrality measures based on a graph representation of built environment can provide finer-scaled maps of location advantage with the non-

Euclidean settings, which are also fit for the need of explicitly describing the features of neighbouring urban design situations. The urban built environment here is conceptualised as an opportunity landscape where the individual public spaces and the land-use amenities are treated as spatial and functional opportunities through streets respectively. Accordingly, two groups of the network accessibility measures in the introduced spatio-functional interaction model are used in this chapter: the spatial accessibility measures that are the space syntax centrality indices, including integration and choice, and functional accessibility measures that are the urban function connectivity indices, containing density, diversity and cognitive distance (Figure 5- 2).

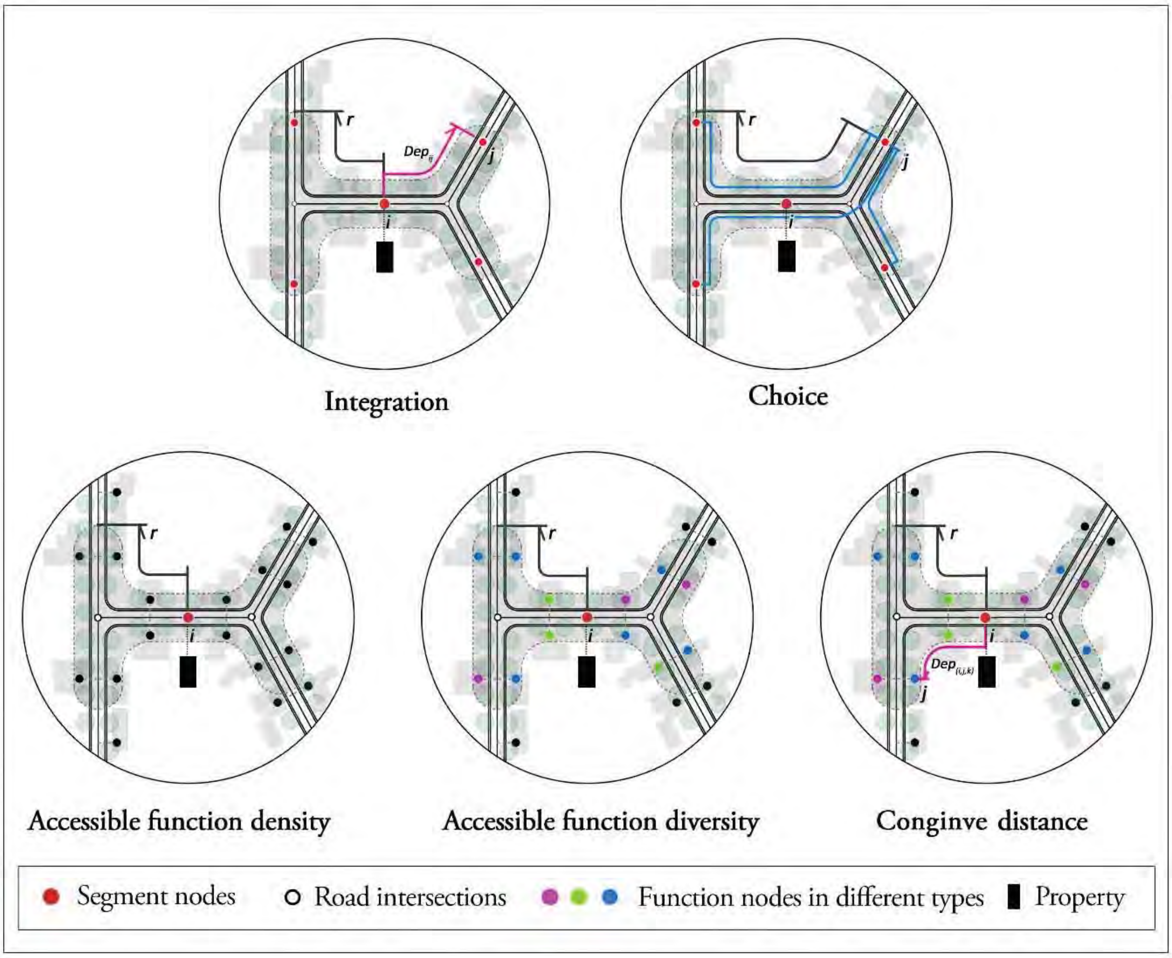


Figure 5-2

Graphic illustration of the space syntax centralities (angular integration and choice) and the function connectivity indices (accessible function density, accessible function diversity and angular distance) within the reachable area for a segment node i where the property was located. The reachable area is defined by a metric radius r. The angular distance from the segment node i to another segment node j is $Dep_{(i,j)}$*; and* $Dep_{(i,j,k)}$ *denotes to the angular distance between the segment node i and the function node j of specific land-use type k (see section 4.2 in Chapter 03)*

3.3 Network-based mixed-scale hedonic model

The purely local regression model may not always be the best approach to explore the relationship between response and explanatory variables. An appropriate solution to address this issue is to apply a regression model in which both local and global effects are properly defined and positioned. The mixed-scale hedonic model is such a model, in which the coefficients that are proven to be non-fluctuant across locations will be kept constant, thus improving prediction efficiency. Therefore, the purely local hedonic model can be extended into a mixed-scale hedonic model to reflect real spatial complexity in housing price modelling. A standard mixed-scale hedonic model can be formulated as follows:

$$y_i = \sum_{g=1}^{k_a} \beta_g \, x_{ig}(a) + \sum_{j=1}^{k_b} \beta_j \, (u_i \, , v_i) x_{ij}(b) + \varepsilon_i \quad \text{(5.1)}$$

where k_a and k_b denote the total number of global and local parameters of the variables, respectively; $x_{ig}(a)$ represent the global variables; $x_{ij}(b)$ represent the local variables; and β_g is the gth parameter associated with the global explanatory variables at all locations, while $\beta_g \ (u_i, v_i)$ us the coefficient for the jth local variable at the location i with a pair of coordinates (u_i, v_i).

In the mixed-scale hedonic model, the spatial relationship between the observed samples is defined through a spatial distance matrix that is relatively independent from the GWR model. Therefore, converting the conventional mixed-scale hedonic model to a network-based mixed-scale hedonic model can be achieved by using a pre-specified non- Euclidean distance matrix to replace the default Euclidean distance matrix. In this study, the network distance matrix is computed using the cumulative walking distance along the shortest path between any two residential locations in the sample. The adaptive Gaussian kernel function is applied to estimate the weight of the neighbourhood effects and the minimised cross-validation (CV) score is used to determine the optimised bandwidth for regression.

The adoptability of the mixed-scale hedonic model relies on a calibration procedure in which a multiple stepwise regression algorithm is used to test the geographical variability of each variable. This process is undertaken literally through the model comparisons between all pairs of the fitted GWR model, namely, the purely local GWR and a modified model in which only the kth coefficient is fixed globally. By comparing the difference of fit-goodness in regression models measured by the reduction of the Akaike Information Criterion (AIC), people can then determine which local factors should be regarded as global (Nakaya et al. 2005).

The network-based inverse distance weighting (IDW) interpolation method is adopted to produce the network-based coefficient maps for the detected local variables (Okabe et al. 2006). It is argued that urban street-based maps are closer to the reality of local impact distributions as urban public spaces are unevenly distributed as the carriers of urban daily life.

3.4 Network-constrained clustering analysis

The network constrained k-means clustering analysis is employed to delineate the structure of the emerging submarkets. In order to control the potential correlations between the local coefficient patterns, principal component analysis (PCA) is employed to generate the latent variables for maintaining the most useful information for the further clustering analysis. Spatial continuity of the submarkets is critical for delineating the localised submarket pattern where related policy can be allocated with explicit spatial boundaries. Some approaches to mitigate this issue have been used and discussed, including using factor analysis (Watkins 1999), taking into account the coordinates of spatial units in clustering analysis (Wu and Sharma 2012), adopting spanning trees to constrain the proximity of units (Assuncao et al. 2006), etc.. As the detected housing submarkets in this study are network-based, the spatially constrained rule for the community detection is considered as the node continuity for the network groups that contain the contiguous polyline features. That is, only edges/segments that share a node can be considered as the part of the same community in the cluster analysis. Lastly, this chapter uses the average out-of-sample prediction error (the root mean square error (RMSE)) and AIC of hedonic models for all the clusters to identify the optimised number of submarkets. The whole process for delineating street-based submarkets is data-driven from the bottom up without prior knowledge.

4 STUDY AREA, DATA AND MODEL SPECIFICATION

4.1 Study area

Due to the rapid urban expansion and the booming population, Shanghai, the economic capital in China, has been known for its accelerated increase of house price in the last decade. The coincidence between the spatio-functional change and the house price pattern has provided an ideal case for investigating their interdependency in this analysis. Instead of looking at the whole administrative area of current Shanghai City, this study pays more attention to the highly urbanised area, where the population density is much higher than other places. At such an intra-city level, the area were Central Shanghai is located covering the top 100 census areas in population density is selected as the study area (Figure 5-3).

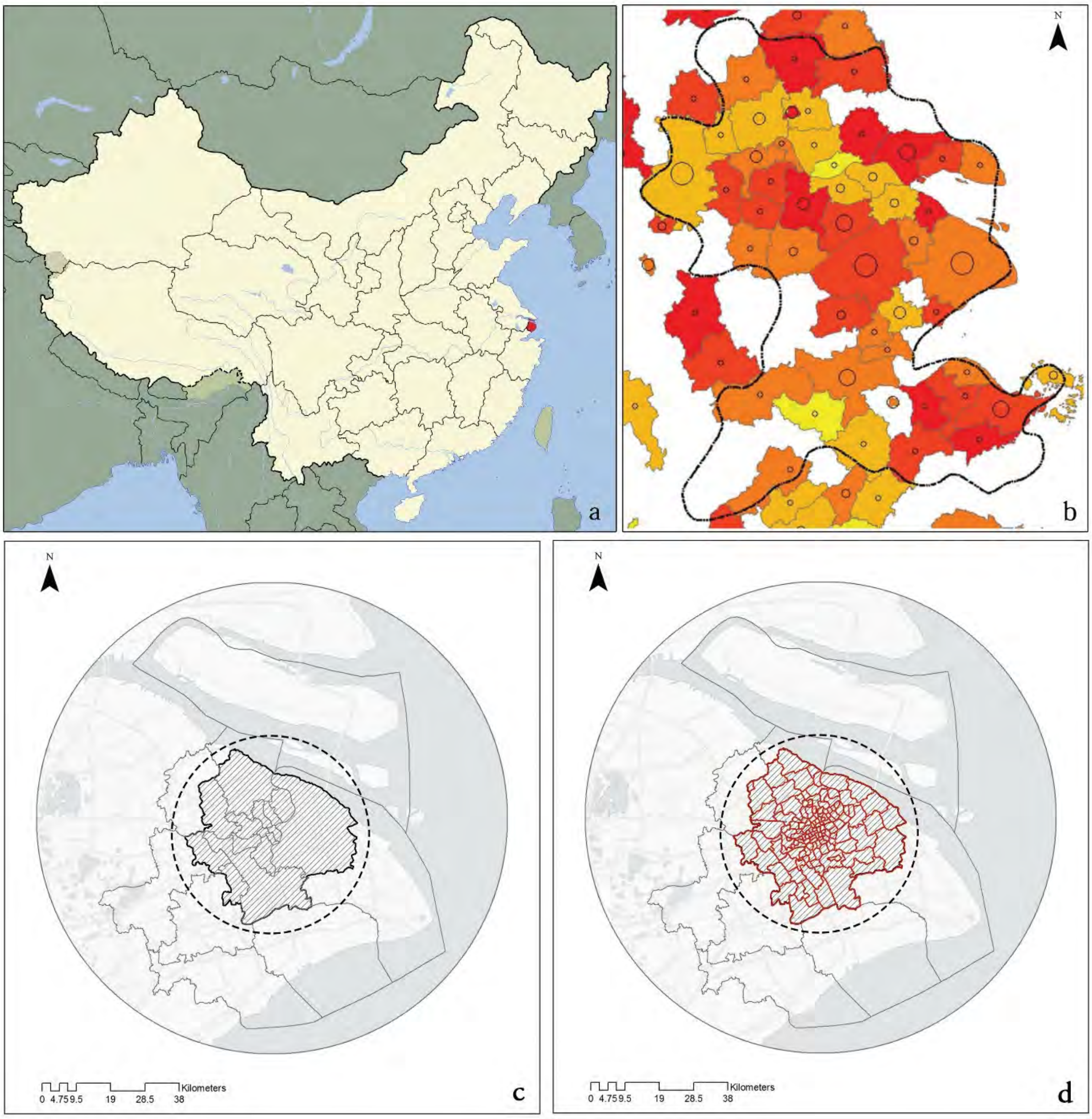


Figure 5-3

Location of Shanghai Metropolitan Area in China (a), in Yangtze River Delta (YRD)[10] *(b), Central Shanghai (c) and its associating census units (d) in the administrative boundary of SMA*

4.2 Asking house price data

The housing price dataset was collected from the websites[11] of local property sales agents using a data crawling approach; hence, this study uses asking price data rather than the actual

[10] In Figure 5-3b, the colour range indicates the variation in total urban area, and the label size refers to the growth rate (data source from (Long et al. 2016)).

[11] The asking house price data of Central Shanghai were mined from two of the largest online agents in China: Ganjiwang (www.ganji.com) and Fangtianxia (www.fang.com).

transaction records for housing sales. With the consideration of the unavailability of the official housing data in China, these datasets are alternatively reliable with sufficient details and a large coverage. Previous studies have also validated these records by comparing them to actual selling prices of houses and have asserted the reliability of these datasets (Chandler and Disney 2014). The obtained datasets cover the period from October 2014 to December 2014. The sample size is 8,262 with 3,818 unique locations after removing duplicate records. Figure 5-4 shows that the housing price distribution generally follows a steep trend of decay from the downtown area to the suburban areas. The housing price distribution indicates that the highest price cluster emerges at the city centre, and the decay trend is extremely significant because of the high value of the alpha parameter (α=5), indicating that the house price in Shanghai follows a relaxed scaling law that there are far more properties with lower price than the properties with higher price.

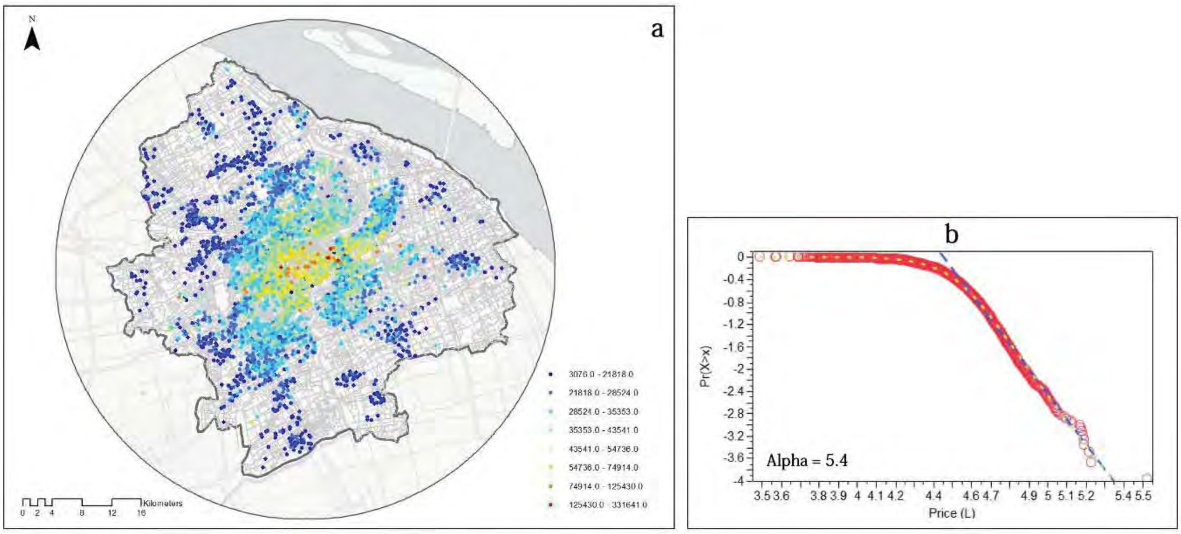


Figure 5-4

Housing price map of central area in Central Shanghai (a) and the complementary cumulative distribution function (CCDF) pattern of housing prices (b)

4.3 Road network, POIs and social media check-in data

The road network and the scored POIs data are collected from a navigation company and a social media service provider in China, respectively, as stated in previous chapters. The segmental map has 92,920 segments after being converted from an axial map, whereas the POI dataset consists of 191,035 point-based land-use venues with social media check-in records. The check-in POIs are reclassified into eleven main types of active land-use for reflecting the complementarity among land-uses (Hess et al. 2001). The defined active land-uses include retail, catering, hotel, office, recreation, public service, park, education, hospital, culture, and transportation. All land-uses are used to compute accessible function density, whereas only the defined active land-uses are employed to accessible function diversity. Residential properties were featured by the configurational centrality indices of their nearest street segments. A sample of the road network and POIs datasets are shown in Figure 5-5.

Figure 5-5

Roadwork and POIs in the study area: (a) road network overlapped with POIs in the study area; (b) road network and checked-in POIs in the sample area (the darkness of POIs denotes to the check-in scores in the social media)

4.4 Variable selection

The variable design in the various hedonic equations services for verifying different theoretical assumptions. In this study, from an urban design perspective, the overarching assumption is that the contextual design of the spatial network and land-use system influence the house valuation process across space. Although some other factors have been evidently studied to impact the housing price in Chinese cities, e.g., green space viewing (e.g., Jim and Chen 2007), distance to CBD (e.g., Mok et al. 1995), distance to tube stations (e.g., Wu et al. 2012), school accessibility (e.g., Wen et al. 2014), managing cost (e.g., Chen 1996), etc., these factors are not included as variables in the hedonic model used in this research because they either form the independent markets by their own factors or have been reflected by the network accessibility measures to a large extent (Law et al. 2013). Therefore, the present study use the asking house price per square metre as the dependent variable with two main types of explanatory variables including the structural variables and the location variables for describing the contextual characteristics of the housing market in the study area.

Table 5-1

Variables and their definitions used in the proposed hedonic house price model in Central Shanghai

Variables	Unit/coding	Type	Definitions	Expected sign
House price variable				
HSP ¶	RMB	Numeric	The asking price of the residential property	NA
House structural variables				
SIZE ¶	m^2	Numeric	The total unusable floor area	+
TYPE	0/1 (0=no; 1=yes)	Dummy	Existence of detached house	+
BEDR ¶	Count	Numeric	Quantity of bedrooms	+
LIVR ¶	Count	Numeric	Quantity of living rooms	+
BATR ¶	Count	Numeric	Quantity of bathrooms	+
AGE ¶	Count	Numeric	Age of the house in years	+
ORIT	0/1 (0=no; 1=yes)	Dummy	Existence of north-south exposure	+
FLOR ¶	Count	Numeric	The floor where the flat locates	+
FAR ¶	-	Numeric	The floor area ratio of the residential community	-
GR	%	Numeric	The site green intensity of the residential community	+
Location variables				
Space syntax centrality variables				
INT %radius% ¶	-	Numeric	The angular closeness of street network at a fixed radius	+
CHO %radius% ¶	Count	Numeric	The angular betweenness of street network at a fixed radius	-
Urban function connectivity variables				
DEN %radius% ¶	Count	Numeric	The accessible function density of accessible POIs at a fixed radius	+
DIV %radius%	%	Numeric	The accessible function diversity of accessible POIs at a fixed radius	+
DIS %radius% ¶	Count	Numeric	The mean angular step depth to the accessible POIs at a fixed radius	-

Note: '¶' indicates that a logarithmic transformation is applied. '+' denotes to the augmenting effect and '-' refers to the suppressing effect. %radius% includes 500m, 1,000m, 2,500m, 5,000m, and 10,000m

The structural variables, such as the useable floor size, typology, the number of bedrooms, the number of bathrooms, etc., are used as the inputs to the proposed model. They have been recorded in the obtained house price data. The location variables include the space syntax centrality measures and the function connectivity metrics at different levels. The detailed definitions of all variables included in this study and their expected effects on housing price are given in Table 5-1. The factors describing spatial comfort and convenience are expected to be positive variables. Consequently, floor area, the number of rooms, the degree of depreciation, property's direction (indicating the design-related energy efficiency (Kroll and Cray 2010)), floor level and the neighbour's greenness are the augmenting factors, only the floor area ratio – the indicator of development intensity – is expected to be a suppressing structural factor. In the family of space syntax centrality measures, the angular integration, capturing the spatial convenience by indexing the space relatedness, is supposed to be a positive factor, while the angular choice is expected to be negatively related to house price as it represents the possible places where traffic congestion might happen with potential noise and air pollution. Accessible function density and diversity are assumed to have positive impacts on house price growth, and the cognitive distance measure is considered as a suppressive factor since they illustrate the richness and the shallowness of the existence of daily amenities for the desired convenience in people's minds.

5 EMPIRICAL RESULTS

5.1 Preliminary results

In order to evaluate the necessity and suitability of using streets as the basic units and adopting simultaneously spatial and function centrality measures for house price analysis, this chapter preliminarily addresses two issues here the regression results are reported. The first issue is about the unevenness of the sample which caused traditional regional models unstable, and the second is regarding with the interactive relationship between the spatial and functional centrality measures, which reasons the variable selections of both these two type of centrality metrics as location factors. The first test is conducted by measuring the spatial correspondence between the density maps of the streets network, POIs and the house price samples to test if urban streets are a proper spatial unit for analysis in comparison with other commonly used approaches in house price studies. The second examination is accompanied by series of simple regression analyses focusing on the competition among centrality indices at the same radius to inform the necessity of adding these factors in the models for house price estimation. Meanwhile, the contribution of the social media check-ins scores to improving the basic regression models is also discussed to demonstrate the novelty of using the weighted function connectivity indices in the house price modelling procedures. These pilot studies produce theoretical and technical proposition for the proposed model specifications in which non-weighted space syntax centrality indices and the weighted urban function connectivity metrics are employed as a comprehensive description of the externality of the built forms for house price valuations.

5.1.1 Spatial correspondence of density maps

Before conducting the proposed regression analysis, this research first compares the contour maps regarding the density of homes' asking prices, POIs density, and street network density. In Figure 5-6, the developed areas of Shanghai are highlighted and generally identified on all the density maps. The figure illustrates that the areas where more homes are seeking the potential buyers would be more likely to maintain higher morphological densities. Although a general correlation is recognised among density maps, the detailed correspondence is inconsistent. This finding implies that housing price distribution forms a complex pattern across places. The spatial association between the density patterns of urban form, functions, and housing properties is also evidence that local estimates are not spatially continuous across all directions but differ between the places with different degrees of urbanisation. Also, it suggests that the widely adopted methods using arbitrary definitions of the urban space, such as grid cells, census units, or administrative areas with the assumption that urban landscape is homogeneous, hardly address the spatial variation of urban densities. Consequently, setting urban streets as the basic units for the housing price analysis is more appropriate than that used in traditional studies on house price patterns because of the association between urban form, function and the housing properties in urban reality.

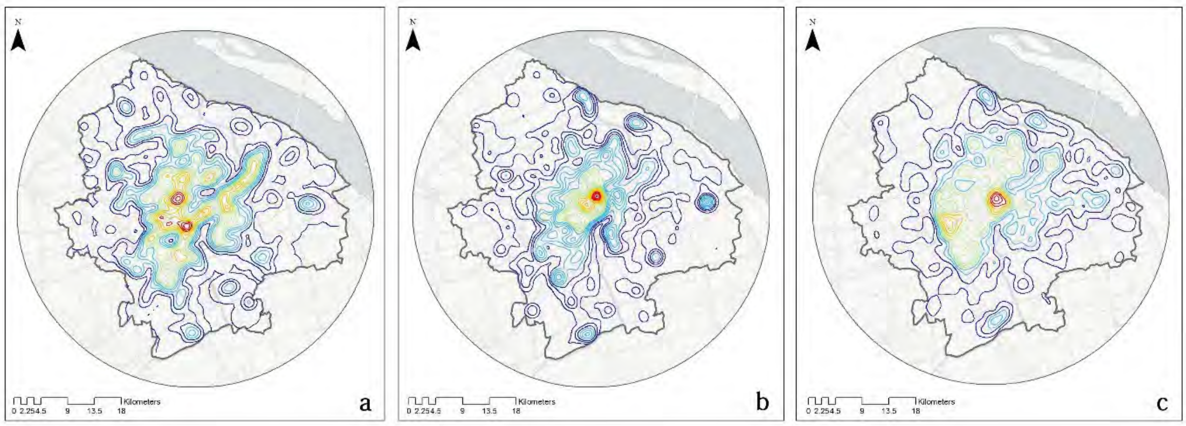


Figure 5-6

Comparison among contour maps in terms of properties density (a), POI density (b), and street network density (c) in Central Shanghai

5.1.2 Statistical performance of spatial and functional centrality variables

By using a comparison of the correlation coefficients in the ULR (Unary Linear Regression) and the t-values of variables in MLR (Multivariable Linear Regression) analysis, this study primarily explores the effectiveness of the indices weighted by the social media scores for modelling house prices. The validation process is conducted in two scenarios: in the first scenario, each metric for comparison is treated as a variable in the ULR model and then the adjusted correlation coefficients are mapped and compared to reveal the predictability of urban function connectivity indices at each radius by controlling space syntax centralities and the planar distance to Central Business District (CBD); in the second scenario, density, diversity, and delivery efficiency at a certain radius are entered in the MLR model with the standard network accessibility indices at the same radius as variables to compare their statistical significance neck to neck.

Four accessibility measures, the distance to CBD), angular integration, the weighted and non-weighted function connectivity with social media scores, are computed and compared as a single variable in ULR so that the role that social media check-in data play can be unfolded in the first scenario (Figure 5-7). Overall, the network measurements perform significantly better than the distance to CBD, which suggests that the definition of CBD is arbitrary and that the network centralities can summarise the importance of urban spaces more strongly. Moreover, the urban function connectivity weighted by the social media check-ins, correlates with asking house price more significantly than the one without check-in information and segmental integration, indicating the importance of check-in data for inferring the real functionality of point-based urban functions. The best correlation appears at 2,500 m for the weighted function connectivity with an adjusted R2 value of 0.426, while the peak of the correlation (0.362) between non-weighted composite accessibility and the house price is present at 5,000m. This demonstrates that the clustering pattern of human activity is more compact than the density of functions, whereby the economic externality of residential properties is captured at a relatively local scale by the function accessibility based on social media data. If the economic externality of urban space is considered as the key aspect of urban locality, a safe argument can be made is that incorporating the geo-tagged social media check-in data with the spatial network can improve the accuracy of modelling place locality and its socioeconomic significance across radii.

In the second test, all of the network centrality variables at different radii are statically significant (Figure 5-8). This suggests that the location centrality cannot be reflected by a single measurement; rather; it is impacted by the interaction between different types of network centrality variables, which further illustrates the interaction between spatial and functional elements in the built environment at various scales. The peak of the significance for the accessible density is found at the scales around 5,000 m. The closeness of the spatial network and the accessible density of urban functions experience a similar trend across all radii, in which function diversity is more significant at the local and semi-local scales from 500 m to 7,000 m and become less significant when the study scale increases. In contrast, the significance of the angular choice variable and delivery efficiency index grows from 7,000 m to 10,000 m, indicating the geometric or topological connection between land-uses and that route choice matters more significantly when functionality information is more aggregated at the macro scale.

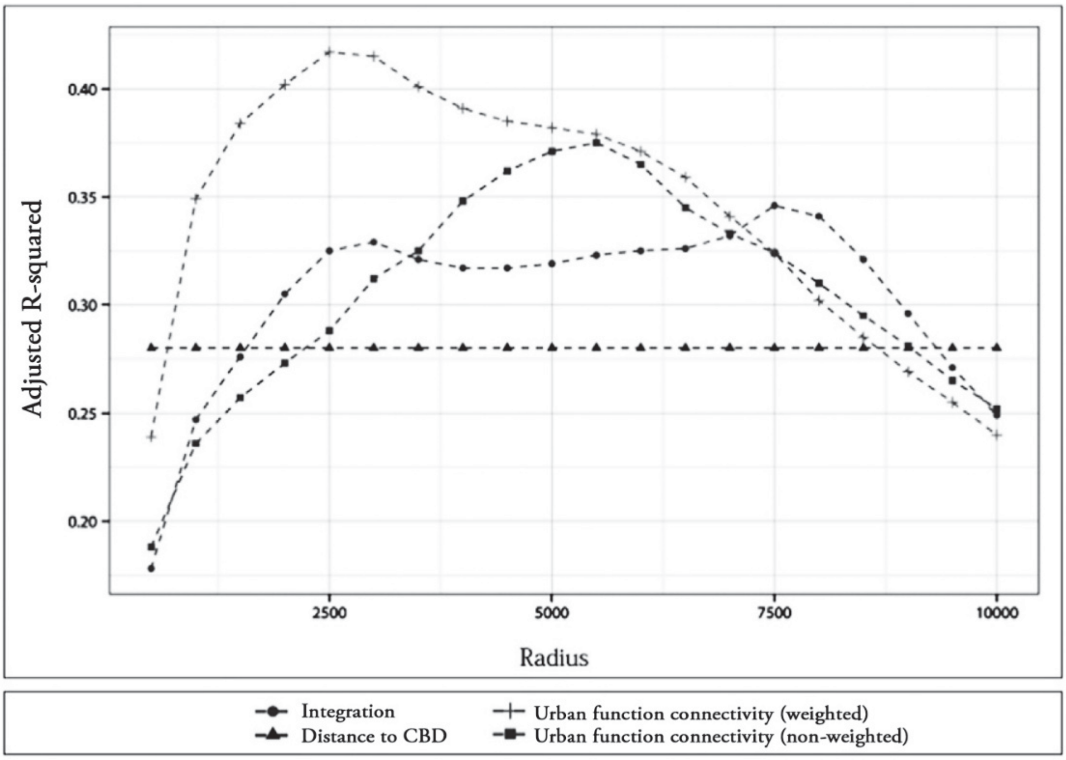


Figure 5-7

Comparison of adjusted R-squared values of urban function connectivity with and without social media weights, angular integration and distance to CBD in ULR models at different radii of modelling the variation of asking house price (the performance of angular choice is excluded in this analysis as its R-square values at all radii are below 0.1)

At the radii below 5,000 m, the significance of angular choice continuously falls and the t-value of the cognitive distance variable rises, indicating that cognitive distance from homes to daily amenities at the semi-local scale is essential for the location selection while the clustering of through-movement at the middle scale is less important for the potential buyers than that on the local level. The shifting relationship among these variables across scales indicates that the proposed individual index of urban function connectivity can provide additional valuable information on existing descriptions of the spatial network to infer the housing price variation. The interaction between spatial configuration and functional system characterises the locality of urban space in terms of modelling the physical and functional externality of housing properties.

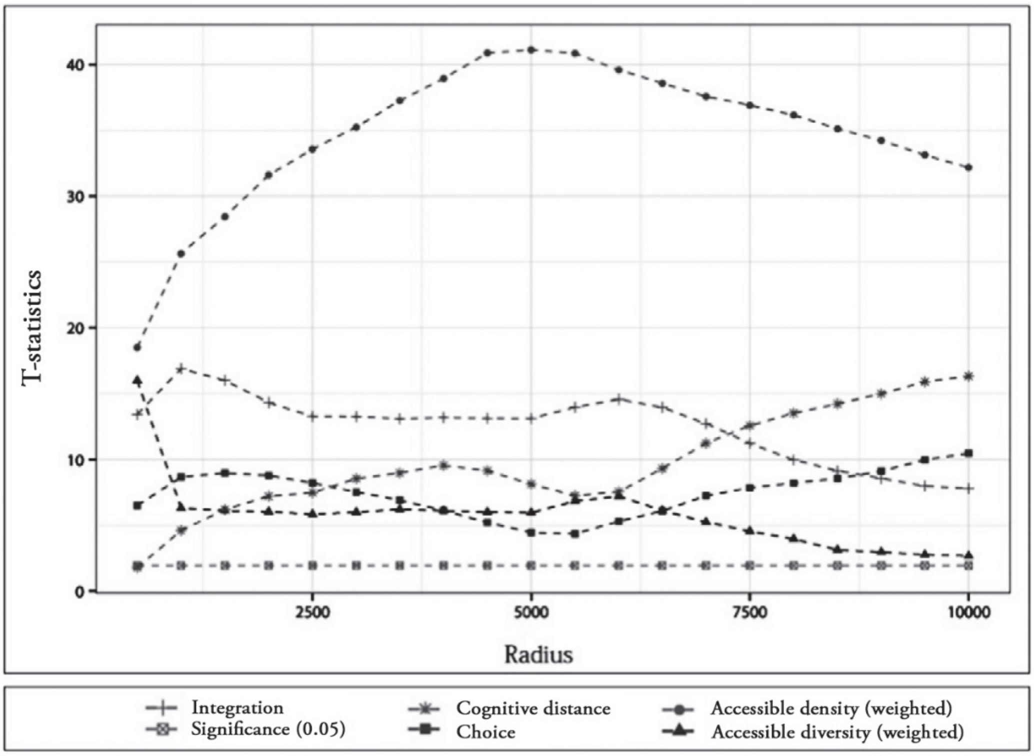


Figure 5-8

Comparison of t-values of selected location variables (weighted function density, weighted function diversity, cognitive distance to land-uses, angular integration, and angular choice) in multivariate regression models at different radii for describing the variation of asking house price

In short, these two tests demonstrate that the urban function connectivity indices weighted by the social media scores are more effective than other traditional centrality measures at various scales on the one hand; they, on the other hand, show that every principle dimension of the urban function connectivity is effective for estimating the house price variation even if the impacts of the built-form variables are taken into considered. These findings showcase that every measure of urban function connectivity and the space syntax centrality indices should be coordinated in the proposed hedonic models.

5.2 Regression results

The analysis of the residuals generated by the global hedonic model in Shanghai implies that a significant spatial autocorrelation has been empirically discovered (Moran's Index = 0.367, z-score= 25.128, $p<0.001$), which further suggests the potential spatial instability of the hedonic modelling of housing patterns and confirms the necessity of addressing the neighbourhood effects in the mixed-scale hedonic model.

The results of the stepwise ordinary least squares (OLS) analysis, the standard mixed-scale hedonic model with straight line distance and the network-based mixed-scale hedonic model are reported in Table 5-2. Minimising the AIC is applied as the criteria with a threshold of the generalised variance inflation factor for the variables (VIF<3) in the stepwise variable selection procedure for producing a parsimonious OLS model. Only 14 variables are captured as the critical factors accounting for the house price variation in the final model. House orientation, the number of living rooms, and the FAR are the insignificant factors in the global hedonic model. The function accessibility metrics at the global scale and the spatial accessibility indices at the local scales (except for the choice at 1,000m) are absent from the model, indicating that Shanghai is still in the process of urban growth in which the spatial adjustment of the global centre have not been sufficiently followed by the land-use transformation at the city-wide scale.

Table 5-2

Regression results for the house price variation in Central Shanghai

	OLS	Standard MHM	Street-based MHM		
Variable	Beta coefficients	Mean. estimate	Mean. estimate	Min. estimate	Max. estimate
Intercept		0.018	0.021	-2.164	2.658
BEDR	-0.094***	-0.095	-0.100	-1.629	0.864
BATR	0.158***	0.110	0.119	-0.481	1.502
SIZE	0.256***	0.201	0.218	-1.258	1.646
DIS500	0.014***	0.012	0.019	-0.512	0.467
DIV500	-0.049*	-0.036	-0.052	-1.983	0.877
DEN2500	0.299***	0.254	0.241	-1.824	2.787
CHO1000	-0.046***	-0.015	-0.011	-1.864	1.180
TYPE	-0.038***				
FLOR	0.042***				
AGE	-0.100***				
GR	0.085***				
DIS2500	0.166***				
INT10000	0.369***				
CHO10000	-0.071***				
AIC	7632.549	6752.267	6103.285		
AIC reduction from OLS	0	1280.282	1529.264		
Adjusted R^2	56.958%	69.216%	75.479%		

Significant: '***' – 0.001, '**' – 0.01, '*' – 0.05;
Note: VIFs (variance inflation factors) for all the variables are below 3 in the OLS model.

By comparing the performance of these particular forms of hedonic models, the effectiveness of employing the network-based mixed-scale hedonic model is illustrated. The explanatory power of street-based mixed-scale hedonic model is 18.521% higher than that of the global model. Moreover, the goodness-of-fit of the standard mixed-scale hedonic models is also improved when the Euclidean distance metric is replaced by the network distance. Therefore, it suggests that the network-based version of mixed-scale hedonic model is statistically favoured because the travelling distance can describe the neighbourhood effects more explicitly.

The optimised bandwidths for the standard mixed-scale hedonic model and the network-based version are 108 and 116 respectively. The reduction of AIC values demonstrates that 7 variables in the total 14 variables are better assumed to be local in both specified mixed-scale hedonic models. The stationary counterparts of mixed-scale hedonic model show the clearly identical performance across Central Shanghai. Specifically, the newly-built properties with higher green ratios are more likely to be preferred in Shanghai's housing market regardless of the houses' geographical locations. Simultaneously, for all the properties, space syntax integration has a significant impact on property values at the large scale (10,000m). Furthermore, the exhibited negative impact of the choice measure at the large scale (10,000m) and the positive effects of the cognitive distance to urban function at the semi-local scale (2,500m) are both statistically significant without spatial variation, which implies that the disamenity impacts of the over-crowded human movements and the traffic congestion on housing price patterns are spatially homogeneous. This result validates the results in other studies that integration and choice perform positively and negatively in the housing market (Law et al. 2012; Xiao et al. 2016; Shen and Karimi 2015) and further suggests an additional finding that the angular proximity to existing land-uses at the semi-local level would be not favoured for the whole housing market. The coexistence of the stationary and non-stationary coefficients demonstrates that the Shanghai's housing markets are economically interconnected based on the global factors on the one hand, but they are differentiated relying on the local factors on the other hand.

The model fit for the network-based mixed-scale hedonic model varies from 0.20 to 0.95 across the study space. Figure 5-9 illustrates the interpolated coefficient maps of 7 non-stationary variables which exhibit both negative and positive effects on housing price. The structural variables quantifying the indoor layouts including the floor area, the number of bedrooms and the number of bathrooms can generally distinguish the city centres from its context, and the violent fluctuation of the effects mainly occur in the city centre. In the city centre, floor size has the highest positive effect except for the Jinan district where bigger houses are not preferred for the potential buyers.

By holding the effect of floor size, the design of the indoor layouts represents different effects for various places. Additional bathrooms are favoured by the buyers with more budgets in Jinan and Huangpu districts where housing price are highest in Shanghai. This effect is reduced for other locations with the negative elasticity in Changning district and the area that is located in the west end of Pudong new district. Also, the significantly negative impacts of the number of bedrooms are recognised to be more pronounced in the Huangpu district, but its positive influence can be observed in other places. The spatial performance of local structural factors illustrates that the design features of residential properties are the key dimension reflecting the varying balance between the housing locational supply and associated demands in different urban areas.

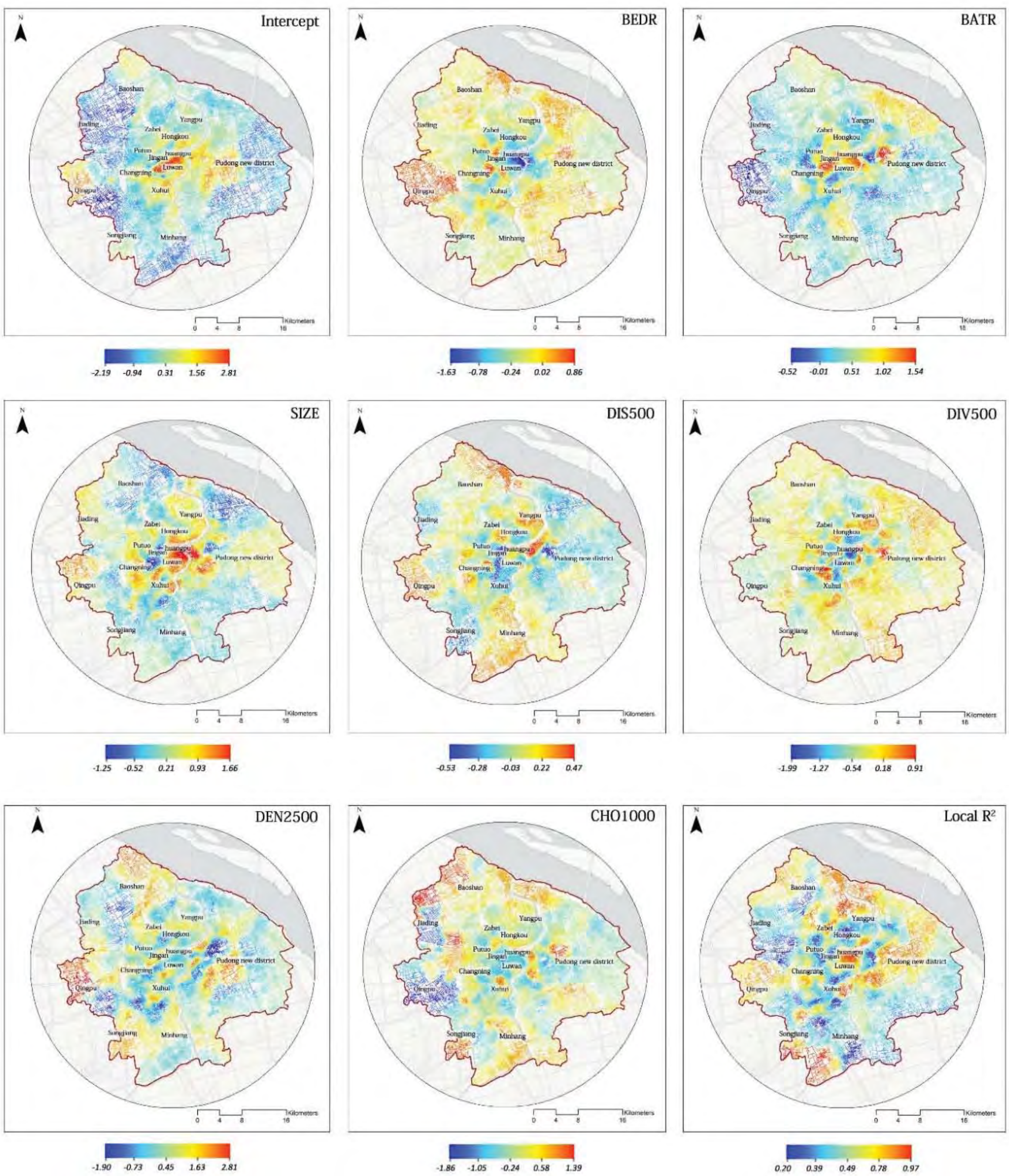


Figure 5-9

The interpolated coefficient maps of local variables in the street-based mixed-scale hedonic model

The effects of spatial design and land-use distributions at the local and semi-local radii vary across the street landscape, illustrating the externality of housing prices at different scales. Most areas are characterised by the positive influence of accessible urban diversity at 500m, angular choice at 1,000m and the urban density at 2,500m, although the rise and fall of the local coefficients are dramatically significant in the central districts.

By contrast, the angular distance to urban land-uses at the local scale is recognised as a negative factor for many areas, particularly for the relatively historically developed areas on the right bank of the Huangpu River. House buyers are more likely to pay more for a home located on a street that is configurationally proximal to the land-uses at the pedestrian level in Pudong new district where most of the properties are designed in the large gated communities with more cognitive distance from the main roads in nature.

5.3 Street-based submarket detection

In this section, the produced coefficients of local factors detected are utilised to generate the submarkets, a pattern to indicate the localities of the overall housing market identified by various modes of combination of spatial price impacts of local variables. The street-based results show a submarkets map with clear boundaries illustrating an aerial representation summarizing the multi-dimensional coefficient maps shown in Figure 5-9. More importantly, this submarket pattern is produced by a statistical technology to reduce regression residuals, whereby the overall performance of hedonic models of submarkets is normally better than the overall hedonic model for the study area. In so doing, this study generates the submarket structure that is statistically optimised with boundaries in streets, which illustrates the local modes where urban form and function influence house price differently.

The coefficients landscapes of 7 local variables are used in a network-constrained k-means clustering analysis to segment the entire study area into submarkets. Before that, this research employ PCA to determine the principle components (PCs) to reduce the potential multicollinearity among the coefficients of local variables thereby increasing the robustness of the clustering results. Six PCs are finally selected to present 84% of the information in the original dataset. As shown in Figure 5-10, the optimised number of clusters for the projected study area is 10 because of the minimised scores of the out-of-sample AIC and RMSE. The overall pattern of the street-based housing submarkets identified and represented in Figure 5-11.

Compared with the submarkets determined based on the assumed spatial units such as grid cells or census wards, the spatial partitions of submarkets in Central Shanghai in this study reflect the real spatial connectivity relationship without the scattered distributions. The rivers, hills, and large parks without dense road connections are considered as the natural boundaries of the detected submarkets. Only the submarket 8 spans across two areas that are connected by many bridges, which can be validated by the administrative boundaries that cover these two areas as well, suggesting that spatial policy might also matter in this submarket. However, the non-correspondence between census districts and the generated street-based submarkets in other regions implies that submarkets are formed in a sophisticated manner and are difficult to be captured if the predefined spatial units are used.

The partitioned submarkets patterns showcase noteworthy differences concerning the compositions of the average local estimates (Figure5-12). Table 5-3 summarises the final annotation of each submarket by combining the observed place characteristics and the significant estimates of local variables. The adjusted R-square value varies from 0.54 to 0.71. The Chow test confirms that the 10 submarkets based on detected coefficients of the stationary variables are statistically differentiable at 1% confidence level (Table 5-4). In comparison with other transitional segmented models in terms of the weighted standard error (WSE) reduction, our alternative specification improves 17.15% the performance of the city-wide model, while the segmented model based on administrate boundary at the district level reduces 10.88% of the baselined WSE value (Table 5-5). Moreover, the building-type and orientation submarkets do not pass the significance threshold of 5%. This finding is supportive of the evidence that the spatially varying impacts of the design of the built environment and the property provide the more essential information for segmenting housing submarkets than the existing administrative districts, although the spatial allocation of local policy in different districts is still influential.

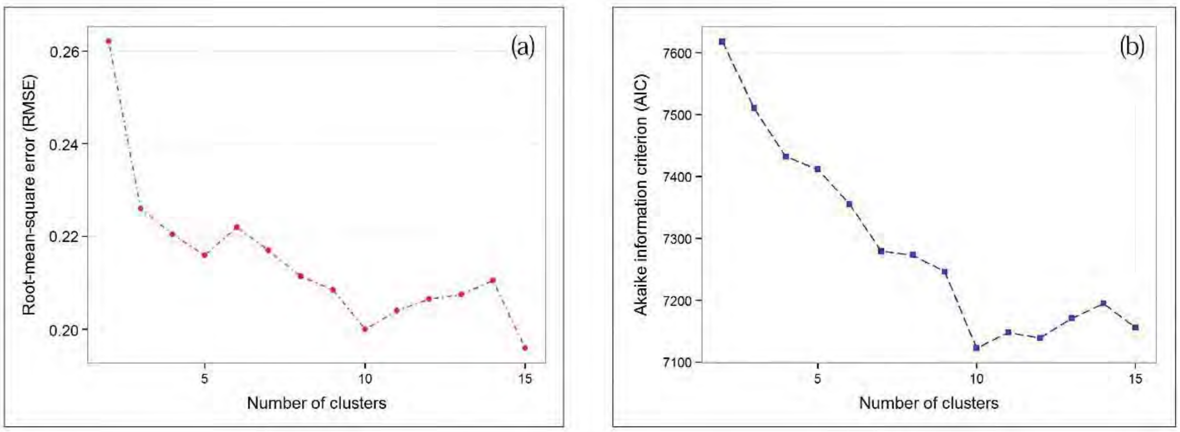


Figure 5-10

Calibration of the optimised number of clusters based on the AIC and RMSE values in the test models

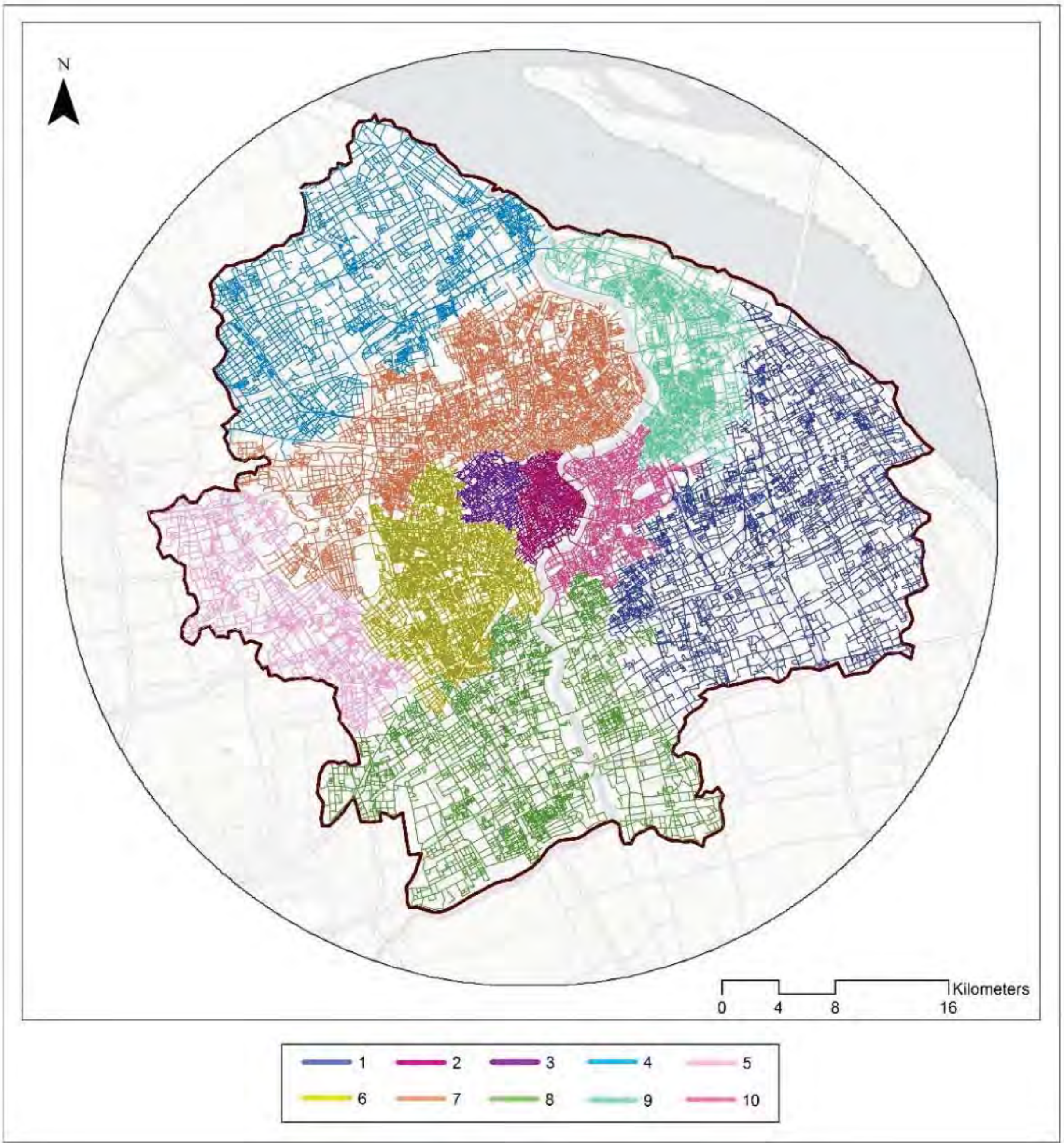


Figure 5-11

Detected submarkets in Central Shanghai

Apart from the overall pattern for describing the housing market, the emerging individual submarket can be identified with the influence features - the estimates of the significant local factors. By using average housing price of 30,000 RMB per square metre as the threshold, this analysis preliminarily groups the submarkets to two main categories: the developed submarkets and the developing submarkets. The spatial and functional configurations in developed submarkets have a longer history and are denser than that in the developing submarkets, which suggests that the defined submarkets patterns based on the coefficients in the network-based mixed-scale hedonic model can capture the spatial characteristic of the built environment.

The estimates of local structural factors significantly contribute to distinguishing the submarkets. The impact variations of Floor area size is more critical for developed city areas with larger coefficients, illustrating the status quo in contemporary large Chinese cities where the house floor area are strongly demanded due to the shortage of the housing supply and the rapid growth of urban population. The most significantly positive effect of floor size is found in the submarket 2 where the Chinese old town and the oldest colonial areas are located. Furthermore, the number of bathrooms is recognised as positively related to housing price in many submarkets (2, 3, 6, 9, and 10), with the exception of submarket 5 where this effect turn to be negative and the additional number of bed rooms are more favoured.

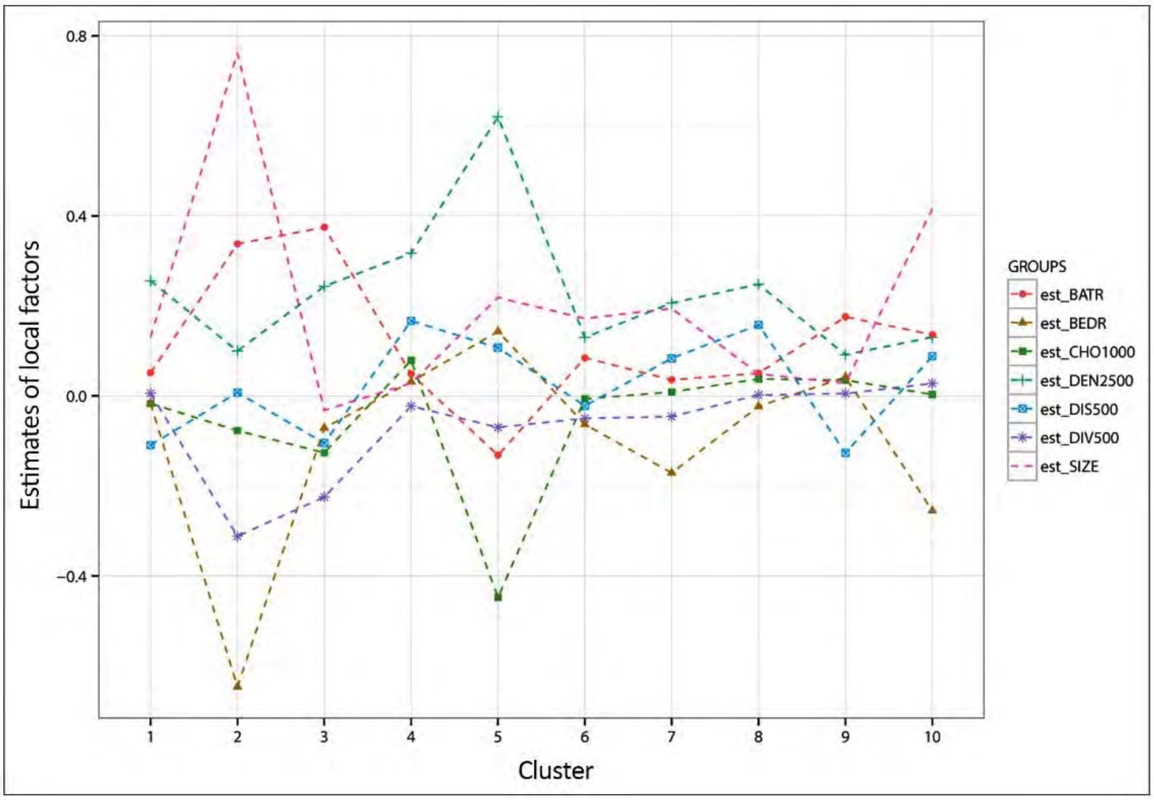


Figure 5-12

The estimates of local factors in every submarket based on the test data

By holding the effects of structural variables, the design of the built environment is also recognised to be crucial elements for differentiating the submarkets. Accessible function density at the semi-local scale (2,500m) is found to be the positive factor for all the submarkets, but its importance is inconsistent between submarkets. For the submarkets that are highly urbanised, the effects of semi-local perceived function agglomeration are relatively smaller; they turn to be more significant when the submarkets in the developing regions are the new focuses. This implies that the demand strength of urban services is dramatically increased for the urbanising areas due to the urban growth and regeneration. The accessible urban diversity at the pedestrian scale (500m) is statistically significant with a negative sign in the submarkets (2 and 3) within the historic inner city. This can be explained by the fact that the urban amenities have been already pronouncedly clustered and mixed and the extra mixture of urban functions might lead to long-time noise thereby losing the locational enjoyment. Table 5-3 also shows a significant negative relationship between space syntax choice and housing values at the radius of 500m in the submarkets 2, 3 and 5, indicating that local traffic in these submarkets will depress the house value.

Table 5-3

Annotation of the emerging submarkets by using the significant local estimates

Observed characteristics	Submarkets	Coefficients of the significant local factors		Average house price (RMB per square metre)	Adj. R^2
		Positive factors ($p < 0.05$)	Negative factors ($p < 0.05$)		
Central city centre (West bank)	2	SIZE, BATR, DEN2500	BEDR, DIV500, CHO1000	50,736	0.71
Developed city centre (West bank)	3	BATR, DEN2500	DIV500, CHO1000	47,909	0.54
Modern business region (East bank)	10	SIZE, BATR, DEN2500	BEDR	39,903	0.72
Developed sub-centre region (West bank)	6	SIZE, DEN2500, BATR		36,783	0.69
Developed sub-centre region (West bank)	7	DEN2500, SIZE, DIS500		31,095	0.63
Developing region (East bank)	9	BATR, DEN2500	DIS500	29,995	0.59
Developing region (East bank)	1	DEN2500, SIZE	DIS500	25,934	0.63
Developing region (East & west bank)	8	DEN2500, DIS500		25,340	0.64
Developing region (West bank)	5	DEN2500, SIZE, BEDR, DIS500	CHO1000, BATR	22,865	0.63
Developing region (West bank)	4	DEN2500, DIS500		19,824	0.65

Another important element for grouping submarkets is the significant influences exerted by the angular distance to local land-use at the radius 500m. Being similar to the performance of other detected local factors, the sign and the significance of its impacts vary differently between the submarkets. By grouping the submarkets according to their relative locations on the Huangpu River that passes through the study area in the middle, it is found that the developing submarkets on the west bank are the regions with the positive impacts whereas this tendency is reversed in the submarkets on the east bank. This result might be related to the existing features of the spatial layout and the land-use system in these two regions, because the areas that was described as the developing submarkets on the west bank are relatively self-organised and more walkable with less angular depth steps to the local functions (2.9 steps in average), while developing submarkets on the east bank are newly planned after 1980s with the logic of modern urban design and more car-dependent with more angular depth to the locally neighbouring attractions (4.6 steps in average).

Table 5-4

Chow test for the test dataset

Submarket	Obs.	Submarket								
		1	2	3	4	5	6	7	8	9
1	317									
2	233	11.755¶								
3	234	18.843¶	5.972¶							
4	361	23.254¶	22.932¶	25.078¶						
5	130	24.641¶	11.845¶	11.361¶	4.883¶					
6	902	18.126¶	12.587¶	8.549¶	32.824¶	17.037¶				
7	819	14.385¶	10.849¶	8.553¶	22.601¶	14.436¶	8.056¶			
8	488	6.961¶	10.455¶	14.246¶	15.549¶	14.809¶	9.797¶	9.185¶		
9	302	6.879¶	9.816¶	14.603¶	32.245¶	32.221¶	28.626¶	26.629¶	16.669¶	
10	345	9.791¶	2.347¶	8.365¶	26.78¶	18.60¶	43.84¶	38.00¶	16.62¶	5.039¶

Note: ¶ denotes to the significance at 1% level.

Table 5-5

Weighted standard error analysis of the submarket segmentation based on the test data

Definitions of submarkets	Standard error	Percentage of reduction
City-wide model	0.239	
Definition with house orientation	0.238	0.42%
Definition with house type	0.234	2.09%
Definition with administrative districts	0.213	10.88%
Definition with local impacts of urban configuration and the structural features	0.198	17.15%

5.4 Related implication

In the empirical study of Central Shanghai, it is standard for all the places that the properties located on the streets with higher angular closeness, smaller values of angular betweenness at the large scale and longer angular distance to the nearby land-uses at the meso scale are bided higher by the potential purchasers. For the planning and design practice, this finding reveals that the city centres with higher street segment density and connectivity are the areas where the property values are higher, whereas the traffic corridors and the global high streets are both the negative factors decreasing house value. The performance of the detected global location variables has been confirmed in other empirical studies, which implies that these regular patterns can benefit the urban planners and designers in practice for estimating the fine-resolution price effects of spatial interventions without the prior knowledge of the urban context. There is also a consensus on the more valued properties in Shanghai in terms of their structural design. For the housing market as a whole, the more newly built flats on the higher floors with better green coverage add more premiums to property value. This observed relation, however, might be different across cities since the preference on the properties' structural design is related to the socioeconomic conditions. Identifying the price impacts of these variables for a particular city can still contribute to making proper planning and design decisions on the design of housing supply.

Given the two modes of equilibriums observed in the developing submarkets on the two banks of Huangpu River in terms of the existing distinguished geometric properties of the local land-use network and the reversed signs of the associating price effects, this thesis find that the pedestrian-oriented neighbours on the west bank with less angular depth steps to the local functions shape the demand for the spatial privacy, whereas the gated communities with more angular step depths to local amenities on the east forester the desire of spatial convenience to daily destinations. Within the process of urban growth, the clustering of land-use will reduce the cognitive cost to the urban attractions naturally thereby making the housing price in the large-scale gated submarkets grow faster as the demand on spatial convenience there will be met. By contrast, the demand for spatial privacy in the pedestrian-friendly submarkets will be increasingly strong if the walkability to local amenities in this area has not been changed via the spatial interventions. These findings yield a suggestive evidence that continuously developing the pedestrian-friendly neighbourhoods and securing the publicity of urban space in the walkable areas could be an alternative way to against the excessive growth of the housing price in Chinese cities. This is can also be confirmed by the detected globally positive effect of the angular distance to land-uses at the mesoscale for all the submarkets (see Table 5-2). However, it is noteworthy that reducing the cognitive cost of reaching local functions in the submarkets where the existing large-scale gated communities clustered might increase the risk of speeding up the house price growth till the new equilibrium with the desire for spatial privacy is formed. Besides, the impacts of the structural variables should also be taken into account in the action plan for stabilising house market. For example, fixing the floor size ceilings of the newly-built residential properties would be a useful measure to decelerate the growth of the house price in the city centre.

For framing a comprehensive guidance for designing the cities with stable housing economy, the present study proposes a comprehensive model to achieve an understanding of the role of urban configurations in changing home prices (Figure 5-13). The interaction between the spatial network and the land-use system provides various types of co-presence among various network accessibilities at different levels. The overall effects will be perceived by homebuyers, developers, and designers, who will select a suitable home or design and build ideal homes for an improved price in the market. Housing price patterns, including spatial heterogeneity and the related segmental submarkets, are simultaneously influenced by these complex urban interactions. The entire process could be triggered by the plans of the urban configuration and the design of the property plans.

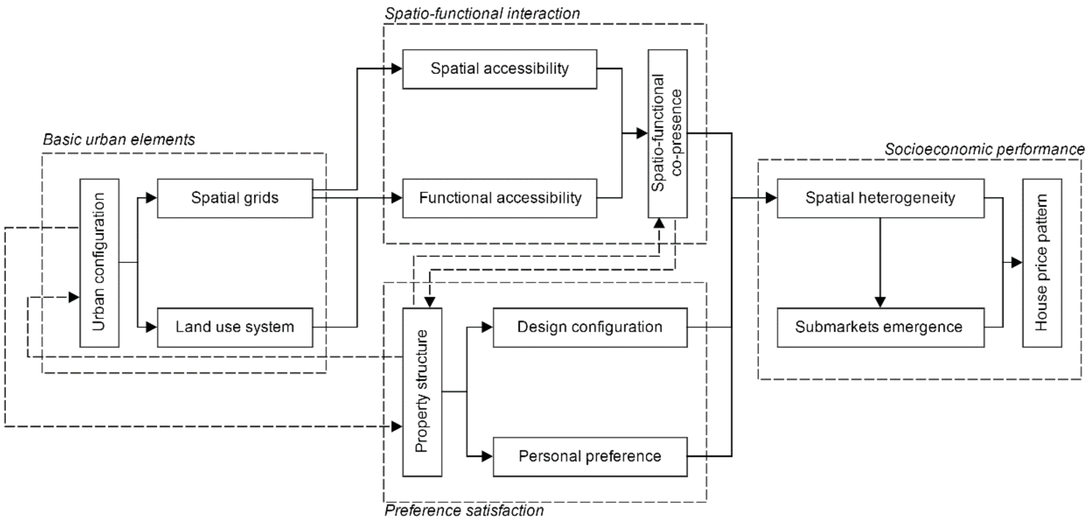


Figure 5-13

The chart describing the process that how the spatio-functional interaction influence the housing price pattern with property's structural design

6 SUMMARY AND DISCUSSION

Quantifying the relationship between built environment and the spatial variation of the housing price is increasingly important for urban design and the related strategy distribution. This demand is more pronounced for the cities within the process of rapid urban growth and regeneration. With the aim to advance the current knowledge of the spatial heterogeneity of housing price and the submarket regionalisation captured from the urban design perspective, this study used the network-based mixed-scale hedonic model where the dimensions of the built environment layouts are measured by the street network centralities and the function connectivity measures instead of the distance features of some specific attractions to reflect the perceived features of the spatial design and land-use allocations. The varied influences of the spatio-functional interaction at different levels are then adopted to identify the submarket distribution with the estimates of the local structural variables. The core aim of this chapter is to verify the effectiveness of the introduced spatial and functional centrality measures for describing house price distributions and to explore their spatial varying price effects for enriching existing knowledge of urban economy processes in housing markets.

The primary analysis on the density co-presence between the urban grid, POIs and house price sample indicates that novelty of using street segments as the units for house price analysis and the submarket mapping. The statistical significance of individual centrality measures at all radii demonstrates the complementary relationship between spatial and functional centralities, which is the evidence for the model specification in this chapter. The empirical analysis of the housing price pattern in Central Shanghai shows that the utilisation of the metric distance and the recognition of the local variables can improve the predictability of the spatial statistic model. The scales of the street accessibility measures are related to the discrimination between the global and local variables in the network-based mixed-scale hedonic model. The global location variables are basically at the larger scales, and the local location variables are at the smaller scales, which suggests that the local built-environment features are essential determinants of the observed heterogeneity of house price patterns. In addition to the known effects of the global angular closeness and betweenness indices in other studies, the geometric properties of land-use system are also crucial for describing house price patterns and generating the submarket segmentation. The obtained submarkets based on the local coefficients maintain spatially contiguous boundaries that are more realistic and the performance of the intra-submarket global hedonic models are also enhanced. For instance, the angular distance to the active urban functions at the radius 2,500m is discovered as a global force impacting positively the overall pattern of the house price. The cognitive distance to the pedestrianaccessible functions, on the other hand, is a vital factor for submarket segmentation with the local structural variables and other location variables, such as accessible function density at the mesoscale and the local urban diversity.

The interplay between the price effects of the spatial and functional centrality measures in various submarkets informs design-related policy implications. By comparing the detected equilibriums in the developing submarkets, this study suggests that designing pedestrian-oriented neighbourhoods in the walkable areas could be helpful for stabilising the house price growth in the process of rapid urban expansion and renewal. The study has shown that our delineation of submarket performs better in prediction accuracy than the traditional submarket specifications. The aforementioned results support the argument that urban form and function largely determines the heterogeneity of house price patterns and the formation of submarket structures. It is also noted that determining relationships are not constant across space; rather, they fluctuate from place to place with the influence of housing design factors.

CHAPTER 06

SPATIO-FUNCTIONAL INTERACTION AND THE PATTERNS OF CO-PRESENCE

1 INTRODUCTION

A city is a complex system for interaction. In geography, the link between the theory of spatial form and other temporal processes has been explored theoretically and empirically (Harvey 1969). The geographical landscape shapes the spatial generator for the (re)production of the temporal process from place to place. Such an idea has formed the theoretical foundation for configurational studies focusing on the interrelation between the spatial configuration and movement. The concept of 'co-presence' in space syntax theory has been argued to be a by-product of the organisation of the built environment that often manifests itself in people's 'movement' due to the fact that connections between spaces create the possibility of mutual visibility between people (Hiller and Hanson 1989). By combining the concept of 'co-presence' in space syntax and social sciences, Marcus (2010) provided the possibility of linking the so-called spatial capital with social capital. Some studies have been conducted to prove the interdependency between them, but the relationship between spatial configuration and spatio-temporal encounter patterns has rarely been investigated explicitly in empirical studies at a city-wide scale.

The main scope of this chapter is to further test the introduced methodology in previous chapters and to establish a better understanding of urban spatial and functional centrality structures and their social impacts. Addressing this, the present study explores empirically the extent to which the spatial and functional built environments influence the physical face-to-face interaction between different groups of people - the social media users, to be more precisely, in the contemporary digitalised society. Two types of people are the focus of this study: the *local random users* who frequently move in a space, and the *remote visitors* who only visit the space irregularly. The spatiotemporal co-presence between these two groups is quantified as an interplay between various types of social capital, including social difference, spatial distance (metric and geometric distance) and time distance. The relevant results are mapped in street segments to illustrate fine-resolution distributions of the co-presence intensity. This study also groups the streets according to the differentiation among the observed co-presence modes along streets. Thus, the spatiotemporal changes of the co-presence intensity and their modes shed the insightful lights on the social interaction patterns in Central Shanghai's public spaces.

The specific focus of this chapter is then shifted to unfolding the configurational logic of the spatiotemporally changing encounter distributions. Three sub-questions are addressed: 1) do the spatial and functional centrality structures influence the physical co-presence patterns simultaneously? 2) are these relationships temporally uniform? 3) to what extent are the modes of physical co-presence explained by the spatial and functional built-form? For answering these questions, the streets are indexed by quantifying their spatial and function contexts to reflect the urban spatial and functional centrality structures. A multivariate regression and a multinomial logistic regression are used in this research to explore the explanatory power of the spatial and functional centrality variables for the spatiotemporal co-presence intensities and the detected typology of co-presence in streets, respectively. The remainder of this research is structured as follows. Section 2 introduces the background of this research, followed by the descriptions of the methodology as well as the data. Section 5 documents the empirical results in detail. Finally, Section 6 concludes with a summary and a discussion of further steps.

2 BACKGROUND

A society is a system of social interaction, and co-presence is one of the essential conditions for the occurrence of social interaction (Giddens 1984). Its definitions are ambiguous owing to the variation of theories, methodologies, and spatial scales for analysis. It can also be defined as a sense of co-existence between people in their virtual communications via various sharing behaviours, such as photo sharing or social media interaction (Ito and Okabe 2005). In social geography, co-presence can be adequately understood from its antithesis - segregation - which describes the passive separation of certain group(s) of people from other population (Massey and Denton 1993). Owing to its natural linkage to the demographic characteristics of the population, segregation is conventionally explored in the resolution of areas/districts that are artificially defined for spatial statistics, e.g., census units or administrative boundaries (e.g., Ernest Burgess 1928; Wong 1993). The spatial dimension of segregation at the intra-urban scale has been argued as also being critical (O'Sullivan and Wong 2007) and many methods have been developed to model the potential spatial interaction across the activity space, including k-nearest neighbouring aggregation (Osth et al. 2014), kernel density estimation (O'Sullivan and Wong 2007), activity-based modelling (Wong and Shaw 2011), etc. Although the spatial distance between analysis units has been considered in these models, the effects of urban design have rarely been involved in relevant studies.

Physical co-presence, face-to-face encounters, in particular, reflects urban vitality in public space and its publicness (Mitchell 1995). In configurational studies, co-presence is a fundamental concept binding spatial connectivity to urban movement (Peponis et al. 1997), which has been verified by experiments with an agent-based simulation (Penn and Turner 2001). Recently, Marcus (2007; 2010) has reconceptualised spatial centrality as 'spatial capital' and emphasised its quintessence for understanding social performativity. Furthermore, geographical accessibility metrics for different sections of the population and job opportunities through spatial networks were adopted to estimate co-presence patterns (Legeby 2011; 2013; Marcus and Legeby 2012). These efforts have suggested that structural centralities are capable of affecting the co-presence patterns. Nevertheless, these studies were basically on the basis of static spatial data without proper consideration of the dynamics of people's mobility patterns. Consequently, the interdependency between the spatial configuration and spatiotemporal encounters has rarely been investigated explicitly in these empirical cases.

Co-presence is also a critical dimension in mobility patterns indicating that social interaction is associated with people's travel choices. This idea has been widely accepted in transport geography with a focus on the collective results of many individual trips (Kenyon et al. 2002; Gonzalez et al. 2008). Related studies have highlighted the importance of the temporal processes of physical encounters. Some attempts based on human contact networks have been conducted (e.g., Stehlé et al. 2011; Isella et al. 2011). With the help of Bluetooth sensors, Kostakos et al. (2010) have clarified the spatiotemporal patterns of mobility, presence and encounters. Sun et al. (2013) evaluate repeated face-to-face encounters using a time-resolved social encounter network on public buses. However, the datasets adopted in these studies are either embedded in limited samples within small areas or are constrained to one type of transport, thereby failing to produce fine-scaled physical co-presence patterns covering the large landscape.

3 THE METHOD

3.1 The framework

The framework of this study is shown in Figure 6-1. There are four modules, including (a) data processing, (b) measuring co-presence patterns, (c) measuring centralities and (d) exploring the configurational logic of co-presence. In the first module, the required datasets are mined and then processed to abstract the most reliable information for the initial data gathered from the open data resources. For instance, place-based check-in records (check-in points-of-interest (POIs)) are spatially assigned to their nearest street segments, and individual check-in records are aggregated to trips and filtered by removing the invalid information to render them as an exact description of the mobility patterns (Liu et al. 2014). In the next module, trajectory patterns obtained from the social media data are applied to compute presence and co-presence patterns across time using the street network data. Simultaneously, social groups of people are identified according to their travelling behaviours that are recorded in mobility patterns. The physical presence of people based on metric distance and angular distance are combined to take into account the influence of public space on patterns of face-to-face encounters. The presence of people in different groups across time are joined to capture the spatiotemporal patterns of their co-presence. In the meantime, presence densities and the associated angular costs are used to group urban streets to reflect the co-presence modes in streets. In module (c), the street network and placed-based check-in data are employed in the calculations of spatial and functional centrality indices (as introduced in Chapter 03). In the last step, computed co-presence patterns and centrality patterns in streets are used as the dependent variables and the independent factors in regression models, respectively. Two regression models are adopted in this study: a multivariate linear regression model to capture the impact of the organisation of form and functions on the hourly varying co-presence intensity patterns and a multinomial logistic regression to identify the contributions of the design of the built environment to the formation of the emerging co-presence modes in streets. By doing so, this study investigates the configurational logic of the temporal significance of physical co-presence and its inherent differentiation from street to street.

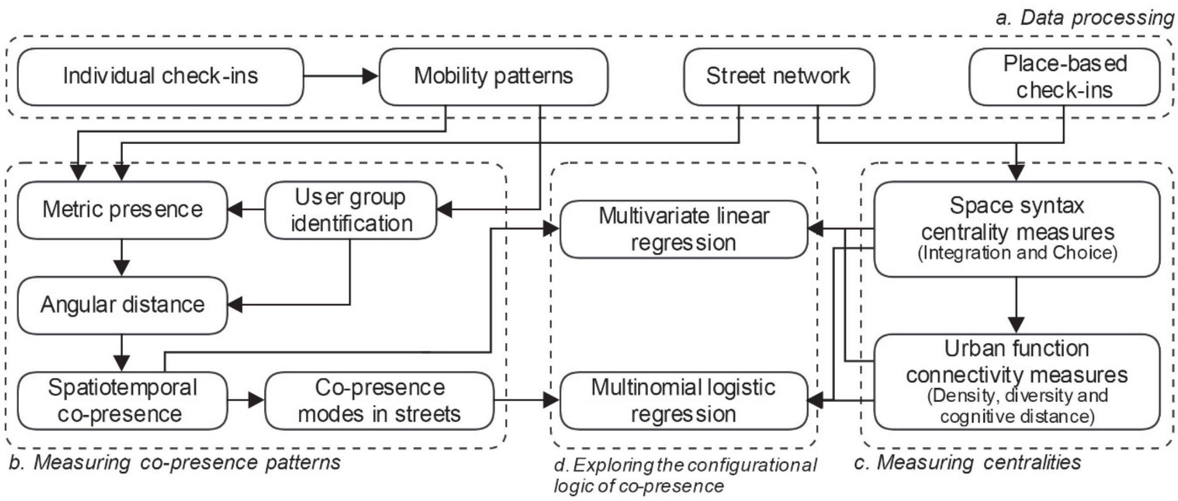


Figure 6-1

The research framework

3.2 Measuring physical co-presence in streets

3.2.1 The People-Space-Time (PST) model

Co-presence is a multidimensional concept reflecting the interplay among different types of social capital. This study proposes an integrated model in which these interactions between various forms of social capital can be comprehensively addressed. These interactions can be summarised as the social capital of people, space and time, which have been acknowledged to be essential for the creation of social ties (Crandall et al. 2010). Social capital for people denotes to social difference between people, which can be captured by their demographic features, such as social classes, educational backgrounds, etc. Social difference denotes the fundamental cost of human interaction because it captures the internal variance between people. Social capital in space and social capital in time, on the other hand, are the external conditions for people's interaction. The social capital in space, or 'spatial capital' represents the spatial distance that people need to overcome in their trips to see one another. There are two types of spatial capital: metric distance, which reflects the energy cost for people to travel and encounter; the other is angular distance, which captures the cognitive efforts that directly impact the mutual visibility between people. The more two individuals are metrically and geometrically proximal to one another, the more likely they will see one another in the space. Additionally, time constraints are also very important since people could hardly to encounter one another if they are present at the same place at different times.

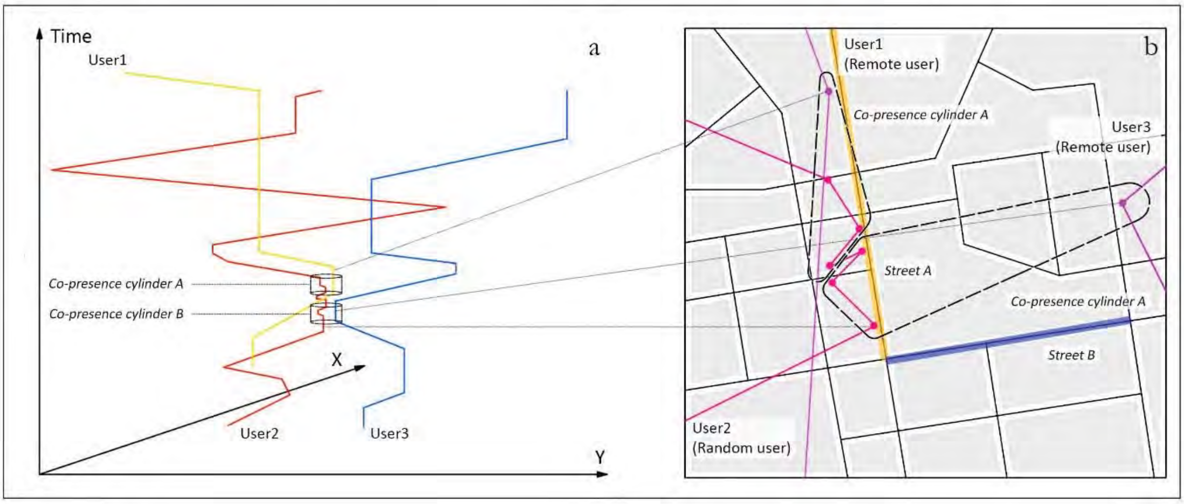


Figure 6-2

Interactions between people in the People-Space-Time (PST) model. (a) The 3D spatiotemporal scatter diagram plotting the movement patterns of citizens as location coordinates (x, y) against time, (b) The planar representation of the 3D spatiotemporal scatter diagram

In Figure 6-2a, the hypothesised moving trajectories of three users are mapped, and two co-presence cylinders are used to capture the co-presence between them occurring at different time periods. Cylinders A and B capture the co-presence between users 1 and 2 and between users 1 and 3 within the same area, respectively. In a planar representation of the spatiotemporal cube with the street network, it is recognised that the average cognitive distance between the users in the two cylinders varies (Figure 6-2-b). Street A is more likely to be the place where users 1 and 2 can encounter one another, while street B is the place for users 2 and 3 to meet. Since street B is more configurationally distanced from the actual places where these two users are present compared to street A, street A will maintain a higher degree of co-presence intensity than B.

Co-presence can be measured in different ways with different spatial unit settings. One typical method is individual-based, in which the personal social network is focused and every person can be treated as a node in his/her social network. Another method is place-based. In those models, the co-presence in place is concentrated by mapping the exposure of people in certain places. These models are also similar to those mapping the spatial segregation of people. This study applies the latter model as it emphasises the role of space in connecting people and it enables a comparison between the co-presence patterns and other features of the built environment.

3.2.2 Co-presence measures

I Identification of user groups

This study focuses on two specified social groups of people (social media users) based on their differentiation in travel (check-in) behaviours, including local users and remote users of the public space as detected by social media. The *random users* for location *i* refer to people who walk randomly between places in the neighbouring area within a fixed time interval. The so-called *remote users* for location *i* are external visitors who use incoming flows towards the neighbouring area of location *i* from somewhere outside. In other words, the local users are part of the internal flow, and the remote users are parts of the incoming flow. In Figure 6-2-b, user 2 is a local random user in the nearby streets, whereas users 1 and 3 are defined as remote users with a far less frequent presence. Based on these definitions of user groups according to their mobility variations, this study focus on the relative, perceived difference in terms of their travelling behaviours instead of the absolute inherent difference between people in their social classes. In reality, few people can directly judge if the persons they encounter in the street are local or non-local for a certain place. Instead, they can tell if they met someone somewhere. That is to say, people define others as locals or not according to their encounter frequency, which is directly related to mobility patterns in urban space. If someone is continuously present in a place, new visitors would feel familiar with him/her when they travel to that place at the same time. This study suggests that using the observable mobility backgrounds of people to define their place-related social groups is closer to the real mechanism that people use to define others in the built environment (e.g., Bourdieu 1987; Crane 2012). Moreover, this method, in some sense, is consistent with methods that are applied in transport geography to detect housing and job addresses, in which visitation frequency is a key factor in determining the place-identities of citizens. In addition, the identification of user groups for a co-presence analysis in this research is movement associated. The agglomeration of random travel behaviours is close to pedestrian movement illustrating the capability to retain people in space; by contrast, long trips are purposeful, reflecting attractiveness on a city-wide scale. Thus, the co-presence between local and non-local users, in this sense, is not only an observation of physical interaction, but also a measure representing the publicness of a place from a mobility perspective, which is one of the core issues in urban design.

II Spatio-temporal Presence

Spatio-temporal presence intensity of local random users

The spatio-temporal presence intensity index of local random users ($PRE^{Random}_{(i,r,\Delta t)}$) *measures the configurational accumulation of transitions between the venues inside the neighbouring area for a location defined by a given radius within a fixed time interval*. Formally, it can be represented in the equation shown below, where presence intensity is the ratio of the metric presence density ($Den^{Local}_{(i,r,\Delta t)}$) to the cognitive distance ($Dis^{Local}_{(i,r,\Delta t)}$). This idea originates from the spatial interaction model, but transforms its initial form to a simpler version. The metric presence density is calculated as the sum of the weights ($W_{(j,t)}$) of all the reachable check-ins at radius *r* within time interval Δt. This analysis uses the mean angular step depth to all accessible check-ins ($MDep_{(j,t)}$) under the fixed spatial and time situations as the extra cost beyond the energy expenditure reflected by radius *r*. Apart from the traditional spatial interaction model in which a distance decay function is adopted with a calibrated parameter, this model maintains the methodological conciseness for result interpretation by using the mean angular step depth as a denominator. By assuming the trips for a user l can be represented as a set of checked-in locations in sequence: $Trip_l = (C^l_1, C^l_2, C^l_3, \dots, C^l_{t-1}, C^l_t, C^l_{t+1}, \dots, C^l_n)$, this analysis applies the walking distance ($dist_{(i,j_t)}$) between the checked-in location *j* and the location of public space *i* and the network distance between ($dist_{(i,j_{t-1})}$) the origin (C^l_{t-1}) towards the destination (C^l_t,) and the location i in question to extract the local random users for a specific location from the mobility patterns. The criterion for this spatial selection is constraining these two distances to a shorter degree than the given radius to identify the buffer zone for location *i*.

$$PRE^{Random}_{(i,r,\Delta t)} = \frac{Den^{Random}_{(i,r,\Delta t)}}{Dis^{Random}_{(i,r,\Delta t)}} = \frac{\sum_{j=1}^{J} W_{(j,t)}}{MDep_{(j,t)}}, \{dist_{(i,j_t)} \leq r, dist_{(i,j_{t-1})} \leq r, t \in \Delta t\} \text{ .... } (6.1)$$

Spatio-temporal presence intensity of remote visitors

The spatiotemporal presence intensity index of the local random users *($PRE^{Remote}_{(i,r,\Delta t)}$) measures the configurational accumulation of the transitions towards the neighbouring area for location i in question from the places outside within a fixed time interval*. Being similar to the presence intensity of random users, this index is defined as the interplay between co-presence density ($Den^{Remote}_{(i,r,\Delta t)}$) and distance ($Dis^{Remote}_{(i,r,\Delta t)}$) for the remote visitors. The mathematical expression is shown below, in which, $dist_{(i,j,t)}$ represents the distance between location i and the checked-in destination (C^l_t) within the same given time interval (Δt), while $dist_{(i,j,t-1)}$ and $dist_{(i,j,t+1)}$ denotes the distances from location i to the previous checked-in location (C^l_{t-1}), and to the subsequent checked-in location (C^l_{t-1}), respectively. Though controlling these distance metrics (having C^l_t located in a local area for the targeted location, but its predecessor and successor outside that buffer), remote visitors can be successfully identified.

$$PRE^{Remote}_{(i,r,\Delta t)} = \frac{Den^{Remote}_{(i,r,\Delta t)}}{Dis^{Remote}_{(i,r,\Delta t)}} = \frac{\sum_{j=1}^{J} W_{(j,t)}}{MDep_{(j,t)}},$$

$$\{dist_{(i,j,t)} \leq r, dist_{(i,j,t-1)} \geq r, dist_{(i,j,t+1)} \geq r, t \in \Delta t\} \ldots\ldots (6.2)$$

III Spatio-temporal presence Balance

The spatiotemporal balance index *measures the equilibrium between the presence densities of predefined social groups of people*. Normalised information entropy is applied to quantify the degree of balance. Assuming there are K (*k=1,2,3,…,K*) groups of people in question, this research calculates the temporal presence probability ($P_{(i,k,r,\Delta t)}$) for each group by subdividing its presence density ($Den^k_{(i,r,\Delta t)}$) by the total presence density of all groups. In this study, only two complementary social groups of people are accounted for (k_1= random, k_2= remote).

$$BAL_{(i,r,\Delta t)} = \frac{-\sum_{k=1}^{K} P^k_{(i,r,\Delta t)} \times \ln\left(P^k_{(i,k,\Delta t)}\right)}{\ln(K)}, \ \{dist_{(i,j,t)} \leq r, t \in \Delta t\} \ldots\ldots (6.3)$$

$$P^k_{(i,k,\Delta t)} = \frac{Den^k_{(i,r,\Delta t)}}{\sum_{k=1}^{K} Den^k_{(i,k,\Delta t)}} \ldots\ldots (6.4)$$

IV Spatiotemporal co-presence intensity

The spatiotemporal co-presence intensity index *measures the extent to which various complementary groups of people cluster at the local area around location i at radius r within a given* *time interval*. The formal expression is shown in equation 5 which is similar to the form of calculating the presence intensity by combining the presence density and diversity. But this measure takes into account the balance factor as a weighting parameter for presence density. In so doing, this research conceptualises the spatiotemporal face-to-face co-presence as the interplay among density, distance and their balance with the people, space and time constraints.

$$COP_{(i,r,\Delta t)} = \frac{Den_{(i,r,\Delta t)}}{Dis_{(i,r,\Delta t)}}^{BAL_{(i,r,\Delta t)}}, \{dist_{(i,j,t)} \leq r, t \in \Delta t\} \quad (6.5)$$

V Grouping streets based on modes of spatiotemporal co-presence

Although the proposed spatiotemporal co-presence index is a reasonable summary of the interplay between various forms of social capital under different social, spatial and temporal conditions, it may simplify some detailed difference in the model of the co-presence. Therefore, to capture the spatiotemporal co-presence modes across streets, a clustering analysis is applied to group streets according to the observed difference in the presence density and distance of the defined social groups of people. This analysis applies the k-means clustering analysis, with the principal components derived from the raw data to determine the membership for each street. The pseudo F-statistic is used to judge the performance of the grouping results and select the most appropriate number of clusters for the analysis. The principal components are generated by a principal components analysis.

VI Settings

The proposed framework and detailed measures are extendable to the applications of relevant questions at various spatial scales. In this study, street segments are selected as the basic units for analysis since they are real spaces where face-to-face co-presence occurs with the metric and geometrical distance metrics, and it is vector-based without the modifiable areal unit problem that would impact the robustness of the analysis. The other two basic parameters in the introduced measures are the radius r for defining the local area of the segment i and the time interval Δt for identifying the time resolution. This study utilises a 750 m walking distance as the radius that defines the buffer zone for segment i based on an assumption that the average walking speed is approximately 5 km/h and the average walking time is 9 min (Bohannon 1997; Long and Thill 2015). Additionally, 1 hour is used as the interval because it was found that 1 hour is an optimised time scale for the proposed analysis, as making the time scale smaller would risk compromising the reliability of data since the average sample size would be accordingly smaller. Face-to-face encounters normally occurs within a short time, maybe a few seconds or a few minutes. Nevertheless, such a fine-scale co-presence pattern may generate bias with a large amount of variability but less regularity thereby constraining the production of reasonable patterns (Zhong et al. 2016). Thus, it is argued that selecting 1 hour as the time interval is a rational choice for producing robust results with a good balance between temporal singularity and regularity.

3.3 Indexing the centralities of the spatial configuration

The spatial configuration contains two interdependent sub-systems: the spatial network and land-use patterns. By converting these two systems into graph-based representations, this study computes the graph centralities of these two systems separately, including the space syntax centrality and urban function connectivity measures. The former measures the shallowness between space and space, while the latter covers critical aspects of relatedness between urban functions along the spatial grids.

Table 6-1

Centrality measures of spatial configuration

	Abbreviation	Definition
Space syntax centrality measures		
Integration	INT %Radius%	The angular closeness of street network at a radius
Choice	CHO %Radius%	The angular betweeness of street network at a radius
Urban function centrality measures		
Density	DEN %Radius%	The accessible function density of POIs through the street network at a radius weighted by place-based social media check-ins
Diversity	DIV %Radius%	The accessible function diversity of POIs through the street network at a radius weighted by place-based social media check-ins
Distance	DIS %Radius%	The mean angular step depth to the reachable POIs through the street network at a radius

3.4 Regression analyses

To explore the influence of the configurational centrality measures on the spatiotemporal co-presence intensity and the related community structure, a multivariate linear regression model and a multinomial logistic regression model are applied, respectively. Although these two approaches are rooted in the theory of linear regression, their application scenarios are significantly different. Multivariate models serve the purpose of modelling the numeric dependent variable; multinomial logistic regression technologies are developed to estimate the impact of factors when the dependent variable is nominal with more than two categories. This study employs stepwise technology in these two regression models to select the most important factors determining the observed variation of the dependent variables by filtering out the factors with less contribution to the model goodness-of-fit. This method can efficiently control the risk of over-fitting and produce an essential variable structure. Before the stepwise variable filter method is applied, the variables maintaining a higher risk of multicollinearity are detected and removed. The principle is defined by setting the threshold of the variance inflation factor (VIF) for each variable. In this study, the variables with VIF values larger than 10 are removed from the models.

4 THE MATERIALS

4.1 Study area

Central Shanghai is selected as the case for the empirical investigation in this research. Shanghai is one of the mega-cities in current urban China (Figure 6-3). Per the national economic capital growth, it has been growing dramatically since the 1860s. The urbanisation process in Shanghai is Chinese modernisation in miniature. The spatial expansion and the shift of the spatio-social structures provide an ideal case to examine the interactive relationship between the spatial form and temporal social processes. Meanwhile, as one of the most developed cities in China, Shanghai maintains the largest group of social media users due to its large population base and a high rate of social media penetration, which enables the presupposition of using the social media dataset to precast people's movements within the city.

4.2 Street network and checked-in POIs

The street network of Shanghai was gathered from an online navigation service provider with detailed spatial information. The street network data in Central Shanghai were spatially clipped from the raw data and transformed into a segmental map by maintaining the spatial axiality of the streets, which represents the topo-geometrical nature of the spatial grid. The processed segmental map consists of 92,920 street segments.

POI data and the associated check-in information were obtained through an application programming interface (API) of a Chinese social media service provider – Sina microblog, which is equivalent to Twitter in western countries. This dataset consist of a type of place-based data recording the total accumulated check-ins and the number of users who checked-in. Other features include the typology of the POIs and their coordinates. There are 191,035 checked-in POIs within the study area, which are categorised into eleven main types of complementary non-residential land-uses, including retail, catering, hotel, office, recreation, public service, park, education, hospital, culture and transport. The criteria used to classify the land-uses is the intergroup similarity of the check-in behaviours. This process can reduce the dimensions of land-use types by maintaining the most inherent information regarding land-use typology. In this study, 256 types of land-uses in the social media location-based service system are summarised according to the defined active land-uses.

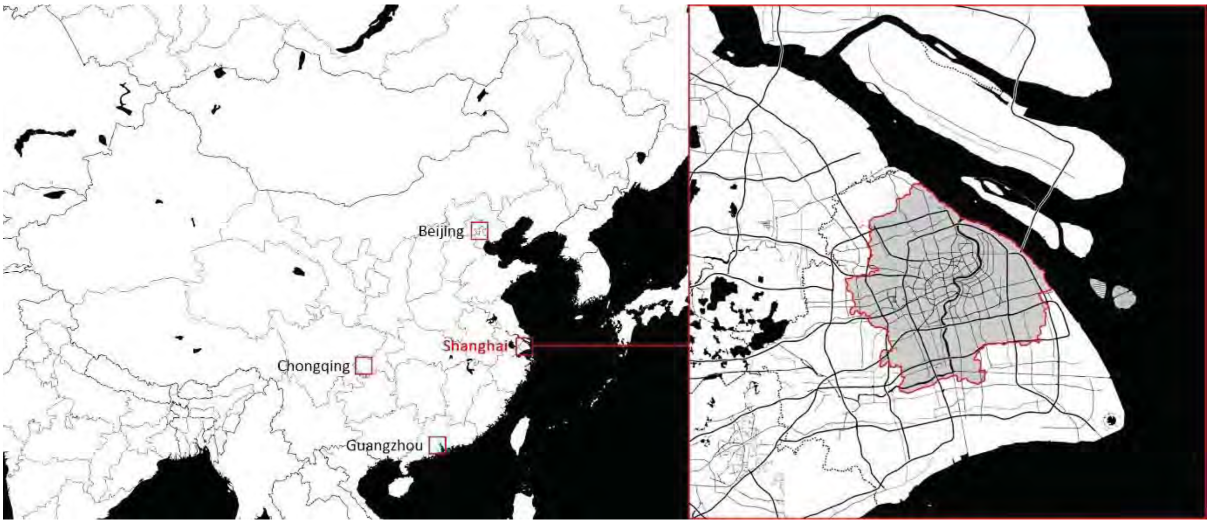


Figure 6-3

The study area

4.3 Trajectories in social media check-in data

The intra-city trajectory patterns of social media users are extracted from individual check-in records collected on workdays for a quarter-long period from March to May 2016. The raw dataset includes 2,868,972 records of 73,427 users across 48,234 venues within the boundary of the study area. Even though social media check-in records are a type of fine-scale location data regarding the spatiotemporal presence of smart-phone users, they can hardly be directly used to estimate the real mobility distributions due to the existence of fake check-in records. Following the method proposed in the study conducted by Wu et al. (2014), this study applies a rule-based method to produce a spatiotemporal dataset regarding the trips of individual social media users on a typical workday. The steps to extract the spatiotemporal trips include: 1) removing invalid check-in records in which the actual locations of the smartphone users do not match the locations of the venues to which they want to check in; 2) removing the users who have only checked in once; 3) producing spatiotemporal trips of a person based on his/her consecutive check-ins; 4) eliminating anomalous trips with unexpected travel speed or duration (the thresholds of speed and duration are 400 km/hour and 12 hours, respectively); 5) merging extracted trips into a typical workday (the initial check-in trajectories for a user on different days are segmented as substantive groups with unique IDs); and 6) eradicating the trips that do not move towards the locations in the study area. The data that were ultimately obtained include 584,746 trips towards destinations in Central Shanghai. The aggregated results between the census units are shown in Figure 6-4, in which the directional polycentric structure is illustrated.

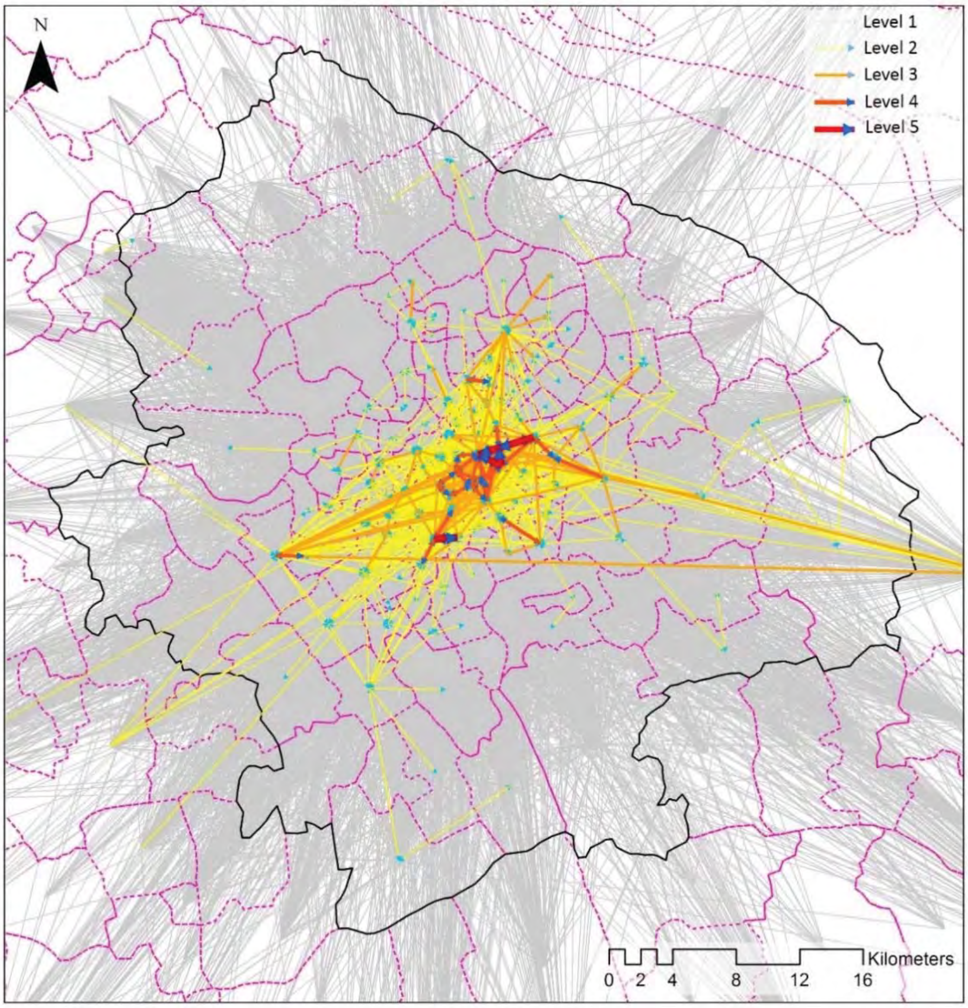


Figure 6-4

The aggregated trips between census units in Central Shanghai

4.4 Gate counts

Gate count data were collected on several workdays in November 2016, covering the main streets in 10 census areas that were randomly selected (Figure 6-5). In each gate for an individual street segment, the aggregated flows in three one-hour-long intervals are counted. These are the time periods from 9:00 to 10:00, 14:00 to 15:00, and 21:00 to 22:00. These data are prepared to validate the reliability of social media check-in data in describing urban movement and to prove the effectiveness of the proposed method to quantify the co-presence intensity.

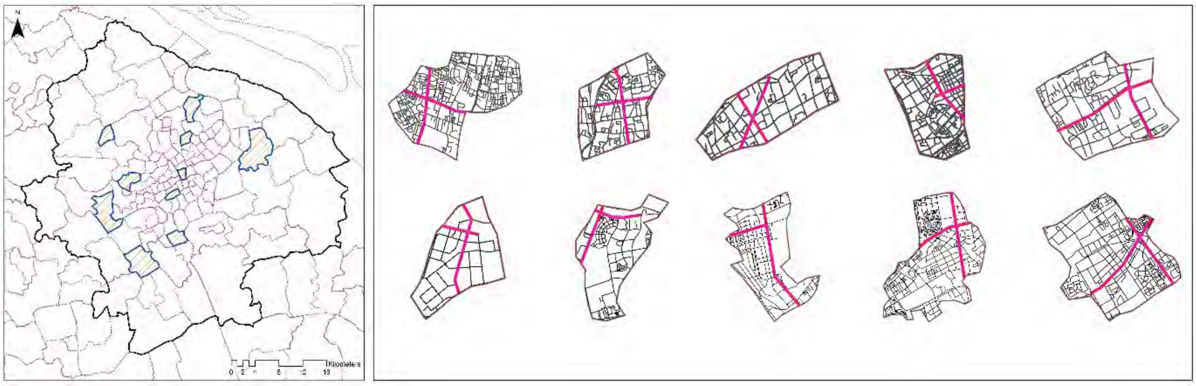


Figure 6-5

Gate count data in randomly selected census areas

5 EMPIRICAL RESULTS

5.1 Preliminary validation

Before the introduction of the empirical results, one primary task is to validate the reliability of the extracted trajectories and the computed patterns of the spatiotemporal co-presence between the random users and remote users. This aim is achieved in the present study by conducting two comparisons. The first comparison concerns the scaling nature of the mobility data in social media check-in records, while the second concerns the goodness of the correlation between the calculated co-presence intensity and the surveyed gate counts. In this regard, this study verifies the effectiveness and applicability of the proposed methods and the framework.

5.1.1 Scaling nature

It has been widely discussed that scaling phenomena are common in mobility patterns. The scaling property of a distribution can be specified and modelled in several ways. For instance, it can be fitted by a pow-law function ($f(x) \sim kx^{-\beta}$) or an exponential function ($f(x) \sim e^{-\alpha x}$). In this study, both models are tested. It is found that individual movement records in social media check-in data are more likely to be governed by an exponential law. As shown in Figure 6-6, the pattern of the trip length has a good fit (R^2=0.952) with an exponent of $\alpha = 0.121$, and the duration distribution is well modelled with a larger exponent $\alpha = 0.144$ (R^2=0.977). These results are in accordance with the findings in previous studies (e.g., Liang et al. 2012; Liu et al. 2014; Wu et al. 2015). This is evidence that the extracted trips in this study maintain the inherent scaling structures of human movement distribution, indicating the feasibility of using the social media check-in records in relevant studies.

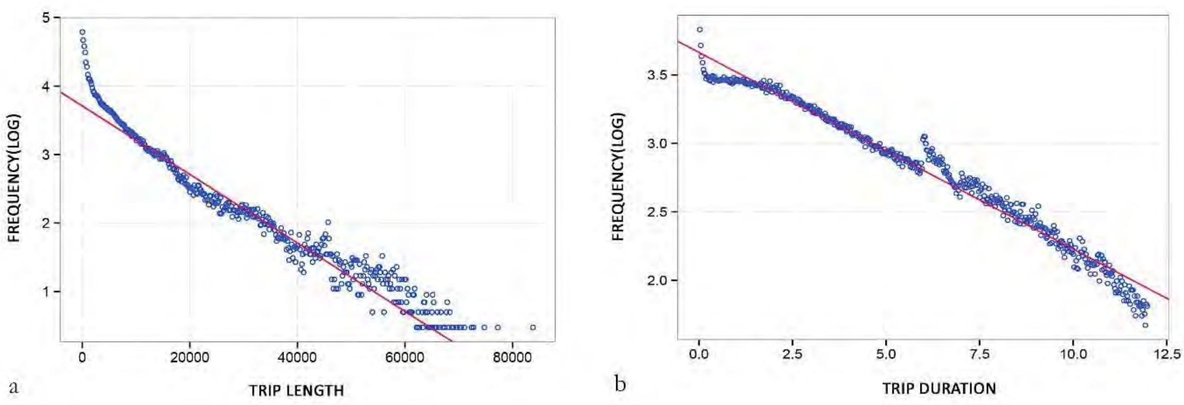


Figure 6-6

Distributions of trip length and duration ((a) the exponent fit of the trip length pattern; (b) the exponent fit of the trip duration pattern)

5.1.2 Correlation with gate counts

Co-presence patterns are rooted in urban mobility distributions. Despite the fact that co-presence patterns are more complex than the flow volume, the urban flow volume is the primary factor determining the underlying probability of people's physical interactions. Spatially varying co-presence patterns should be reasonable estimations of pedestrian flows. Consequently, the accuracy of the produced results is evaluated preliminarily by the examination of their correlation with the survey data. Figure 6-7 illustrates the scatter plots in which the gate count is understood to be a function of the co-presence variable over three time periods. The results indicate that spatiotemporal co-presence patterns generated by the proposed method are highly correlated with the survey data and this trend is sTable 6-across time, with R-square values larger than 80%. These findings show that the dynamic co-presence patterns can not only capture the spatial discrepancy of urban flows but also portray their temporal disparity.

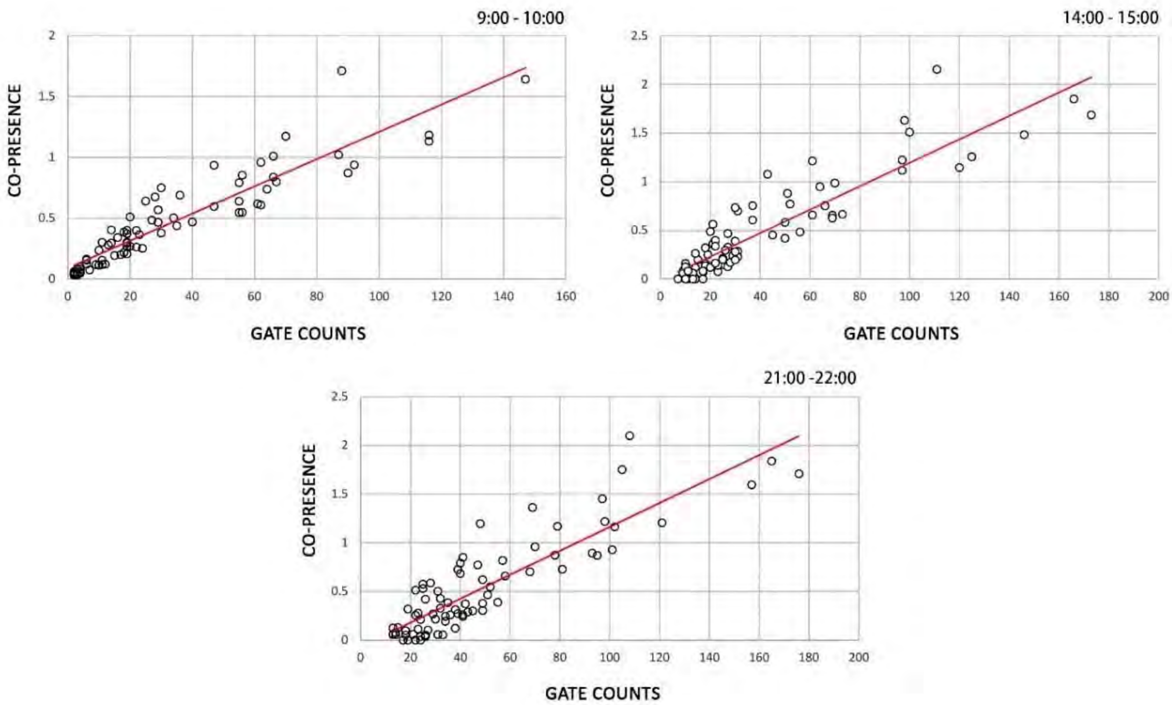


Figure 6-7

Scatter plots of gate counts against co-presence index (Correlation (9:00-10:00) - R2:0.8522, (14:00-15:00) – R2: 0.8207, (21:00-22:00) – R2; 0.8068)

5.2 Spatiotemporal co-presence patterns

5.2.1 Descriptive statistics

I Frequency distribution of trips

Figure 6-8 shows the frequency distributions of all trips extracted from individual social media check-in records. This pattern demonstrates that the check-in behaviours of social media users tend to be more frequent in the evening. There are two peaks that can be clearly observed in the distribution: one is the morning rush-hour at approximately 8 am to 9 am, and the other is dinner time, at approximately 6 pm, which is similar to what has been found in other studies (e.g., Wu et al. 2014). This distribution is different from the patterns observed in transport hubs, in which the morning and evening frequency peaks are typically equal. The main reason for this dissimilarity is that social media behaviours will be more frequent at non-working times when users are engaging in daily leisure activities, such as catering, recreation, etc. Although the trip datasets extracted from various data resources might vary in terms of the frequency distributions, their trends are comparable, indicating the representativeness of social media data regarding human movement.

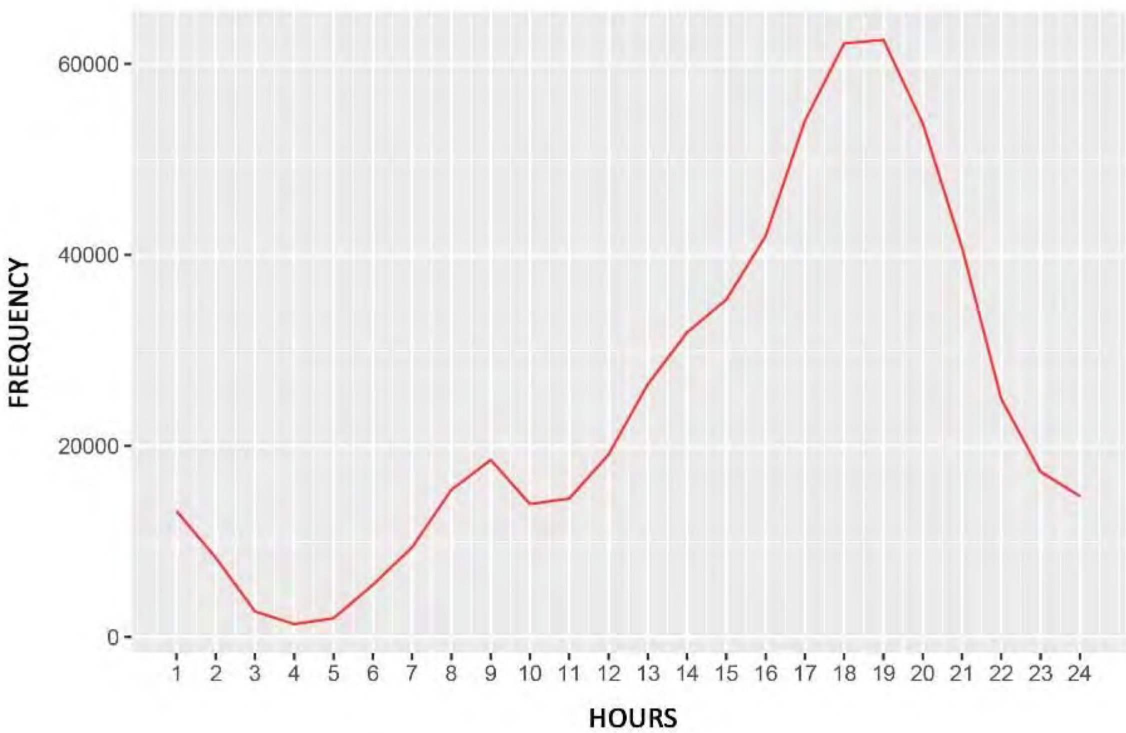


Figure 6-8

Temporal distribution of detected trips

II Temporal patterns of presence/co-presence

Figure 6-9 describes the temporal changes of the average presence and co-presence measures. In terms of co-presence density (Figure 6-9-a), the average degree of the clustering of random users in streets is higher than that of the agglomeration of remote users during most time periods with the expectation that the latter is slightly stronger than the former from 12 am to 2 pm. The temporal shift of the balance degree is captured in Figure 6-9-b, in which the interaction between the presence of random and remote users is lowest at 3 o'clock in the morning and moves to over 0.4 after 8 am. The lower values observed before 8 am indicate the spatial differentiation between the local and non-local people flows because many trips occurring during this period are towards residential communities where few people will be active at typical sleeping times. The balance index then decreases to 0.45 at 11 am and increases back to 0.5 after 2 pm. This may result from the reallocation of destinations during lunch time. Similar to the trend observed in the change of the balance index across time, the value of the cognitive distance for the presence of both remote and random users reaches the lowest point and moves to the peak, but a short time collapse is also seen around lunch-time (Figure 6-9-c). This trend demonstrates that the presence of people is more geometrically concentrated in some places but is more dispersed from a city-wide perspective during the periods when the presence density and balance degree are temporally lower.

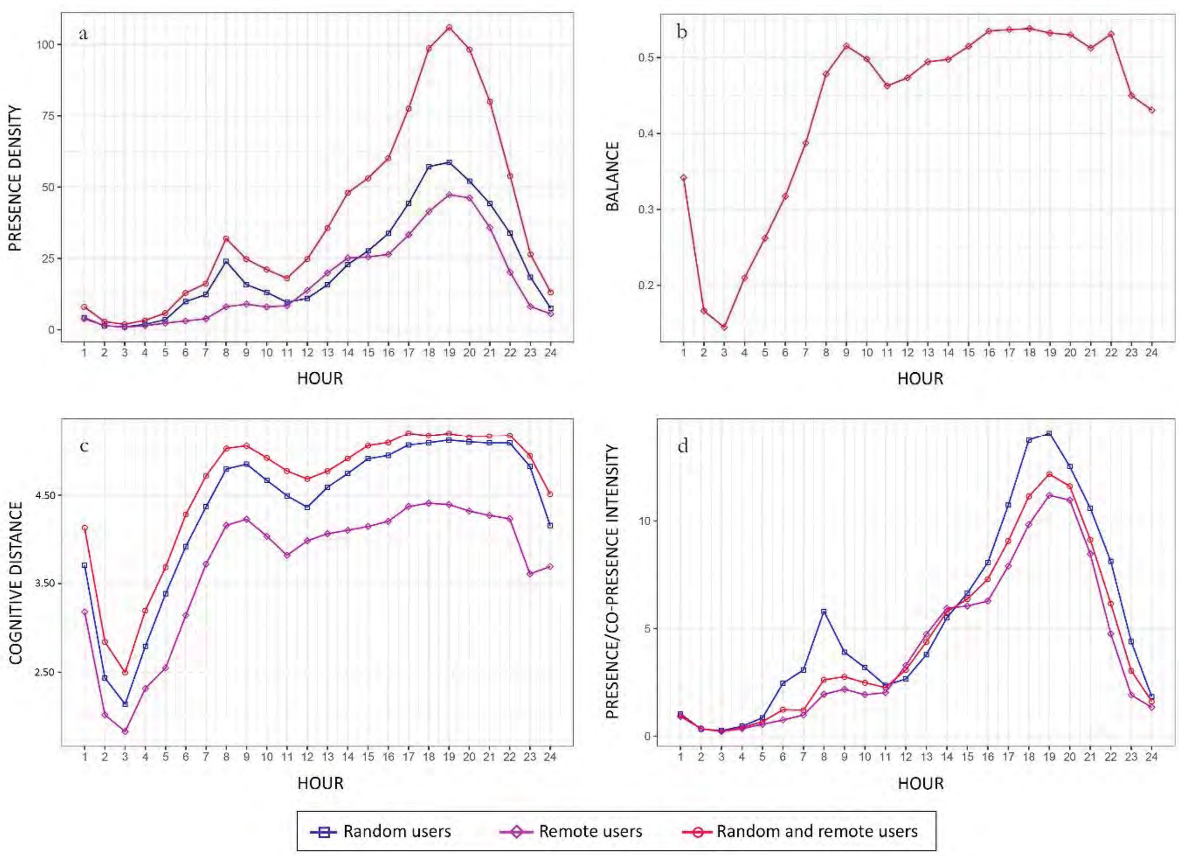


Figure 6-9

Change of the average presence/co-presence measures across time in Central Shanghai. ((a) Presence density; (b) Co-presence balance; (c) Mean cognitive distance (angular step depth); (d) Presence/co-presence intensity)

It can also be noticed that the average cognitive distance for all users is always higher than the mean angular distance between people in the same group. Furthermore, the mean angular distance for local users encountering one another in the street is higher than that for remote users, which suggests that destinations for non-local users are more configurationally closed, whereas the journey's ends for local random walkers are geometrically scatted but are metrically concentrated. The maps of presence/co-presence intensity indices are illustrated in Figure 6-9-d. The gap between the presence patterns of local and non-local users in terms of presence density is shortened when the cognitive distance is taken into account. The co-presence intensity index exhibits a relatively smooth change and is located in the interval between the two presence intensities of individual groups. In short, the significant fluctuation of the presence and co-presence intensity patterns reveals the temporal complexity of co-presence patterns which is difficult to capture in aggregated descriptions of urban flows.

5.2.2 Spatiotemporal co-presence maps

The spatiotemporal change of the co-presence intensity is mapped in Figure 6-10 with the same symbolising method. The overall urban polycentric structure can be discovered across time based on visual judgement, although the shape of the co-presence cores changes dynamically. This suggests that the co-presence pattern has its roots in the urban structure. In the early morning, the co-presence pattern becomes compact around the city centres, particularly from 4 am to 5 am. When the commuting time approaches, the co-presence intensity turns to be more spatially homogeneous since people are travelling to workplaces that are distributed in a more scattered manner. The global city centre regains its dominance after 9 am in the morning, and this trend remains significant during the rest period. Notably, some locations are also highlighted for an all-day period. Hongqiao Airport, for instance, maintains a high degree of physical co-presence values at all times. This is evidence that modern mix-used complexes, such as transport hubs, shopping malls, etc., and the streets connected to them are emerging places for human interaction.

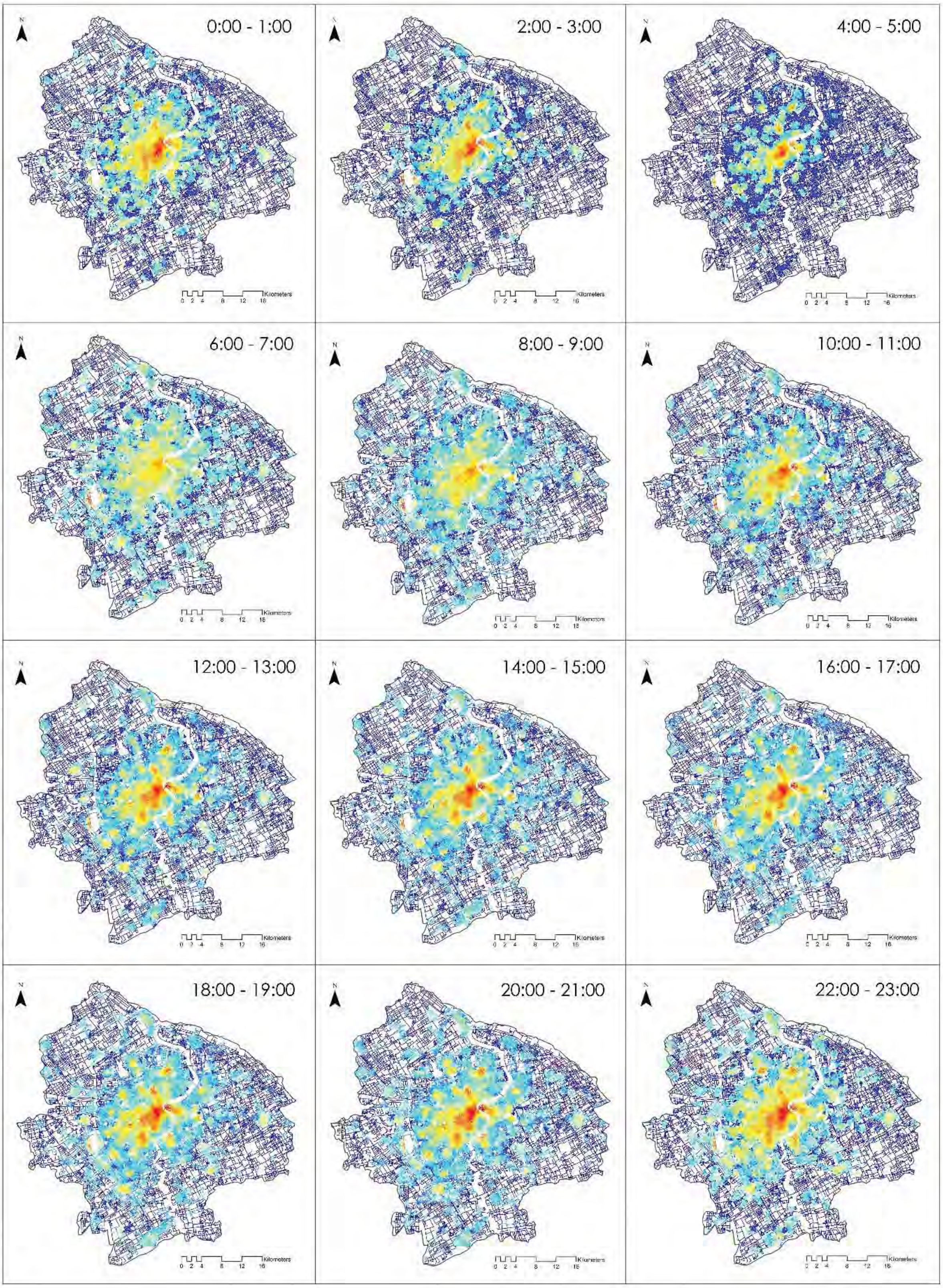


Figure 6-10

Spatiotemporal co-presence maps in Central Shanghai

5.3 The configurational logic of spatiotemporal co-presence

This study applies a stepwise multivariate regression method to explore the impact of every centrality measure on the variation of co-presence intensity at every hour of a workday by controlling the influences of other factors. The regression results are shown in Table 6-2. It is standard for all model specifications that accessible function densities at the microscale and mesoscale are the main determinants significantly correlated with co-presence intensity. The global density, however, exerts negative effects on it. This suggests that land-use clustering at smaller scales provides the basic landscape for physical interaction between local and non-local citizens. Another general trend documented is that pedestrian land-use diversity is a suppressed factor but the global diversity is an augmented factor, which yields a tendency where the local mixture of urban functions is not simultaneously preferred by the two defined groups of people if the density effects are fixed. Likewise, the places where people are more likely to be co-present are inferred by a longer angular distance at the local scale, but less cognitive efforts at the global scale. These results imply that co-presence occurs at the locations that are metrically proximal to but configurationally distanced from the areas where the clustering of urban functions manifests at the middle scale. In other words, the stages for physical co-presence may not always be high streets; rather, they are more likely to be the places connected to central streets as the interfaces between centre and centre.

Angular integration and choice variables at low levels are also positively associated with the change of co-presence intensity across time, but their statistical significance varies. Angular integration variables are more significant in specific models before 12 am. In the afternoon, angular choice variables are more significant than the integration elements. What results this might be the fact that the co-presence that occurs in the morning is related to the to-movements driven by the closeness between spaces. This demonstrates that developing areas – the places lacking sufficient local amenities but being fulfilled with adequate housing and employment opportunities – are captured by integration variables at local scales, play more important roles in the spatial co-presence patterns in the morning work hours and late night, when people are commuting across the city to their workplaces and homes. By contrast, non-working and non-residential activities are more dominant during other periods within a typical workday; thereby, the impact of angular integration becomes less statistically significant. In a nutshell, spatial centrality measures are significant factors for predicting temporal co-presence patterns using functional centrality indices, and the dynamic change of their significance reveals the composition of various types of urban movements across time.

Table 6-2

Centrality performance against encounter intensity (Only significant variables are shown)

		0:00-1:00	1:00-2:00	2:00-300	3:00-4:00	4:00-5:00	5:00-6:00	6:00-7:00	7:00-8:00	8:00-9:00	9:00-10:00	10:00-11:00	11:00-12:00
Urban function connectivity measures	DEN_R500	0.575	0.516	0.574	0.572	0.597	0.606	0.614	0.367	0.645	0.577	0.636	0.684
	DEN_R2500	0.429	0.465	0.417	0.350	0.414	0.434	0.228	0.157	0.326	0.360	0.330	0.366
	DEN_R10000	-0.263	-0.282	-3.353	-0.31	-0.302	-0.231	-0.146		-0.190	-0.112	-0.113	-0.157
	DIV_R500	-0.132	-0.124	-0.153	-0.113	-0.12	-0.112	-0.079		-0.084	-0.082	-0.099	-0.094
	DIV_R1000												
	DIV_R2500							-0.078	-0.121	-0.057			
	DIV_R5000								-0.032				
	DIV_R10000	0.025	0.028	0.037	0.037		0.043	0.067	0.096	0.057	0.033		0.029
	DIS_R500								0.023				
	DIS_R1000											-0.052	
	DIS_R2500	0.064	0.056		0.037	0.038	0.063	0.073	0.062	0.069	0.096	0.077	0.068
	DIS_R5000			0.052									
	DIS_R10000	-0.065	-0.066	-0.080	-0.055	-0.069	-0.048	-0.043		-0.047	-0.044		-0.041
Space syntax metrics	INT_500	0.076	0.053	0.047			0.082	0.052	0.067		0.078	0.107	
	INT_2500	0.151	0.180	0.175	0.170	0.163		0.076		0.103			
	CHO_500	-0.026					-0.029		-0.047		-0.068	-0.064	
	CHO_1000			0.032	0.091								
	CHO_2500		0.021			0.047	0.038				0.034		0.045
	CHO_100000				-0.012							0.029	0.025
Performance	Adj. R2	0.777	0.743	0.714	0.664	0.748	0.734	0.575	0.349	0.701	0.671	0.723	0.787
	Adj. R2(SSX)	0.474	0.462	0.430	0.405	0.442	0.399	0.309	0.233	0.378	0.368	0.394	0.425
	Adj. R2(UFC)	0.717	0.669	0.642	0.607	0.703	0.684	0.547	0.328	0.667	0.634	0.688	0.751
	Enhancement¶	7.722%	9.960%	10.084%	8.584%	6.016%	6.812%	4.870%	6.017%	4.850%	5.514%	4.841%	4.574%

¶ denotes to the change of the correlation coefficient in the model with only urban function connectivity measures to the model with both urban function connectivity and space syntax centralities, DEN: accessible function density; DIV: accessible function diversity; DIS: cognitive distance to the reachable land-uses; INT: angular integration; CHO: angular choice.

Table 6-2

Centrality performance against encounter intensity (Only significant variables are shown)

		12:00-13:00	13:00-14:00	14:00-15:00	15:00-16:00	16:00-17:00	17:00-18:00	18:00-19:00	19:00-20:00	20:00-21:00	21:00-22:0	22:00-23:00	23:00-24:00
	DEN_R500	0.699	0.755	0.728	0.751	0.759	0.806	0.824	0.815	0.789	0.772	0.660	0.576
	DEN_R2500	0.388	0.329	0.364	0.322	0.286	0.227	0.234	0.263	0.292	0.306	0.398	0.469
	DEN_R10000	-0.205	-0.203	-0.220	-0.201	-0.203	-0.198	-0.173	-0.196	-0.200	-0.249	-0.264	-0.281
	DIV_R500	-0.096	-0.106	-0.110	-0.115	-0.123	-0.124	-0.141	-0.140	-0.136	-0.124	-0.128	-0.117
	DIV_R1000							0.033	0.038	0.036			
	DIV_R2500												
	DIV_R5000												
	DIV_R10000	0.039	0.039	0.039	0.036	0.030	0.028	0.033	0.028	0.029	0.040	0.038	
	DIS_R500												
	DIS_R1000												
	DIS_R2500	0.061	0.055	0.047	0.05	0.049	0.041	0.016	0.041	0.045	0.040	0.052	0.056
	DIS_R5000												
	DIS_R10000	-0.047	-0.046	-0.044	-0.048	-0.052	-0.050		-0.04	-0.042	-0.048	-0.048	-0.068
Space syntax metrics	INT_500											0.037	0.042
	INT_2500					0.054	0.056				0.060	0.092	0.124
	CHO_500												
	CHO_1000												
	CHO_2500	0.044	0.049	0.053	0.048	0.032	0.028	0.040	0.041	0.046	0.025		0.016
	CHO_100000	0.024											
Performance	R2	0.804	0.803	0.793	0.782	0.785	0.787	0.801	0.806	0.805	0.805	0.784	0.785
	R2(SPACE)	0.421	0.403	0.397	0.382	0.394	0.382	0.381	0.379	0.389	0.393	0.422	0.458
	R2(FUNCTION)	0.765	0.771	0.756	0.760	0.754	0.76	0.775	0.778	0.775	0.769	0.735	0.718
	Enhancement¶	4.851%	3.985%	4.666%	2.813%	3.949%	3.431%	3.246%	3.474%	3.727%	4.472%	6.250%	8.535%

¶ denotes to the change of the correlation coefficient in the model with only urban function connectivity measures to the model with both urban function connectivity and space syntax centralities, DEN: accessible function density; DIV: accessible function diversity; DIS: cognitive distance to the reachable land-uses; INT: angular integration; CHO: angular choice.

When the goodness-of-fit for every model is scrutinised, co-presence patterns in streets are proven to be properly captured by the centralities of the spatio-functional context where they are embedded. For most of a typical workday, the models with both families of configurational centralities maintain correlation coefficients greater than 0.65. However, this trend is interrupted during the period around the morning peak from 6 am to 8 am. This result implies that the co-presence patterns may be simultaneously driven by other variables that are currently absent from the present models in a more complex sense. For models with spatial and functional centrality measures, their predictability is higher than the other two types of models with either spatial or function centrality indices, suggesting the theoretical proposition that spatio-functional interaction is the essential determinant of spatiotemporal encounter patterns. In addition, models with urban function connectivity measures perform better than those with space syntax centrality metrics in terms of the size of the correlation coefficients. Nevertheless, this does not mean that the impact of the spatial network can be substituted by the influences exerted by the land-use system. Instead, these findings suggest a complimentary relationship between urban form and functions for an in-depth understanding of people's interactions in the streets. These results further exhibit that the physical co-presence that happens in an urban reality is far more complex than was expected and hypothesised in the theory of space syntax. Additionally, the spatial centrality and land-use patterns are more important in the formulation of the landscape for people to communicate and to make a space socially public. More importantly, in comparison to the roles that the spatial grid plays, the effects of the geometrical properties of land-use patterns on the spatiotemporal encounter are more direct and powerful.

5.4 Co-presence modes in streets

Figure 6-11 illustrates the results of street typology in terms of the co-presence modes. There are five types of streets that are clustered and defined based on the statistical performance of the inter-group difference and within-group similarity. These groups are annotated according to the mean values of the co-presence density and distance for each group of space users (Table 6-3; Figure 6-12). The first detected group of streets (C3) is named 'central streets', which has the highest degrees of co-presence density and balance and a middle length of cognitive distance. These streets are more patchwork-like, representing core areas for citizens to encounter one another. These areas include various types of centres, including historic cores covering the Nanjing Road area and Jing'an District, which were colonial areas in history, newly planned urban centres, such as the Lujiazui central business centre, Wujiaochang, Xujiahui, and areas near large urban complexes, such as the Hongqiao transport hub and Hongkou Stadium. It is evident that places for human face-to-face interactions in contemporary society are not only public spaces but also areas where large complexes for experiential consumption are clustered. The second and third groups of streets maintain high levels of co-presence intensity, but they can be clearly distinguished from one another according to their detail properties in temporal co-presence density and distance. The second group of streets (C4) detected is called ‘active roads’ because the streets are highlighted on the basis of the low degrees of co-presence density and cognitive distance. In the street, people are more likely to see one another when they are present simultaneously, although there are few people clusters there. The third group of streets (C2) is ‘daily streets’, where co-presence density and mean angular distance are both high. When passing through these streets, people must make more geometrical turns than those on ‘active roads’, even though the flow volume is greater. Another group of streets is the ‘neighbourhood streets’. These are the places where many people gather, but their face-to-face probability is largely constrained by the spatial configuration. The average angular step depth for people to encounter one another in certain streets within this group is more than 9 for most of the typical workday. There are such places in historic areas and central areas in large residential communities. As an example, the traditional Chinese inner city of Shanghai is basically defined in this group due to its complexity in the organisation of space. The remaining group is defined as ‘non-central streets’ where few people will be present even if the cognitive distance for their encounter is short.

The change of the average balance degree between the local and remote users is recorded in Figure 6-13. The ranking of street groups in the balance level is the same as the order in the presence density. This can be considered as a proof that the volume of urban flows is a fundamental factor impacting on the physical co-presence between the different groups of people defined in this study. However, the dynamic change of the balance index values shows that it is not merely a dependent variable for the presence density. Central streets retain the highest mean values over 24 hours with little variation, whereas neighbourhood streets, daily streets and active roads are characterised by three similar trends with higher co-presence balance values after 10 am, and the lowest values at 3 am. This consistency demonstrates that dynamic shifts of co-presence patterns in most of the urban streets are inherently significant except for in the detected central streets. The non-central streets, as expected, are inferred to have the lowest degree of co-presence balance.

The spatial patterns of the grouped streets also reveal the potential relationship between the co-presence modes and the street hierarchy (Figure 6-12-b). The central streets are the convex areas indicating the cores geometrically connected by the active roads that are typically the main roads in the central area. The daily roads are the paths interlinking the peripheries of the blocks defined by the active roads. The so-called neighbourhood streets, on the other hand, are private paths encompassed by daily roads. In contrast, non-central streets are the background of these urban roads, which are relatively non-urban and they mainly include expressways or country roads that serve non-pedestrian travelling purposes. The relevant visualisation can also be interpreted as a result of urban communities subdivided by the active roads and identified by the modes of co-presence between the local walkers and the non-local visitors. These results yield that the design of a road system and its hierarchy plays a major role in the ways in which people interact with one another configurationally.

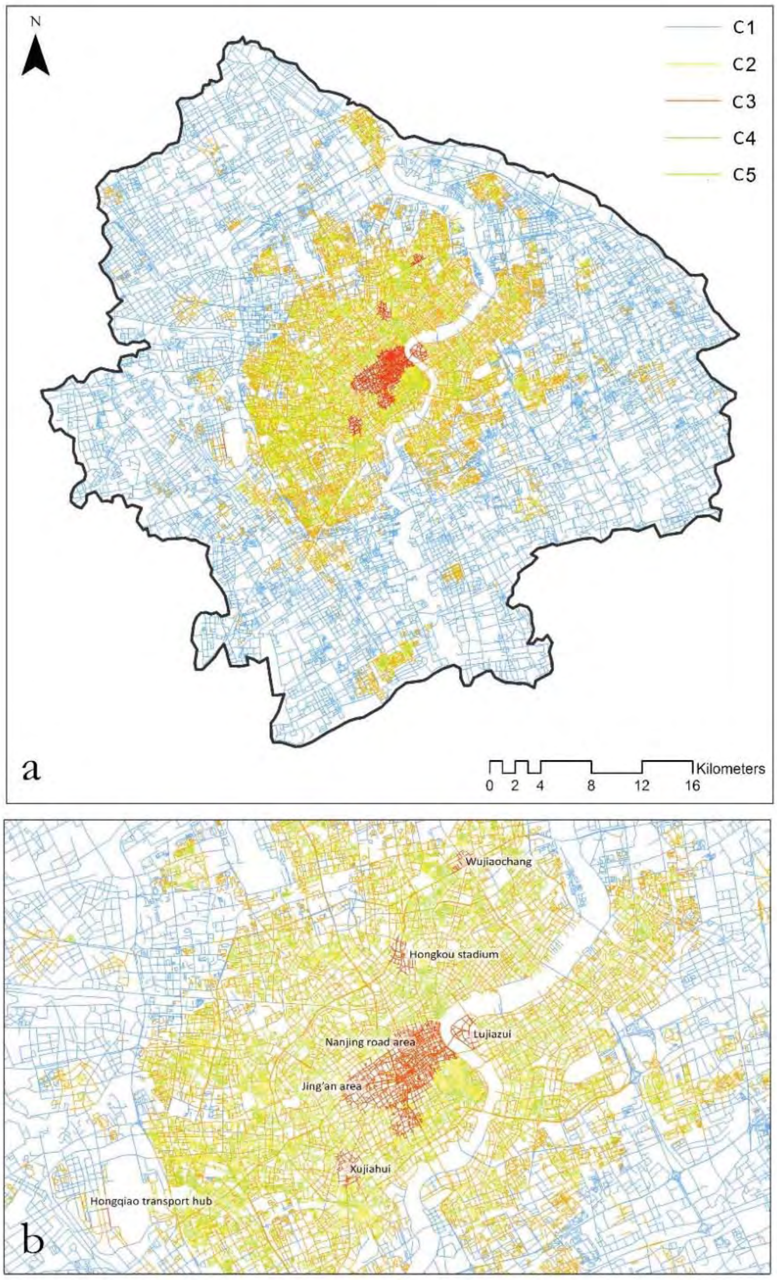


Figure 6-11

Detected street clusters based on the modes of spatiotemporal co-presence in the study area (a) and in the central area (b) in Shanghai

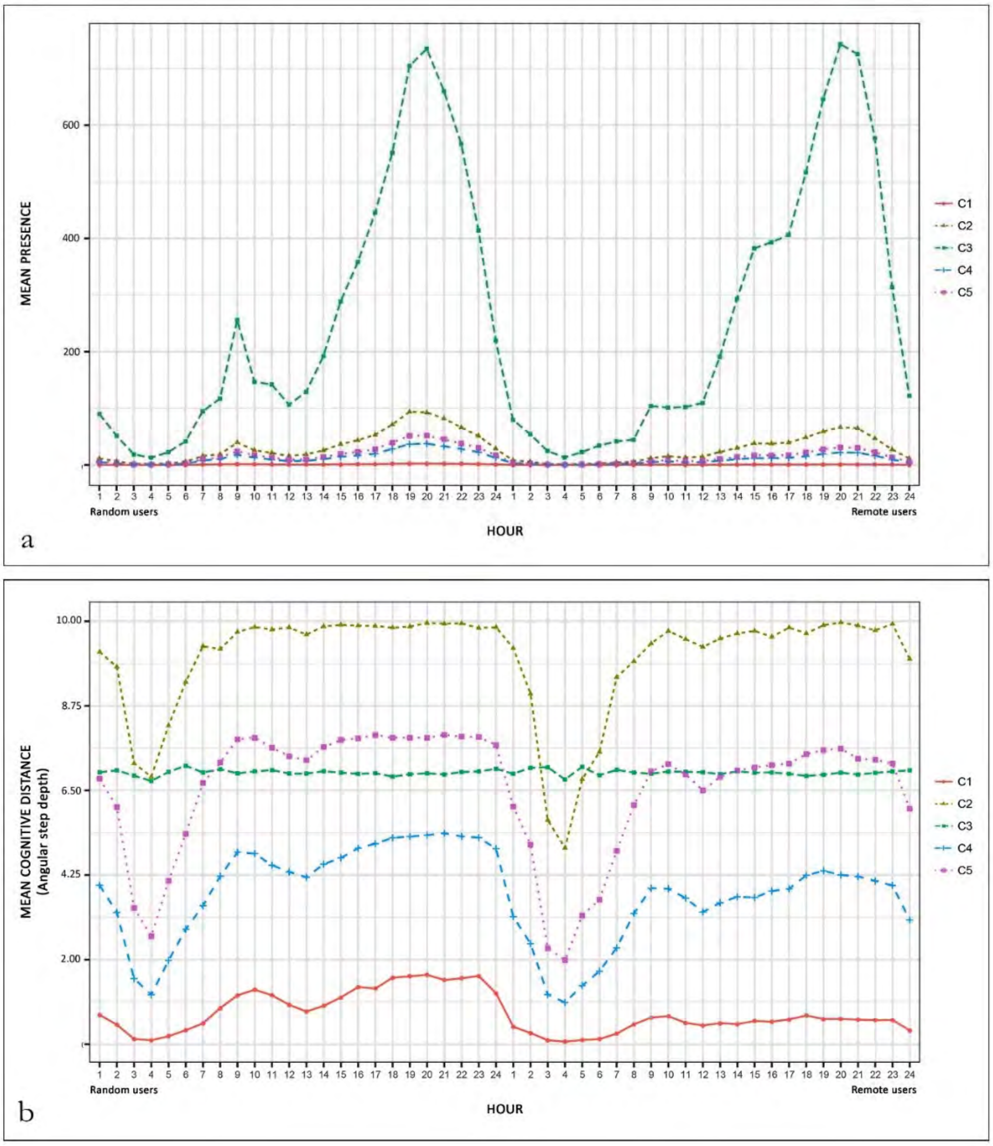


Figure 6-12

Mean values of the presence density (a) and cognitive distance (b) across time for random and remote users in Central Shanghai

Table 6-3

Annotation of street typology in terms of co-presence modes

	Annotation	Presence		Cognitive distance		Co-presence
		Random users	Remote users	Random users	Remote users	
C1	Non-central streets	Lowest	Lowest	Lowest	Lowest	Lowest
C2	Neighbourhood streets	Higher	Higher	Highest	Highest	Lower
C3	Central streets	Highest	Highest	Middle	Middle	Highest
C4	Active roads	Lower	Lower	Lower	Lower	Higher
C5	Daily streets	Middle	Middle	Higher	Higher	Middle

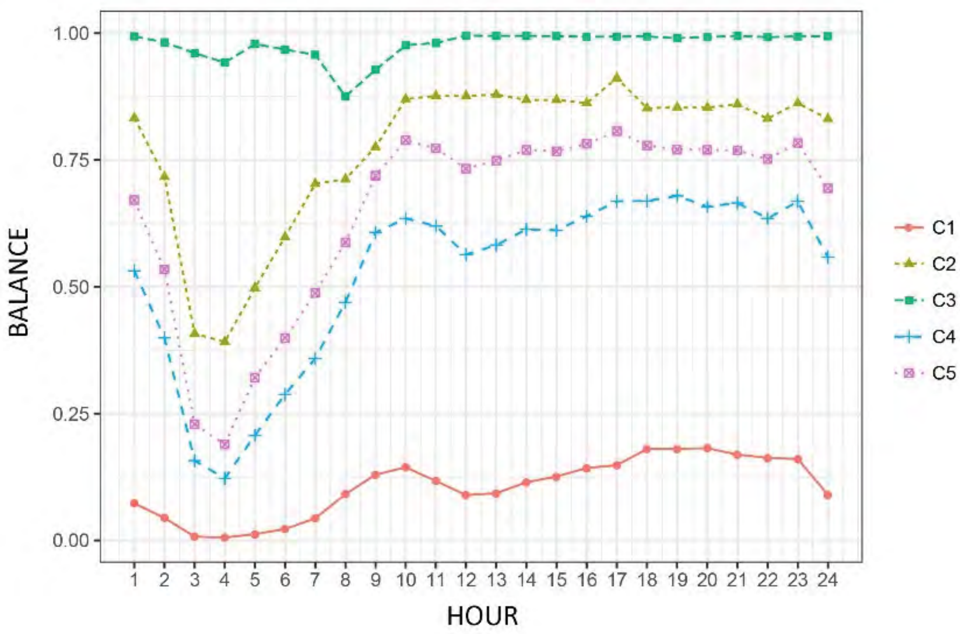


Figure 6-13

Mean values of the co-presence balance across time in Central Shanghai

5.5 The configurational logic of co-presence modes

By computing the mean values of spatial and functional centralities for the streets with the same co-presence mode, this section first inspects the overall contributions of the spatial configuration to the delineation of the co-presence groups. According to the results recorded in Figure 6-14, the detected five groups of streets can be distinguished more precisely by using the urban function connectivity measures than by applying the space syntax centrality indices. Angular integration is an effective variable for identifying central and non-central streets, but it is less useful for discerning the other three groups from one another. Angular choice variables, on the other hand, can differentiate between urban streets sufficiently (C2-C5).

An in-depth investigation is conducted via a multinomial logistic regression, in which the set of daily streets is used as the reference group. The related results are shown in Table 6-4, in which the outcomes of the likelihood ratio (LR) Chi-Square test and the pseudo R^2 estimation show that the proposed model has good explanatory power. Although the signs of one type of centrality measure at different scales may vary, their coefficient sizes still create a clear picture regarding the structure of determinants. Streets with greater accessible function density at various scales are more likely to be the central streets and neighbourhood streets; those with less land-use density are defined as active roads or non-central streets. Moreover, the function density, the accessible function diversity and mean angular distance are also significant factors. With the increase of the average angular distance to the nearby functions and the decline of the function diversity at 1,000 m, the probability of the streets being categorised in the group of non-central streets relative to the risk of falling in the referent group grows. The two most significant factors that distinguish neighbourhood streets from daily streets are the mean angular distance and the function diversity at the pedestrian level. Streets that are more configurationally close to the reachable functions with a higher mixture degree at 1,000 m are more likely to be defined as the neighbourhood streets. This evidence suggests that neighbourhood streets facilitate local functions in residential communities, which are hidden geometrically from the places where the face-to-face encounters between locals and non-locals occur frequently. Compared to the referent group, central streets obtain more probability of having a higher degree of land-use mixture at the local and global scales with a shorter cognitive distance to them. The impacts of the space syntax centrality indices are less significant than the effects of the urban function connectivity measures on segmenting co-presence styles in streets. The most significant factor in the spatial centrality measures is the angular integration at 2,500 m, which is positively related to the probability that the streets in question are central streets. On the whole, given that the impacts of other factors are constant, the urban function connectivity measures at the pedestrian level, the angular integration at the mesoscale and the angular choice at the macroscale in the family of space syntax centrality metrics are critical factors for differentiating between the street-based co-presence modes.

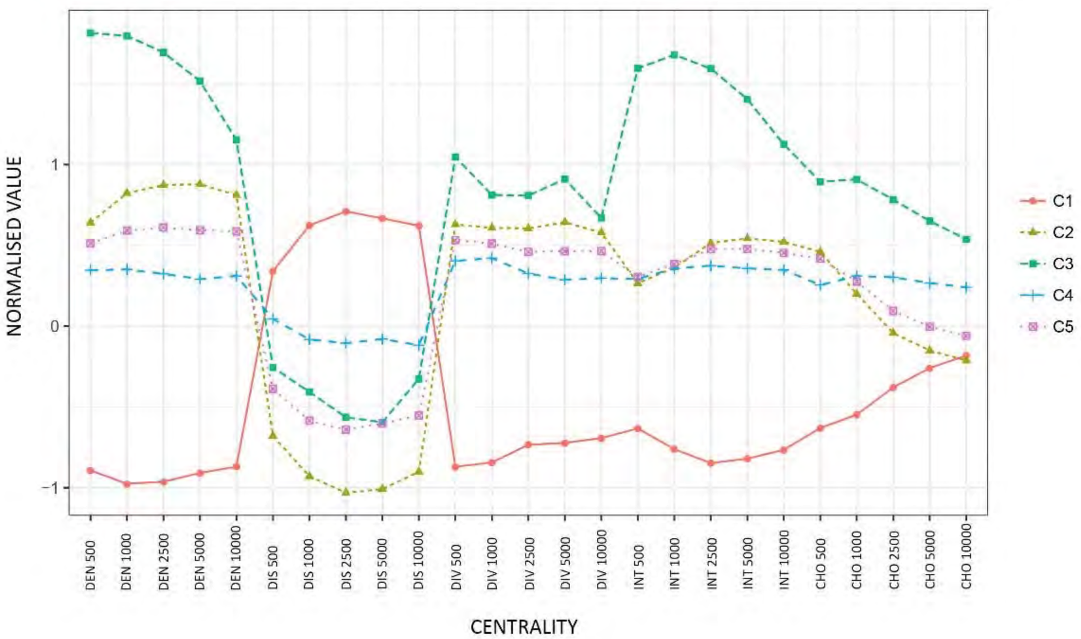


Figure 6-14

Mean values of configurational centralities across scales for each co-presence mode in Central Shanghai

Table 6-4

The results of the multinomial logistic regression for the impact of centrality structures on the co-presence typology of streets

	C1: Non-central streets		C2: Neighbourhood streets		C3: Central streets		C4: Active roads	
	B	Exp(B)	B	Exp(B)	B	Exp(B)	B	Exp(B)
Intercept	2.835***		-10.093***		-97.526***		3.788***	
Urban function connectivity measures								
DEN_R500	-2.411***	0.090	0.934***	2.544	7.748***	2315.279	-1.002***	0.367
DEN_R2500	-4.552***	0.011	1.657***	5.243	10.024***	$2.255*10^4$	-1.517***	0.219
DEN_R10000	-0.299***	0.742					-0.273***	0.761
DIV_R500	0.235***	1.265	0.231***	1.260	-5.121***	0.006	-0.104**	0.586
DIV_R1000	-1.729***	0.177	1.356***	3.880	10.893***	$5.379*10^4$	-0.534***	1.166§
DIV_R2500	0.720***	2.054					0.154***	1.659§
DIV_R5000	0.616***	1.852	-0.412***	0.662	-23.082***	0.000	0.506***	0.042
DIV_R10000	-0.136*	0.873			127.022***	$1.461*10^6$		
DIS_R500	-0.303***	0.739	0.887***	2.427			-0.336***	0.715
DIS_R1000	7.419***	1666.953	-9.173***	0.000	-4.682***	0.009	5.219***	184.657§
DIS_R2500	-0.295***	0.745			2.715***	15.108		
DIS_R5000					-1.968***	0.140		
DIS_R10000					1.184***	3.268		
Space syntax metrics								
INT_500	-0.376***	0.687	0.235***	1.265			-0.099***	0.905
INT_2500	0.274***	1.361	-0.218***	0.614	1.114***	3.046	0.168***	1.183
CHO_500	-0.236***	0.790			-0.585***	0.557	-0.225***	0.798
CHO_2500	-0.746***	0.474					-0.459***	0.632
CHO_100000	0.999***	2.714					0.674***	1.961
Chi-Square=160022.518 Sig.=0.000								
Pseudo R^2(Cox and Snell)=0.823								

* - significant at 10%; ** - significance at 5%; *** - significance at 1%. Referent group: daily streets (C5). B - Estimated coefficient; Exp(B) - odds ratio for the coefficient.

6 DISCUSSION AND CONCLUSION

This research examines the spatial logics of the spatiotemporal co-presence between local and non-local people in Central Shanghai. Two main tasks are expected to be achieved. The first is to quantify the spatiotemporal patterns based on the individual's check-in records and the street network. The second is to investigate the role that urban design plays in the sensed spatiotemporal co-presence intensity. The main scope of this study is to empirically explore the extent to which spatial design influences the physical face-to-face interaction between different groups of people, social media users more precisely, in contemporary digitalised society.

This study delivers a PST model in which the social capital for people to interact includes three principal dimensions, the social difference between people, the spatial distance (the metric and geometrical distance), and the time cost of people's presence. It is proposed that people can be profiled based on their mobility patterns which can further depict the citizens' place identity from place to place and from time to time. Within a given time interval, social media users who visit a local area frequently are defined as 'local random users' for that location, while users who make a short visit to the local area for a location and travel back to somewhere outside the local area are identified as 'remote users'. From an aggregated scope, local random users and remote users are parts of the internal flow and the incoming flow for the location in question, respectively. Given these definitions, this study anchored its specific focus on the physical encounter between local random users and remote users by considering comprehensively the required energy expenditure and cognitive cost. By giving a time radius and a distance radius, the delivered co-presence intensity addresses the interplay among the co-presence density, balance and mean cognitive distance in every street. The portray of spatiotemporal patterns is not only related to the perceived publicness of the space but also helpful for producing deeper knowledge on how the offline built environment is used by the online population in the current digitised world.

An individual's trajectory pattern is extracted from their consecutive check-in records and is then used to produce the spatiotemporal co-presence intensity in streets using the street network dataset. The reliability of the mined data and the effectiveness of the proposed method are proven by the observation that the processed spatiotemporal trips follow exponential laws in terms of the trip length and duration and of a good correlation between the outputs and the small-sized survey data. The co-presence patterns across time reveal their temporal complexity. City centres, as well as the planned centres and large-scale social complexes, such as transport hubs, shopping malls, etc. are crucial spaces for people to encounter one another. The regression results suggest that the physical co-presence between the random and remote users does not always occur in high streets as expected, but in nearby streets where the pedestrian land-use mixture is lower and the angular distance to the land-use is longer. The impacts of the angular integration in the regression models for describing the deviation of co-presence patterns are more significant in the morning when developing areas are more likely to be the destinations during commuting times. It is validated that the urban function connectivity measures maintain higher standards of predictability than the space syntax centralities, although the model performance can be further enhanced if both types of configurational centrality variables are used. It is also noteworthy that the goodness-of-fit in the integrated model is significantly lower in the morning peak hour.

Five types of co-presence modes are discovered in streets through a data-driven process. They are annotated as central streets, active roads, daily streets, neighbourhood streets and non-central streets according to the temporal presence patterns of the defined social groups of people. Central streets are patchwork-like patterns indicating a polycentric structure of co-presence. The patterns of other detected groups of streets, on the other hand, show a relatively hierarchal structure. The results of multinomial logistic regression indicate that the pedestrian functional centralities are the main factors that discriminate the detected groups of streets, and the spatial centralities at the larger scales are also significant elements, but their impacts are much less than that of the functional indices.

The potential contribution of this work relies on several aspects. First, it is proven that a social media dataset can be adopted to understand human's mobility and presence with large coverage at a fine spatial resolution. Second, it proposes a street-based framework to quantify the spatiotemporal co-presence between defined groups of people. This framework is flexible and can be extended and used to measure other co-presence phenomena. Third, this work suggests that it is a spatio-functional interaction through streets that influences the spatiotemporal variation of the encounters between people and its emergent modes, which may be a reference for further studies on relevant topics. Fourth, it is recognised that land-use patterns are theoretically and methodologically necessary for understanding the social processes in contemporary society where people's travelling decision making is biased by online location services.

Further work can be conducted on, but is not limited to, the following aspects. The time interval for computing the co-presence intensity in this study is set for 1 hour in order to avoid the bias caused by the data's scarceness. In the next step, the time interval can be further divided with better data support to produce results with more temporal singularity. Moreover, the information of the individual check-in trajectories can be enriched by combining it with other big data resources, such as cell phone datasets, etc. Additionally, more empirical studies should be conducted in other cases to validate the generality of the conclusions in this study.

CHAPTER 07

DISCUSSION AND CONCLUSIONS

1 INTRODUCTION

Recognising the way urban centrality structures are formed in the built environment and how they facilitate various social processes remains the core challenge for contemporary urban design. The central aim of this thesis has been to understand the meanings of the functional environments through investigations of the extent to which urban centrality structures can be explained by dynamic patterns of functions, beyond the premises of physical design, and the examination of these dynamic relations with regard to the functionality of public spaces. This research firstly introduced a method of quantifying the geometrical properties of the land-use patterns through the spatial network, investigating the externalities of urban spatial and functional configurations on city transformation processes, housing price patterns and spatiotemporal co-presence distributions. This study introduced the additional proposition that measuring the functional centrality structure can help to predict place functionality in conventional configurational models. With various fine-grained data, this research has gone deeply into the fields of configurational studies, urban economics and spatio-social analysis in order to extend spatio-morphological analysis in general, and the space syntax model in particular, as the main component of a more integrated urban theory.

The purpose of this final chapter is to summarise the crucial findings and highlights of the previous chapters, which include the following: firstly, spatial structures represented by the urban function connectivity measures and urban regions complement the one captured by the space syntax centrality metrics; secondly, space syntax centrality and urban function connectivity measures are concurrently critical variables in models for predicting the variation of urban performance; and thirdly, configurational centralities of the spatial and functional structures are the main determinants for the formation of urban regions, house price submarkets and co-presence models in streets. Based on the findings and the empirical studies in Central Shanghai, and with the aid of relevant theories, this chapter revisits the theory of 'movement economy' and argues for the necessity of adding the function elements to frame a more inclusive theory. This chapter also discusses the potential implications inspired by the empirical discoveries. It advocates the importance of this research for morphological analysis and socioeconomic studies, as well as for the urban planning and design, on the practical side. The limitations of this research are then detailed, after which further steps for expanding the proposed framework in future are proposed. Finally, some closing words are offered.

2 OVERVIEW OF FINDINGS FOR EACH CHAPTER

Chapter 02 reviewed the relevant theory regarding measurement of spatial structures from various aspects. There is increasing consensus now that urban spatial structures are the descriptions of the landscapes for the (re)production of social processes after the 'spatial turn' in social studies, although their definitions are ambiguous in terms of theoretical propositions in various fields, the approaches taken for quantifying them and the spatial scales under discussion. This chapter firstly reviewed the evolutionary conceptualisation of centrality in urban theories as place's importance from its traditional definition as nodality—the absolute importance of centres, based on their internal features, to the centrality; the relative importance of centres relying on external interaction between centres; and then to a novel version, accessibility, using the internal characteristics of cities to approximate the external relations of centres in an urban system. This chapter then focused on reviewing the relevant literature, consisting of two main bodies of theory used to describe centrality structures: geographical accessibility, emphasising the benefit of activities patterns and the cost for approaching them, and configurational centrality, focusing on the nearness of the spatial network governing people's movement. The remainder of this chapter synthesised the similarity and differentiations between the geographical accessibility measures and the space syntax centrality measures in their theoretical and methodological propositions, and reviewed recent efforts made to integrate them. It suggests that there is a necessity of adding geometrical organisations of functional elements in conventional configurational analysis models, exploring relevant methodological enhancements and conducting empirical studies across cases. It is also noteworthy that emphasising geometrical descriptions of the functional centrality structures based on the interplay between the Euclidean and non-Euclidean distance metrics could shed fruitful light on both bodies of theory and the related empirical explorations.

Chapter 03 introduced an integrated framework in which the public space and the land-use distributions could be described quantitatively in relation to the spatial network that connects them based on a so-called path-point model (PPM) or network-interface model (NIM). The spatial centrality measures in the space syntax model contain two main types of centrality indices: angular integration (closeness) and angular choice (betweenness). This chapter delivered a method called urban function connectivity, meant for measuring various aspects of the functional centrality structures on the basis of the spatial network and land-use location data. By using the metric distance to define the buffers for a street segment in question, the proposed approaches measure the accessible function density, diversity and cognitive distance and package them as an integrated index to address the interaction among these principals. According to the composition of the quantified centralities for various types of complementary land-uses in each street, this chapter further projected a data-driven method to group and annotate streets to urban function regions. This typological description supplemented the introduced numeric depictions of the functional centrality structures whereby a comprehensive, deeper understanding of the land-use system can be produced. In a pilot study of Central Shanghai, this chapter introduced the morphological significance and statistical descriptions of all the introduced individual indices, representing the morphological significance of each centrality index at a certain radius and an accompaniment among them. Via a factor analysis, this chapter also identified five critical radii for the analyses in the rest of the thesis for reducing the redundant dimensions but keeping the most important information, as much as possible. This chapter introduced the novelty of using the check-in POIs dataset to present the 'place significance' on the demand side in the computation processes of the urban function connectivity measures. The extension and future enhancements of the introduced method could be achieved by taking into account the supply sides of the function locations and addressing the impact of the energy cost through a calibrated distance decay function.

By reconceptualising urban evolution as a centrality process through which spatial and functional centrality processes co-exist and co-evolve, Chapter 04 investigated the transformation of the urban centrality structures of Central Shanghai in the modern urbanisation process, captured by the shifting interdependence between the spatial centrality indices and the delivered urban function connectivity metrics, generated in tandem by spatial network and land-use patterns. Four critical snapshots of street networks and POIs in history were selected as a spatiotemporal description of the urban transformation of Central Shanghai. The results demonstrate that the centrality structures hidden behind the spatial network and land-use distributions have influenced each other dynamically through history. Certain degrees of inconsistency were observed between these two systems, and the characteristics of urban developments at various stages could be distinguished according to modes of spatio-functional interaction at multiple scales. The findings of the canonical discriminant analysis indicate that shifting complex interrelationships between the spatial network and land-use distributions are the major determinants of the formation of the urban function regions. The proposed framework offers valuable insights into the morphological evolution process of cities as indicated by the configurational interplay between form and function, and it represents a novel way to explicitly identify urban change.

Chapter 05 investigated the extent to which the spatio-functional centrality measures can predict the spatial variation of house prices and the delineation of the submarket. Due to the detected spatial autocorrelation of the residuals of the global hedonic model, a network-based mixed-scale hedonic model was employed to estimate the valuation of the residential properties and the segmentation of housing markets based on the network distance metric. In such a specified model, the submarkets pattern was determined and annotated by the spatially varying estimates on streets. The application of the delivered method in the case of

Shanghai City, China, confirmed the necessity of adopting a non-Euclidean distance metric to represent the coexistence between the stationarity and non-stationarity of the introduced street accessibility variables. The results provided the evidence that the impacts of street accessibility measures at local levels showcased significant spatial variation. It was common for all the places that the properties located on the streets with the higher levels of angular closeness, smaller values of angular betweenness and longer angular distance to the nearby land-uses at the larger scales would be priced higher. The outputs of the model showed that the delineation of submarkets based on the influences of the local factors, including the spatial and functional centrality indices at the local scales, along with some structural variables, performed with higher prediction accuracy than the traditional submarket specifications on the basis of the administrative areas or the typology of residential properties. The detected submarkets pattern showed that reachable land-use diversity at the pedestrian level was not a preferred factor in the housing submarkets located in the developed city centres. The signs of the price effects of the angular distance to local land-uses distinguished the developing submarkets into two main groups with different degrees of geometrical walkability. It was suggested that developing continuous stretches of pedestrian-oriented neighbours in walkable areas might contribute to decelerating the growth of housing prices in the developing submarkets to which these areas belong, in turn demonstrating that the variety of the spatio-functional interaction in the built environment might shape different trends of housing market development. The results of this chapter enriches the understanding of the socioeconomic effects of urban design with greater spatial precision across submarkets.

Chapter 06 examined the relationship between spatio-functional interaction and the face-to-face spatio-temporal encounters between different groups of social media users in public spaces. Using ubiquitous individual social media check-in data in Central Shanghai, China, this study proposed a framework for quantifying physical face-to-face co-presence patterns between defined local random walkers and remote visitors, over time and on every street. In the introduced a people-space-time (PST) model, social capital was reconceptualised as an integration between social differences, spatial distance (metric and geometric distance) and temporal distance. The reliability of the applied data and the effectiveness of the introduced methods were validated by the investigations of the scaling nature of the extracted mobility patterns and the correlation between the outputs and the surveyed data. The produced spatiotemporal patterns of face-to-face co-presence revealed that city centres and large-scale urban complexes (e.g., transport hubs, shopping malls and stadiums) were ideal places for people to encounter each other. The distribution of the co-presence modes in streets illustrated the boundaries of these central places and other detected groups of streets that were hierarchically interlinked with different characteristics of presence density and distance for various groups of social media users. The results of the regression analyses demonstrated that spatial and functional centrality measures were significant variables for predicting spatiotemporal co-presence and its modes in streets, among which the functional centrality structures maintain a higher standard of explanatory power than the spatial network. The temporal complexity of co-presence was revealed by the temporally shifting performance of the integrated regression models across time. The findings in this study showed that the spatio-functional interaction in streets influences the spatio-temporal variation of physical encounters between people and its emergent modes and reclaimed the theoretical necessity of adding fine-scale land-use patterns to the traditional configurational analysis in order to more thoroughly understand social processes when using urban big data in contemporary digitalised cities.

In short, this thesis explicitly defined the social significance of the spatial configuration and provided a novel, comprehensive framework to further illustrate that the spatio-functional interaction through the spatial network is the driving force behind the formation of social functionality. A series of findings in the empirical studies on various issues represented in this thesis implied that the dynamic interaction between the spatial and functional centrality structures impacts the diachronic processes of social development and its synchronic performance. The urban functional and spatial centralities are two main types of factors determining the variations of socioeconomic performance and its distinguishable modes across spatial networks. More importantly, the functional centrality measures, the urban function connectivity indices in this thesis, maintained greater predictive capability than the spatial centrality indices in the same models, due to their significant contribution to the enhancement of the model's predictability, although they cannot replace the latter. The variation of the coefficients' size and signs for the centrality indices in the regression models demonstrated that the impacts of the spatio-functional interaction differ for different social processes, which reveals complexity and divergence in how spatio-functional interaction is perceived by society in various social scenarios. Also, the differentiation between the determinacies of centrality variables for predicting the modes of the same social process showcased that the influence of centrality variables on social performance might vary across space. This thesis demonstrated that equipping the delivered framework can improve the preciseness of urban design to address socioeconomic issues according to the contextual locality. It further provided the possibility of using land-use allocation as a sort of 'soft' spatial intervention to amend social problems in coordination with other implementations in urban design.

3 A COMPREHENSIVE SPATIO-FUNCTIONAL INTERACTION MODEL

Throughout the analyses, spanning several crucial topics about urban performance and its configurational roots using the proposed framework, the empirical findings inform the relevant theoretical discovery. In this section, a hypothesised model summarising the typical ways that the spatial and functional centrality structures matter in the shifting urban performance is firstly discussed, and the focus then shifts to constructing a theoretical model to uncover the detailed process behind how the spatial network and the land-use distributions co-exist and co-evolve, shaping the observed movement patterns.

3.1 How does spatio-functional interaction affect urban performance?

Many aspects of urban performance can be addressed in urban studies. Two of the most vital quantifiable dimensions of urban performance are extensively attended to here: The first one is its *variation,* the numeric values indicating a progression of urban performance; the other dimension is its categorical *modes,* a grouped or classified pattern captured by the inherent statistical structures. The former is more like a mathematical description of urban performance, whereas the latter one is about the morphological explanation of the categories of urban performance in different places. The analytic chapters of this thesis focus on these types of urban performance, and their variations and modes are found to be determined by spatial and functional centrality structures simultaneously. This relationship is summarised in an ideal model and illustrated below (Figure 7-1).

First of all, as stated already, the spatial and functional centrality variables at various scales are significant factors for predicting the dependent variables indicating the variation and mode of urban performance in streets. Admittedly, the configurational centrality variables are not the only determinants. For example, in the analysis of the spatially varying housing price patterns in Central Shanghai, the structural features of the residential properties are found to be important determinants. Moreover, the social conditions, such as the levels of local urbanisation, matter in the processes of interpreting the performance of the configurational centrality variables. Regression models provide a perspective, in which equilibrium between dependent and independent variables is formed. This equilibrium, sometimes, cannot be interpreted if the social context of the model is ignored. In other words, social conditions formulate the basic backgrounds where the detected equilibriums captured in regression models are formed; consequently, they impact the way that the centralities are perceived by the people and finally embodied in the observation of urban performance. Moreover, it is noted that these effects of centrality structures on urban performance are neither spatially nor temporally stable. For certain types of urban performance that are as spatially heterogeneous as housing price pattern is, spatial and functional centralities might be priced differently from place to place. For a specific class of performance that is as temporally varied as encounter patterns are, syntactic centralities are influential in different ways from time to time.

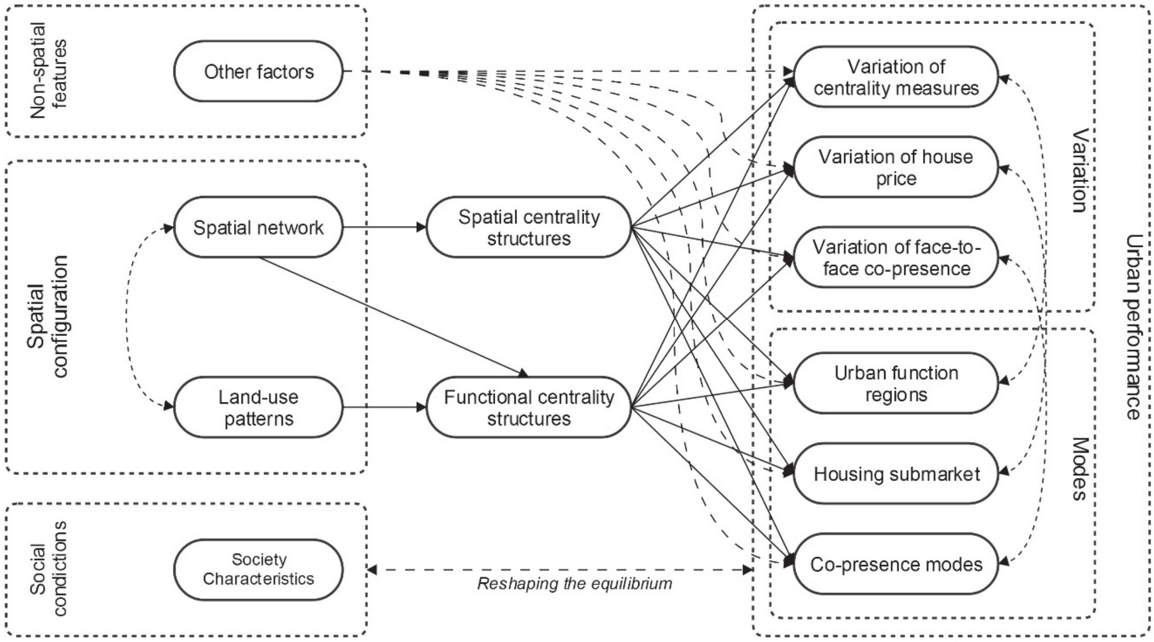


Figure 7-1

Diagrammatic structural equation between spatio-functional interaction and socioeconomic performance

3.2 How does spatial network interact with land-use system?

In the space syntax theory, the theoretical position of spatial configuration is emphasised in Hillier's theory of *movement economies*, in which the configuration of the urban grid shapes the urban movement, and then the movement affects the land-use reorganisation (Hiller et al., 1993; Hillier 1996). In his argument, form and function are interdependent at different scales according to the part-whole structure of cities, and the agreement between spatial structure, movement, and land-use agglomeration becomes a positive feedback loop between the spatial structure and the following reorganisation of the land-use patterns, thereby influencing the movement-related social significance. This argument successfully contributes to reclaiming the vital roles that urban form and functions play in shaping urban social processes with the well-established theoretical purity.

However, as socioeconomic performance is increasingly complex in post-modern large cities, which exhibit rapid urban change, the role of existing land-use networks in producing urban vitality should be explicitly identified rather than being simply summarised as ‘multiplier effects’, as they normally are in space syntax theory. On the basis of the evidence in previous chapters, this thesis proposes that urban movement can be conceptualised as the product of the process of the spatio-functional interaction, which could be considered the extension of Hillier’s model of movement economy, by unfolding the multiplier effects exerted by the functional structures (Figure 7-2). The dynamic interplay between perceived spatial structures and the land-use system creates a sense of spatio-functional synergy which is a fundamental determinant of *natural movement* (Hillier et al., 1993; Hillier 1996), including pedestrian and vehicular flows, and it has further impacts on land-use distributions, density of buildings and other aspects of spatial sustainability (Hillier 2007).

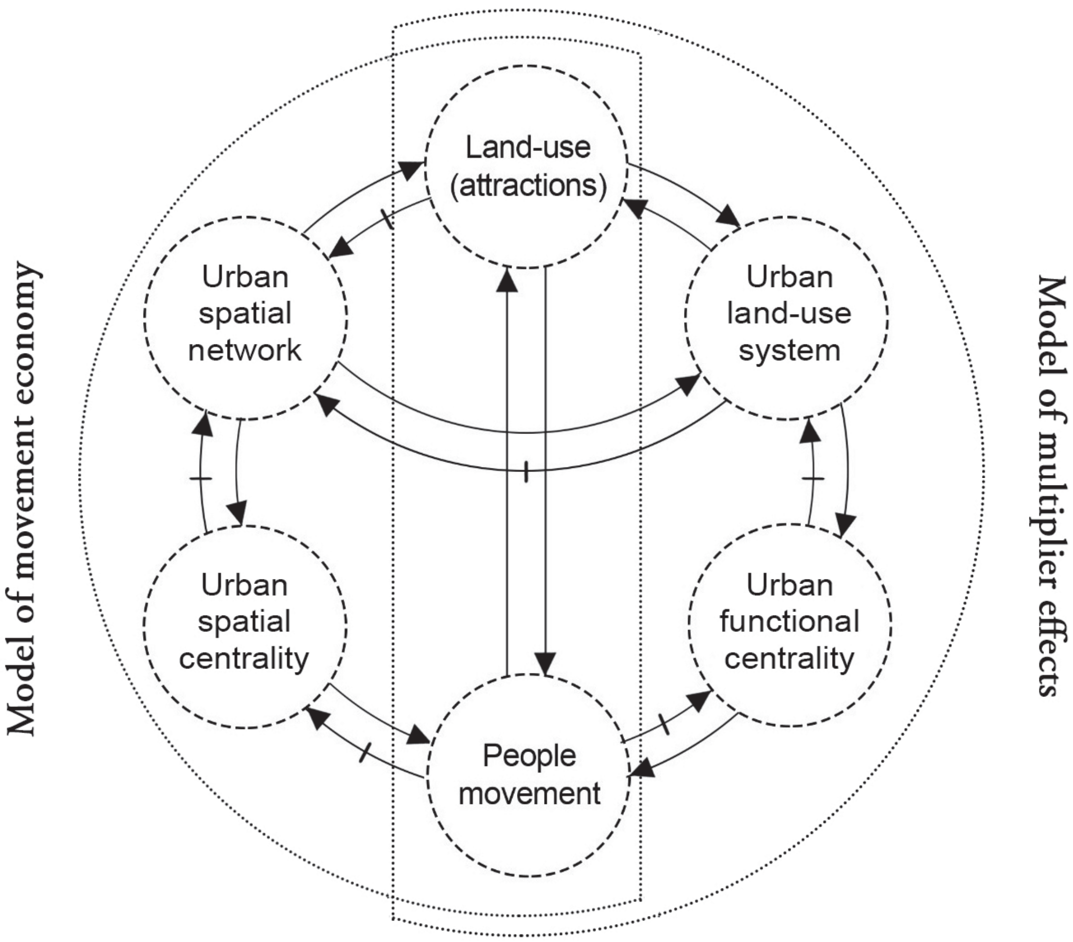


Figure 7-2

The spatio-functional interaction in the process of the movement economy

Figure 7-2 shows the identified 'spatio-functional interaction' in the process of the (re)production of the movement economy, in which urban land-uses or attractions and the movement of people have a mutual influence on each other. There are two sub-models in this modified model: the one is Hillier's model of movement economy, and the other is the model of multiplier effects, in which the functional centrality measures proposed in this thesis are used to reveal the mechanism by which the multiplier effects work under the impacts of existing land-use patterns and spatial layouts. In this model, the observable movement patterns are affected by the spatial and functional centrality structures produced by urban spatial network and land-use system. Urban land-use system consists of the land-use locations and their spatial connections, which suggests that the urban land-use system is fundamentally shaped by the spatial network and the land-use locations. However, the spatial network is not necessarily affected by the attractions distributions over a short period. This timeline means that the spatial network stimulate non-reciprocally the allocation of land-uses and the change of land-uses through reshaping the way they are interconnected. These effects are further reflected by the empirically observed movement of people, which are considered outcomes of the spatio-functional interaction in the built environment. Adding the function elements in the movement economy model captures the constant and complex interaction between spatial configuration and land-use system in urban reality. Compared with the classic space syntax theory, the introduced spatio-functional model—an extended version of Hillier's model of movement economy—can augment current knowledge of urban socioeconomic process with a dynamic perspective to address the short-term movement change biased by land-use patterns, an advanced understanding of self-adjustment in the land-use transformation processes, and an appropriate consideration of the path-dependency of urban evolution.

Dynamic

Hillier's model of movement economy is a long-term model suggesting that attractions are generated progressively by spatial configuration instead of being produced by the people's motivated agencies over a short period. The spatio-functional interaction model introduced here proposes that the short-term emergence of various attraction locations (re)formed in several processes including land-use densification, diversification and cost-saving process, as well as some zoning policies. These temporal processes can be delineated by the introduced function connectivity measures since the motivated agencies of individuals will be impacted by the existing distributed attractions. This logic has deep roots in location theory and spatial economics, in which land-use locations, the retail locations in particular, could be the result of market sharing and subdivisions (Hotelling 1929; DiPasquale and Wheaton 1996;

Christaller 1933; Losch 1954), the complementary agglomerations (Eppli and Shilling 1993) and the competitive clustering (Eaton and Lipsey 1975). These models have successfully counted for the immediate effects of existing land-use patterns on subsequent land-use location decisions, whereby addressing the functional elements in the spatio-functional model makes it possible to provide the *dynamic* perspectives to the existing framework of the static space syntax analysis.

Self-adjustment

The second advantage of the spatio-functional interaction model is its capability to illustrate the detailed developing process of urban centres. In conventional space syntax theory, land-use patterns are typically conceptualised as the corresponding layers of spatial configuration, which delimits the development of knowledge regarding the detailed phases of the land-use, such as land-use densification, diversification, cost-savings, spill-over, and so forth. Against this background, this thesis has introduced concepts of urban function connectivity measures to capture the self-adjustment of land-use network within the developing process of centres through streets over time. The dynamic self-adjustment process includes various specific modes, for example land-use densification, diversification, diffusion (spill-over), decline, and the like. These changes have not been explicitly defined in conventional space syntax models, but can be appropriately captured in the spatio-functional interaction model. By comparing the change of accessible land-use density and diversity, people can scrutinise how land-uses become fewer and scattered, or more clustered and mixed. Moreover, looking at the change of the delivery efficiency of the land-uses or at the mean angular depth to accessible land-uses in the condition that urban density and diversity are controlled can enhance understandings of morphological spill-over effects. As argued in the aforementioned context, the positive feedback loop can be triggered by the change of spatial configuration and delivered though the existing land-use system, which can be understood as the *self-adjustment* of land-use patterns, which would generate the new equilibrium between urban spatial and functional centrality structures.

Path-dependency

Although spatial centrality is one of the fundamental forces driving land-use change and the associated morphological transformation, future land-use change is still impacted and constrained by the present functional patterns. The existing land-use also provides the map of potentials for spatial interactions, which means that the urban transformation process is path-dependent and that any current status would be rooted in its past status. Furthermore, the attractions would be differently sensitive to the change of configuration according to their typologies. For instance, the commercial venues, in general, will react to movement change quickly, whereas large scale urban functions, such as stadiums and libraries, are less likely to be moved and have a lower level of tolerance regarding location advantages. This tendency suggests the differential evolution of the elements in the function landscape with *path-dependency*, thereby illustrating the observed temporal homoeostasis between spatial and function system is related to the historical patterns and indicating that the tension between the new and the old exists universally. In traditional space syntax analysis, the centralities of the physical layout can successfully capture the driving force to change the function patterns placed by urban design, but the centralities lack the capability to quantify the forces to maintain or shift the future urban functional structure exerted by the existing patterns of functions. With the new focus on the existing functional structure, the proposed measures of the urban function connectivity can contribute to opening up deeper understandings of the current urban status and its impacts on the further change.

4 POTENTIAL CONTRIBUTIONS

4.1 Contributions to space syntax theory

The findings in this thesis bear some important implications for morphological analysis, and the space syntax theory in particular. The first main contribution that this thesis makes is the confirmation of the importance of the geometrical patterns of land-uses in configurational studies and the methodological development of the urban function connectivity measures for analysing multi-dimensional functional centrality structures in a comprehensive framework based on graphic representations combing function locations and the street network. This research supports the basic theoretical proposition of space syntax research that the layout of public spaces can be innately comprehended by people, and it provides an extended argument that urban function locations, as the destinations of daily routes, are even more easily understood because of their innate utility for citizens. Therefore, the spatial layouts of urban form and function are the perceivable built landscape for the allocation of urban movements.

In addition, the results of empirical studies in this research imply that the spatial configuration, including its spatial network and functional systems, influences different social processes via discriminable mechanisms; its impact on one social process might vary across space and across time. The research on house-price patterns and spatiotemporal face-to-face encounter distributions in this work verifies this argument and highlights the necessity of addressing spatial and temporal 'localness' for spatial network analyses in the space syntax model and of implementing appropriate spatiotemporal policies.

The findings produced by the spatial regression and data mining approaches in this thesis also suggests that space syntax studies can benefit immensely from advanced statistical modelling methods and large or even full-size samples to robustly generate in-depth causal relationships between centrality variables and performance observations instead of the simple correlations. In all the analytical chapters, all of the samples for every street are focused on and analysed with rigorous multivariate regression models according to the specified requirements, in which the arbitrary sample selection, and the erroneous interpretations of variables' effects due to the multicollinearity among them, can be effectively prevented. Additionally, this work delivers evidence that validates the reliability and applicability of utilising volunteered geographic information data from social media for the future development of space syntax methods. The introduced method in this thesis illustrates an alternative way of incorporating social media data with spatial network analysis to quantify the urban function centrality structures from street to street.

4.2 Contributions to socioeconomic theories

The proposed methods and empirical results of this thesis contribute to socioeconomic studies in several ways. Firstly, the findings indicate that social processes depend on factors widely discussed in the well-established theories in the field of urban studies; and more importantly, they rely on the way they are accommodated by the built environment. The encouraging predictability of regression models with centrality variables reveals that the centrality factors of spatial configuration are not simply a summary of the structures of built environment but also a series of promising variables for estimating the socioeconomic performance. It is shown in this work that the models with only spatial and functional centrality variables can have novel explanatory powers, illustrating the goodness of the delivered variable structure. Moreover, the introduced centrality variables representing the general terms used in urban design, such as density, diversity, distance, and so forth, do not require any prior knowledge of the study areas, which forms a basic proposition for using these variables in other socioeconomic analyses.

This thesis also informs the theoretical findings for other detailed socioeconomic topics. Specifically, it is found that the typical ways in which spatio-functional interactions occur are influenced by the changing ideas of urban design during various periods of the urbanisation process. The modern structures of Central Shanghai maintain lower degrees of synergies between the spatial and functional centrality patterns at the smaller scales and higher levels of the spatio-functional synergy on the larger levels than that in history, showcasing that the modern Chinese cities are more vehicle-oriented. This trend was reversed in history when city size was relatively small and organically organised. The rapid spatial expansion does not naturally lead to a change in the structure of urban centres, but functional expansions with spatial consolidation result in the reorganisation of the hierarchy of centres. In the processes of housing economics, this work suggests that houses are priced by people according to their demands on the spatial convenience and privacy at different locations, represented by the spatial and functional centralities of the spatial configuration across many scales. The price effects of centrality variables are not spatially uniform, and their spatially varying influences on house price contribute to the formation of submarkets. To map the spatiotemporal face-to-face encounter patterns, the angular distance between the check-ins generated by social media users is a critical type of social capital for them to meet. In the meantime, the physical co-presence intensity is determined by the proxy between different functions and between spaces in the spatial configuration. This relationship, however, is not temporally uniform. Meanwhile, the modes of physical co-presence can be largely predicted by the spatial and functional centrality structures, implying that the places that are spatially and functionally well-connected anchor the online and offline interaction in current society. These findings yield deeper theoretical insights into socioeconomic phenomena from the urban design perspective with the explicitly identified mechanisms.

Furthermore, the proposed analyses in this thesis are vector-based at the street level, an approach that is rarely adopted in the traditional socioeconomic studies. An advantage of these results at the disaggregated level is its ability to avoid the scale-dependency for collusion making and the related modifiable areal unit problems (MAUPs) and producing the high-resolution results for visualisation. Therefore, in this thesis, the theoretical and methodological significance of urban streets in urban studies are reclaimed in the future analysis of the socioeconomic performance.

4.3 Contributions to urban design and planning

This research has several possible implications for urban planning and design. Above all, the land-use allocation and the design of urban form should be considered coextensively, which makes the spatial intervention more strategic. Rather than being the by-products of spatial design, the land-use patterns are argued to have their own centrality structures, exerting unreplaceable effects on place functionality. Moreover, it is noted that urban design plans can produce complex socioeconomic effects which are not always linear and clear. Any spatial intervention might exert varying effects at different scales, even with different signs for urban performance. Therefore, unfolding the combined effects of centrality structures on urban vitality with methodological meticulousness has turned out to be a key challenge for today's urban designers. This thesis provides a methodology to use spatial and functional configurational synergies to produce spatially functional environments and to retrieve the necessity of addressing the 'locality' in urban design for enhancing its effectiveness and precision across places. This study confirms the existence of the spatial heterogeneity of the socioeconomic effects of centrality variables, which suggests the symbolic significance of taking into account these local areas to improve the accuracy of the models with configurational variables for predicting performance patterns. The proposed and verified methods of detecting the areas with local effects in this research can be helpful reference for relevant urban design practices.

Furthermore, it is essential to understand the important relationship between the cyber space for the interaction among the users of digital technologies and the real public spaces. In other words, understanding how the real public spaces and the virtual landscapes are bound together is also a task for future urban design research. The development of a morphological method based on the ubiquitous urban big data is the priority for advancing this goal. The proposed research framework and detailed methods with the social media data in this thesis can be considered as a step towards bridging an analysis of the digitalised cities with a configurational study of the built environment.

5 LIMITATIONS

5.1 Data availability

Although this study has used a large amount of data, issues regarding lack of data availability persist. Specifically, the weights of urban amenities on the supply side are simplified to be the same, indicating that the service capability of land-uses is even. This research uses social media scores (check-ins) to represent the place popularity on the demand side. Nevertheless, the place popularity for all the historic land-use locations is assumed to be even due to the absence of information regarding the popularity of urban activities. Richer analyses of the function patterns may be extracted in the future when more data become available. In addition, the proposed analyses of socioeconomic performance can be further validated with the historical socioeconomic data, aiming to illustrate the temporal causality in the detected interrelationship between centrality structures and spatial performance.

5.2 Generalisation for other cases

This thesis anchors its focus on fast-growing cities, using Central Shanghai, in which an intense interaction exists between the rapidly growing spatial grids and the fast adjusting land-use patterns. It has been recognised that pedestrian patterns of pre-modern urban areas are made more predictable by the spatial centrality properties than in modern urban layouts where functional factors play important roles in explaining the attributes of pedestrian distributions (e.g., Lerman and Omer 2013). This recognition formulates the fundamental proposition and the significance of investigating the spatio-functional interaction in rapidly growing modern cities in this thesis. Based on the outputs of the present studies, it is increasingly valuable to ask whether the symbolic significance of the spatio-functional interaction can be discovered in other fast-expanding metropolises and in cities that are more self-organised and naturally transformed. Thus, more studies on different types of cities are required to verify the universality of this thesis's conclusions.

5.3 Variable structure and advanced models

Throughout its analyses, this thesis has employed rigorous regression models to quantify the causal relationships found. In fact, the interpretation of the causality in the relationship between the independent and dependent variables is conditioned by the data quality and the methodological limitations. As a consequence, the regression modelling approaches used in this study can be enhanced to discover the underlying causality in the found correlations. Firstly, other variables with solid propositions in relevant theory could be added to the configurational variables into the models so that the essential impacts of the factors representing the design of the built environment could be further confirmed. In other words, the introduced methods in this thesis can be further validated though a comparison to conventional methods that combine land-use factors and centrality variables. Also, there are considerable degrees of circular causality existing in the introduced models, which resulted from the autocorrelation between the centrality variables at the proximal radii. This phenomenon reveals the difficulty of predicting the consequence of changing the value of a variable.

To minimise the awkward situation in which the simultaneous influence of two related variables on a third is not additive, interaction terms, indicating the combined effects of several variables, can be considered for addition in the regression models, with the aim of taking into account the moderated effects of the explanatory variables. Simultaneously, the introduced centrality variables can be used as the inputs in more advanced models to produce additional insights into the spatial strength for the social (re)productions. For instance, methods of structural equation modelling, including confirmatory factor analysis, path analysis, and the like, can be adopted to assess the unobservable 'latent' constructs among variables. In these models, the hidden hierarchical structures of the dependent variables can be illustrated.

Also, the spatial autocorrelation among dependent variables should be properly addressed in the modelling processes of large-size samples. In this thesis, the spatial autoassociation effects in house price patterns are modelled in a mixed-scale hedonic model with the samples of residential properties that are less than 10,000. However, this network-based GWR model could not be used in other analytical work in this this thesis since the street-based samples are nearly 70,000, representing a computational task nearly impossible for a desktop computer. With the help of emerging technologies, such as cloud computing and ever-better algorithms, future spatial regressions models at the street level with the capability of handling very large amounts of data might offer unprecedented opportunities to understand the correspondence between spatial and social processes in cities.

6 FURTHER RESEARCH

The case study of Central Shanghai, China, conducted in this thesis suggests several directions for the future exploration of relevant topics. Further efforts can be made in the following respects, although efforts should not be limited to these suggestions.

6.1 Spatiotemporal urban function connectivity

This study shows that a social media dataset is an effective representation of the spatiotemporal collective spatial behaviours of people. One key methodological development is producing temporal descriptions of the urban spatial structures. This effort has symbolic significance on the morphological analysis, and the space syntax research in particular, as the conventional morphological portrayals are typically static, lacking the capability to illustrate short-term transformation. With the increasing availability of volunteered geographical information with temporal variations in social media, the proposed methods of measuring the urban function connectivity patterns can be advanced to the temporal version to represent the 'live' analysis of the spatial structures. This improved method will extend our current knowledge of the spatial configuration to a finer time scale, from years to days, and even hours, if relevant data are available. Despite that urban design normally serves long-term developmental aims, computing the spatiotemporal urban function connectivity metrics can illuminate the immediate effects that proposed design plans and strategies will bring to the urban context. This aim can be achieved by adding information regarding time-related accumulated check-ins for all the land-use locations in the research framework of this study. Future efforts addressing time-based planning issues, for example, making the roads safer at night, can take advantage of this development.

6.2 Functional visibility graph analysis

One core conclusion of this thesis is that urban public space is not only characterised by the connection of visible spaces, but also featured by the visible functions, thereby creating a different sense of place in humans' minds. This insight forms a fruitful theoretical and methodological proposition for future extension of the proposed method dealing with micro-scale spatial network analysis. An effort can be made towards enhancing current visibility graph analysis (VGA) in a space syntax model with the scored land-use distributions. By conceptualising public spaces as a set of view shields or isovists linked by edges in a visibility graph representing the mutual visibility between spatial locations and functional places, micro-spatio-functional interactions though public space in the dense built environment can be appropriately measured.

An example is shown in Figure 7-3, where the way in which urban functions are visible from every part of public spaces is formed by the spatial visibility graph, and the land-use locations are illustrated. Just as in the proposed urban function connectivity measures, the visible function density, diversity and the cognitive distance to the visible functions at any given radius can be calculated. The interplay among these three dimensions can be integrated as an integrated index—function visibility—a version of the urban function connectivity on the micro level. Urban spaces, represented by the cells filling them, can be grouped according to the composition of urban function visibility with various types of functions. Tapping the framework of the urban function connectivity into the visibility graph at microscales or the architectural plans with information on spatial occupation allows for detailed study of the function centrality structures of the architectural spaces. This extension, analogous to an attempt to account for land-use in a conventional VGA analysis, can provide additional, valuable perceptions into the analyses of the occurrence of urban regeneration process within the developed built environment where spatial grids are relatively stable, as well as into the configurational properties of urban complexes with significant attractions, such as tube stations or the shopping malls connected to them. In short, adopting the introduced methods of quantifying function centrality structures with the visibility graph representation can empower the VGA analysis of the architectural spaces with complex functional settings.

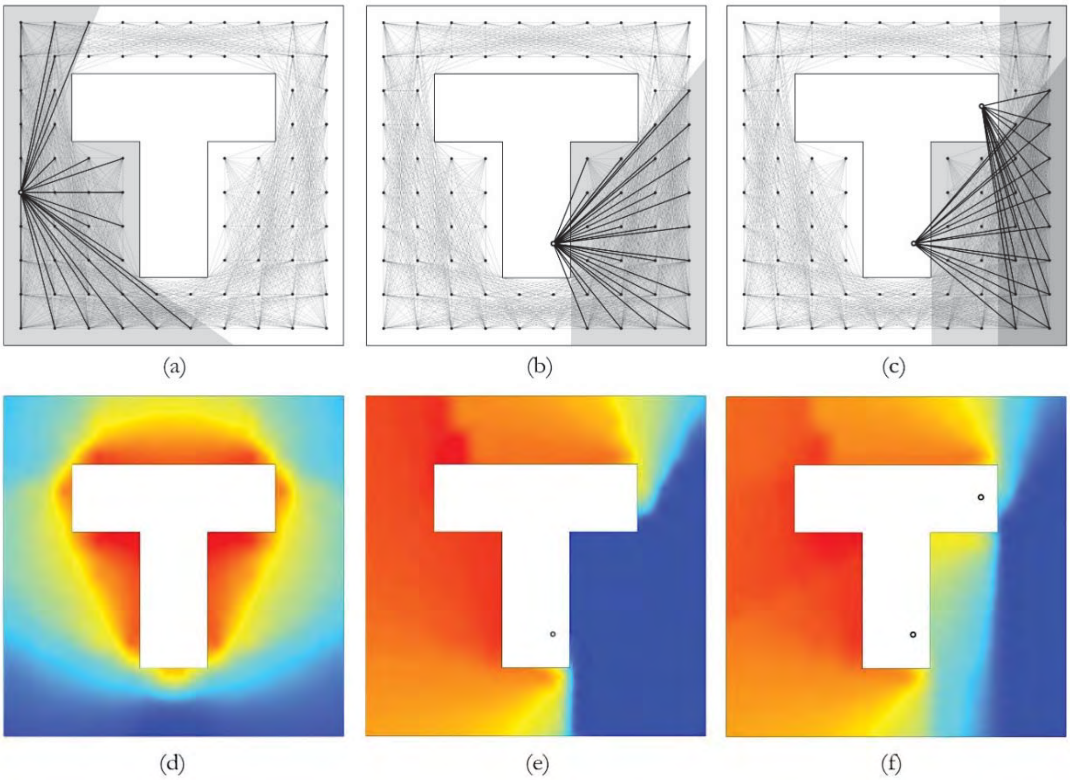


Figure 7-3

The formation of visibility graphs and the mean depth patterns with public spaces and land-use locations: (a) The pattern of connections for a simple spatial configuration in a first-order visibility graph; (b) the pattern of connections for a simple function location in a first-order visibility graph; and (c) the pattern of co-connections for two simple function locations in a first-order visibility graph; (d) The pattern of angular mean depth for a simple configuration; (e) the pattern of angular mean depth from a function location; (f) the pattern of angular mean depth from two function locations

6.3 Dynamic modelling of urban change

In geography, extensive efforts have been invested into the simulation of urban change with various simulation technologies. Cellular automata (CA) and agent-based modelling (ABM) methods, as the two types of the most popular stochastic simulation approaches, have been adopted in predicting the urban expansion and land-use change at different scales from the bottom up (e.g., White and Engelen 1993; Clarke and Gaydos 1998; Batty 2007). Two vital concepts in the computation of cellular automata are the calculation of accessibility and the definition of the neighbouring relationship that governs the allocation of the transit probability of urban entities. On the other hand, the accessibility on various scales is evaluated differently by the agents in a system, and they interact with others stochastically to generate emergent patterns with a calibration based on observations. Combining the proposed methods in this thesis with these dynamic modelling methods will enable future exploration of minute urban change. For instance, for predicting land-use change, the urban function connectivity measures at various radii can be used to (re)calculate the updated functional accessibilities within multi-scale neighbouring conditions after the (re)allocation of land-uses at every step in the simulation processes. This integration can improve the precision of the conventional CA or ABM models at the small levels; in turn, it can provide an alternative way to conduct spatial network analysis with the enhanced dynamic predictability of urban changes. If a visibility graph is constructed, as stated in Section 6.3, the method designated in this thesis can also be utilised in combination with the traditional agent-based analysis in the space syntax model to represent the visual dynamics of spatio-functional morphology (Figure 7-4). The accuracy of such a model for estimating dynamic movement patterns can be upgraded. The proposition that the functional built environment properties can add symbolic value in the space syntax's agent-based analysis for modelling pedestrian gate counts at the urban scale has been verified in other recent studies (Omer and Kaplan 2017). Future work can move towards in-depth advances of the dynamics of urban movement in the spatio-functional built environment.

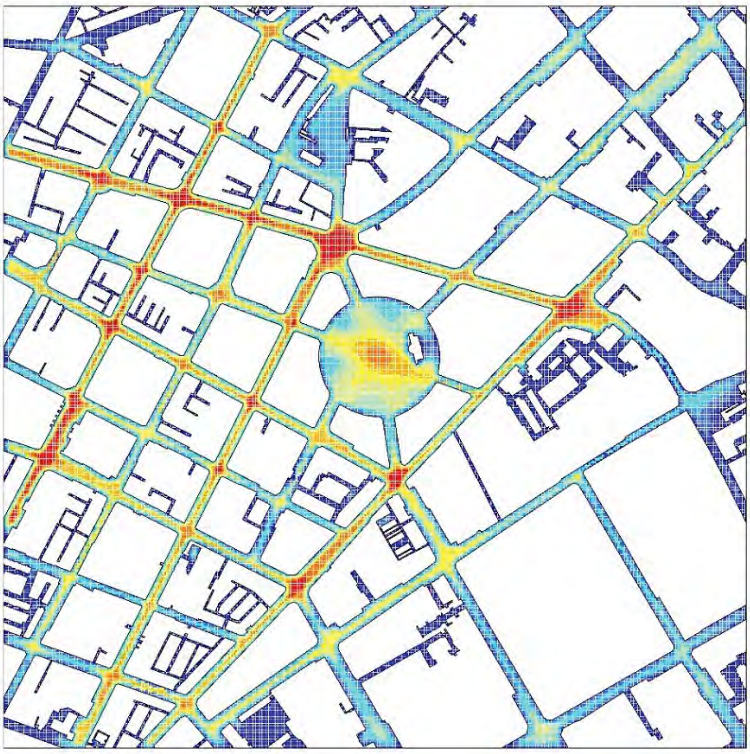


Figure 7-4

An example of an agent-based approach to estimating pedestrian flows with the visible function centrality measures

7 CLOSING WORDS

Cities are places for accommodating various interactions. To understand the relationship between urban form and its functionality is one of the most challenging tasks in modern urban design against the background of a built environment, where we are living, that has been expanding at an unprecedented speed, faster than at any stage in the history of urbanisation. It is argued in this thesis that social processes are highly complex, and the underlying interactions between the spatial and functional centrality structures across scales characterise urban performance over time.

The unclear and weak linkage between spatio-functional dynamics and urban performance is especially evident in modern Chinese cities, where the tension between form and function and between the new and old is increasingly significant. Modern urban design approaches allocate functions based on over-simplified geometrical logics, thereby separating citizens spatially and functionally, lowering the efficiency of the organisation of urban potentials and resulting in a series of social problems. This trend fuels debate over whether and how urban design can be an instrument to upgrade the social functionality of urban contexts left behind by rapidly growing spatial grids. Aiming to address this question, new knowledge produced in the present thesis contributes to the improvement of the social effectiveness of urban design by illustrating the mechanisms by which spatial and functional centrality structures have social consequences. It is argued that socially functional urban design can hardly be made if people fail to quantify the urban spatial and functional contexts, particularly in fast-changing modern environments, where mismatch between form and function is more significant than in pre-modern environments. Therefore, designing more sustainable cities requires advanced knowledge of the interdependence between social performance in public spaces and the spatio-functional interaction within the larger spatial and functional backgrounds in which they are embedded.

In this thesis, it is contended that understanding the complexities of spatio-functional interaction in a morphological analysis can enhance the efficiency of urban design and planning interventions, which aim to improve social conditions. It is more valuable for urban designers, planners and decision makers to understand the mechanisms by which observed urban changes are driven by the balance among the varying effects exerted by configurational circumstances, or other factors, and make spatial interventions transparent and tactical. It is also claimed in this research that urban design practices should pay attention to the locality of the mechanisms, in which the characteristics of urban performance and the social effects of centralities tend to be similar. Two essential prerequisites to making a good urban design scheme for one area are as follows: firstly, taking into consideration the contextual physical space and land-use patterns; and secondly, taking actions that suit the local circumstances identified by homogeneous impacts exerted by spatial and functional centrality structures and other significant factors.

Throughout this research, the adopted methods are as rigorous as those employed in today's social and economic studies, seeking to avoid assertive conclusions made based on simple correlation analyses and aggregate data (Omer and Jiang 2015). These efforts take a step toward the goal of empowering the approaches to assess specific plans for urban designers in practice with improved precision. They also provide a microscopic tool for the policy makers and other professionals to refine the regional policies into architectural spaces and to coordinate policies with design strategies aiming to maximise their effectiveness and efficiency across spaces in consideration of the spatial and functional contexts. Another essential feature of the introduced model is its compatibility and scalability with ubiquitous 'big' data emerging in the current digital society. Exploiting the advantages of quantitative modelling and visualisation with urban big data allows one the opportunity to bridge configurational studies with socioeconomic research, on the theoretical side, and to encourage more inter-disciplinary communication, on the practical side. The models in the present study, through far from perfect due to some methodological and technical limitations, formulate a benchmark for future extensions focusing on exploring the configurational logics of social phenomena.

This thesis creates a broader picture showing urban centrality structures hosting the transformation of urban quality. More precisely, it is argued that it is the spatio-functional interaction in the built environment which facilitates various aspects of the socioeconomic vitality from place to place and from time to time. The produced knowledge not only suggests a valuable extension of the current space syntax model, in which the functional centrality structures supplement spatial centrality patterns, but also indicates possible enhancements in the analyses of socioeconomic performance, which can be achieved by taking advantage of the methodologies established and verified in this thesis. The proposed methods can be new tools not only for urban designers but also for cross-disciplinary professionals to take a series of effective actions with the precision of fine-grained, intra-city detail.

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APPENDICES

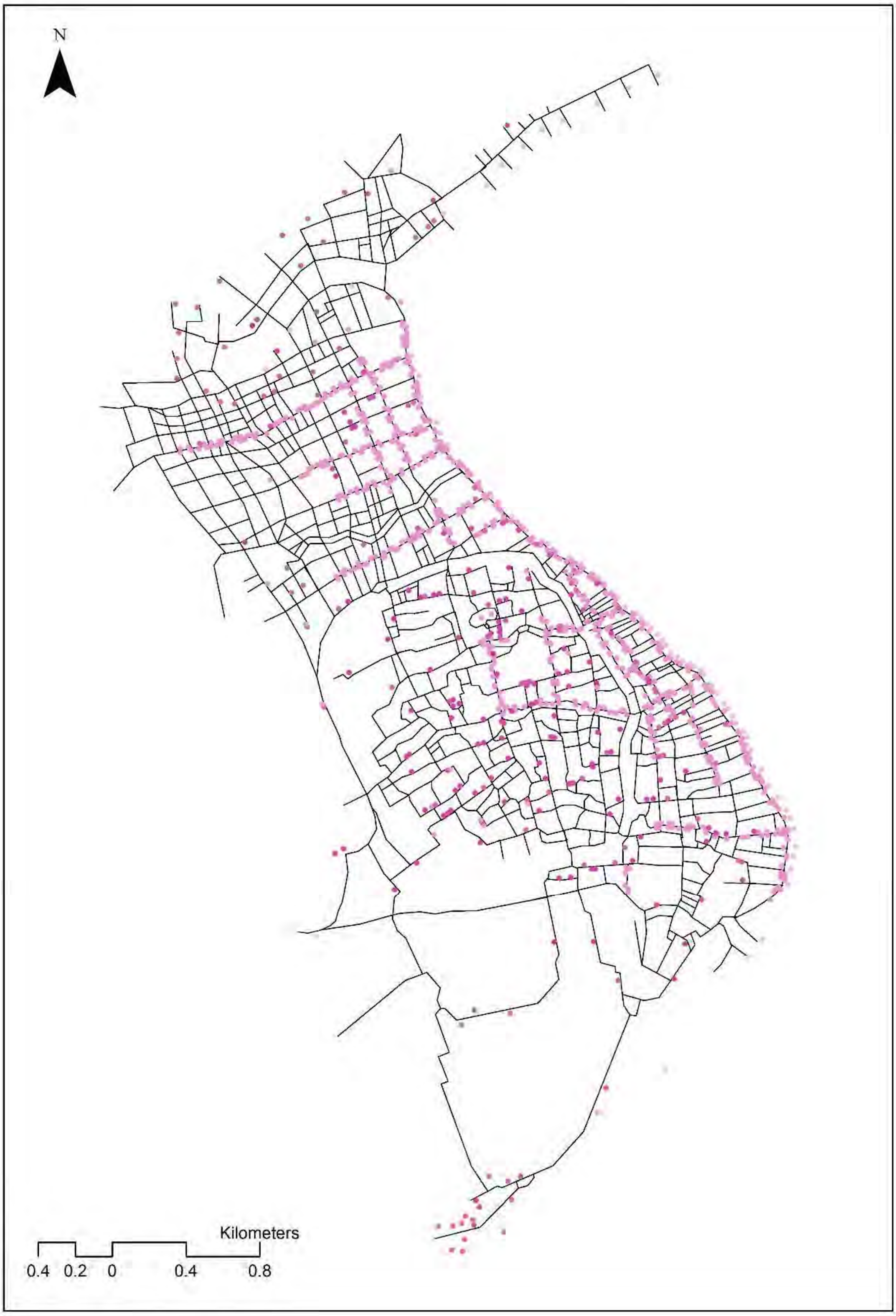

Figure A4-1

Geocoded points-of-interest and the street network data in the 1880s

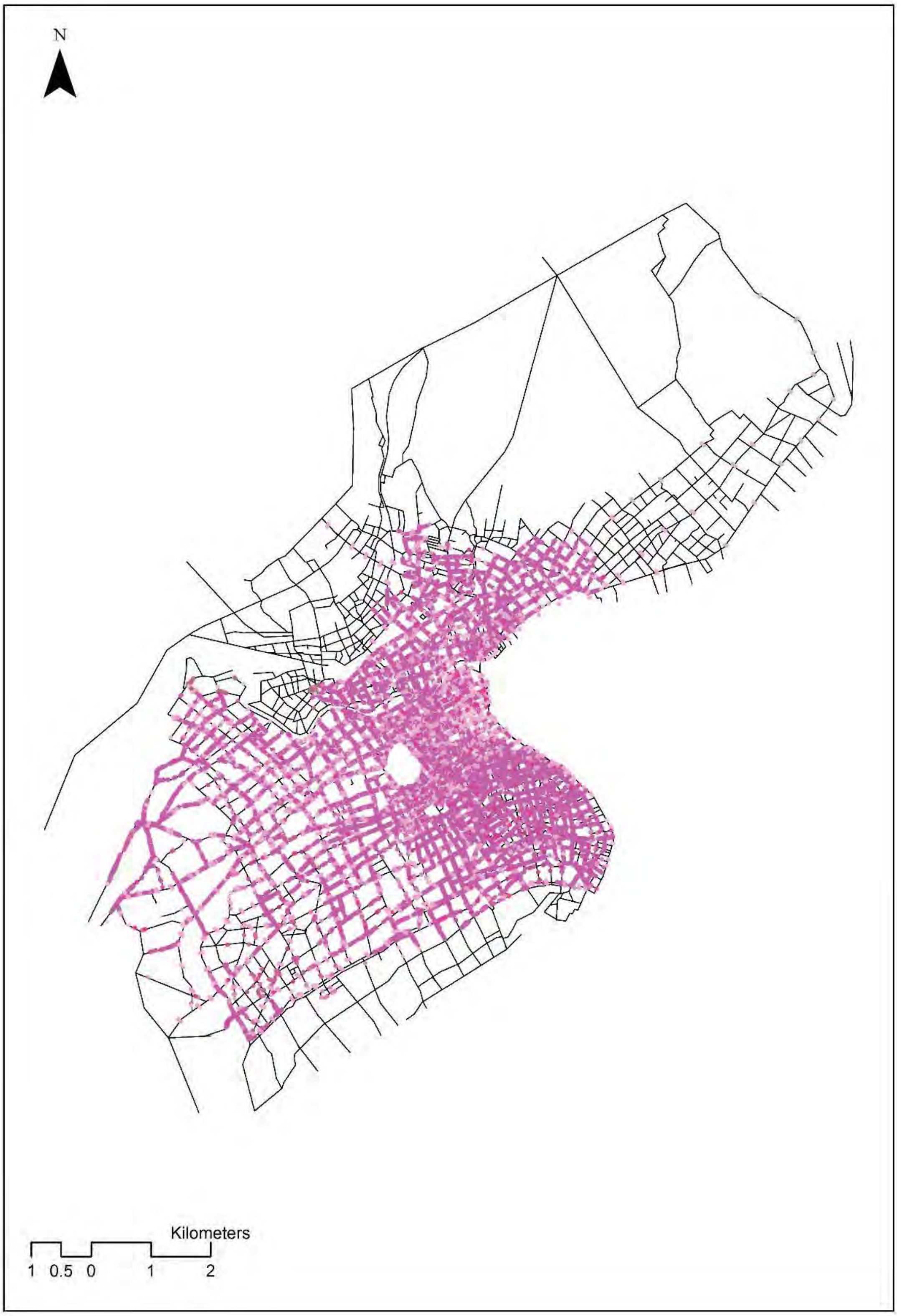

Figure A4-2

Geocoded points-of-interest and the street network data in the 1940s

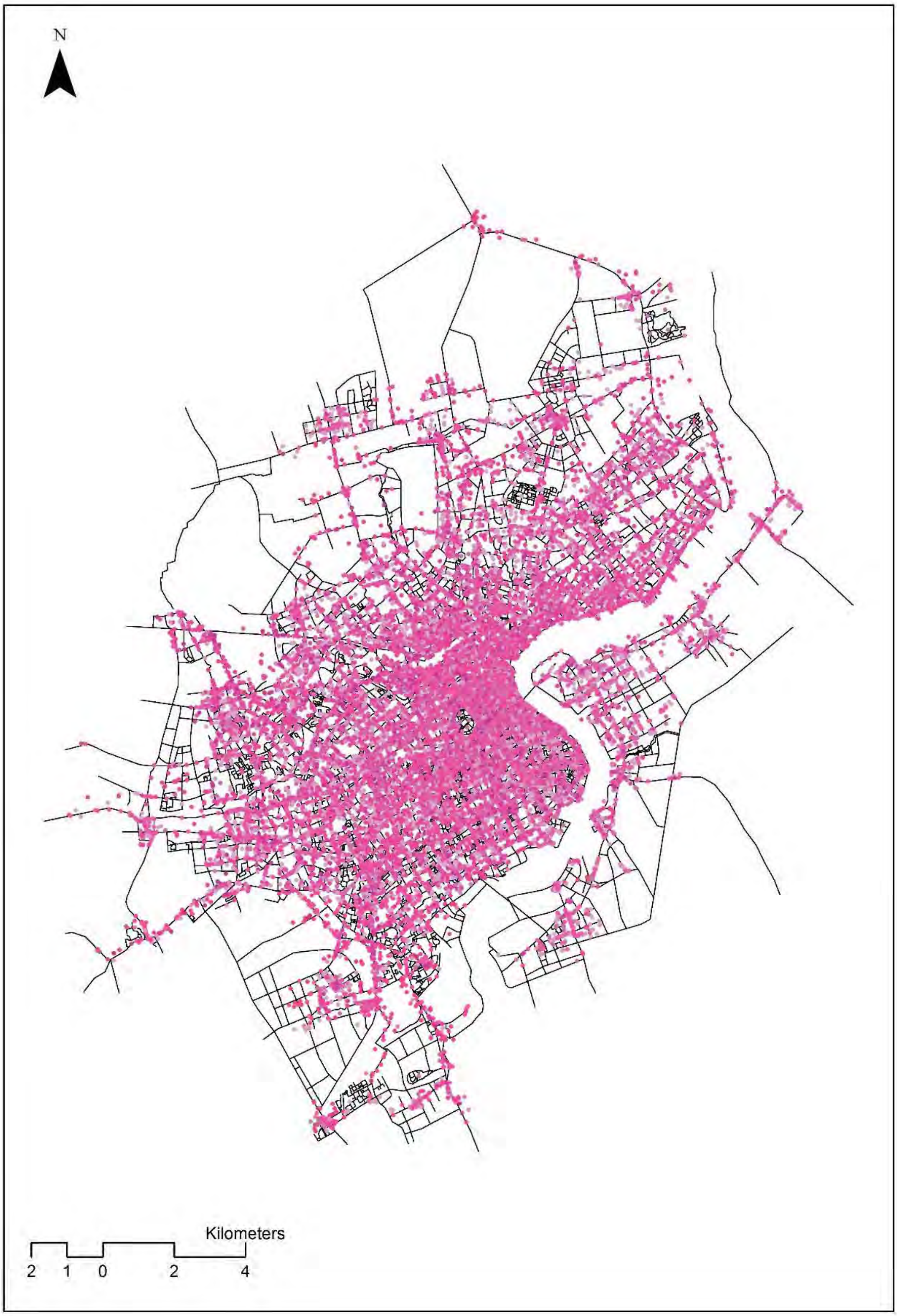

Figure A4-3

Geocoded points-of-interest and the street network data in the 1980s

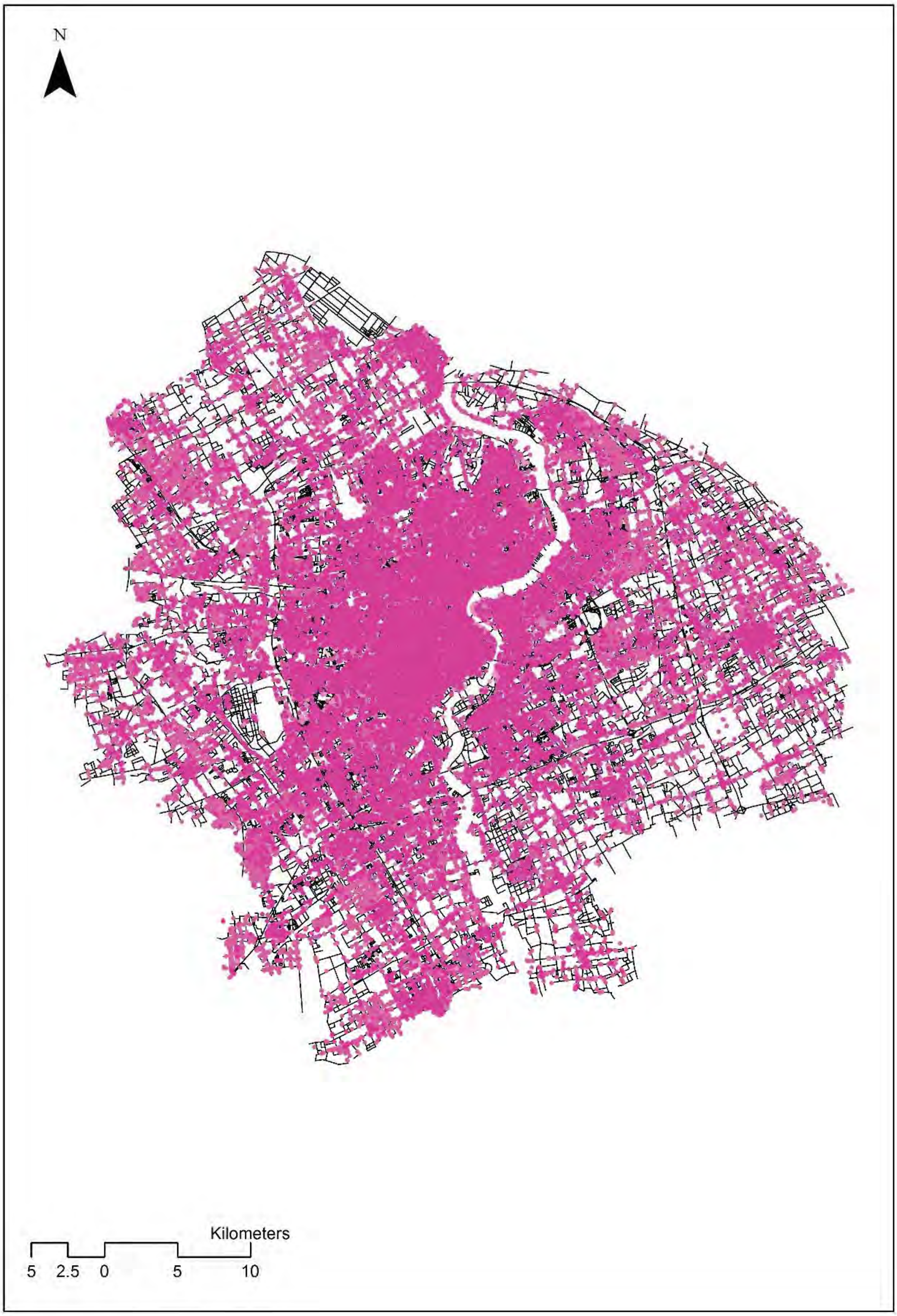

Figure A4-4

Geocoded points-of-interest and the street network data in the 2010s

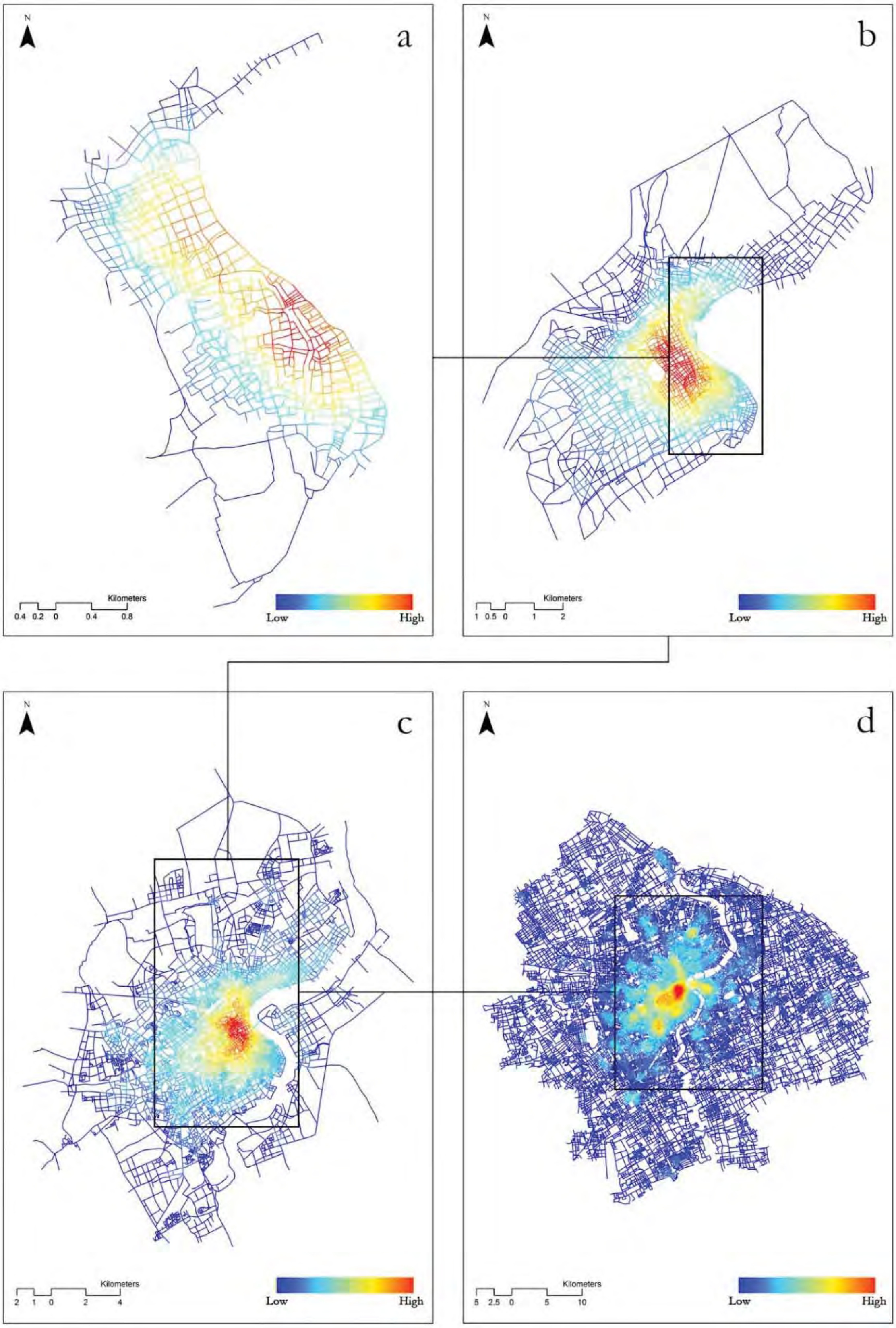

Figure A4-5

Accessible function density maps across periods ((a) 1880s; (b) 1940s; (c) 1980s; (d) 2010s) at 1,000 meters

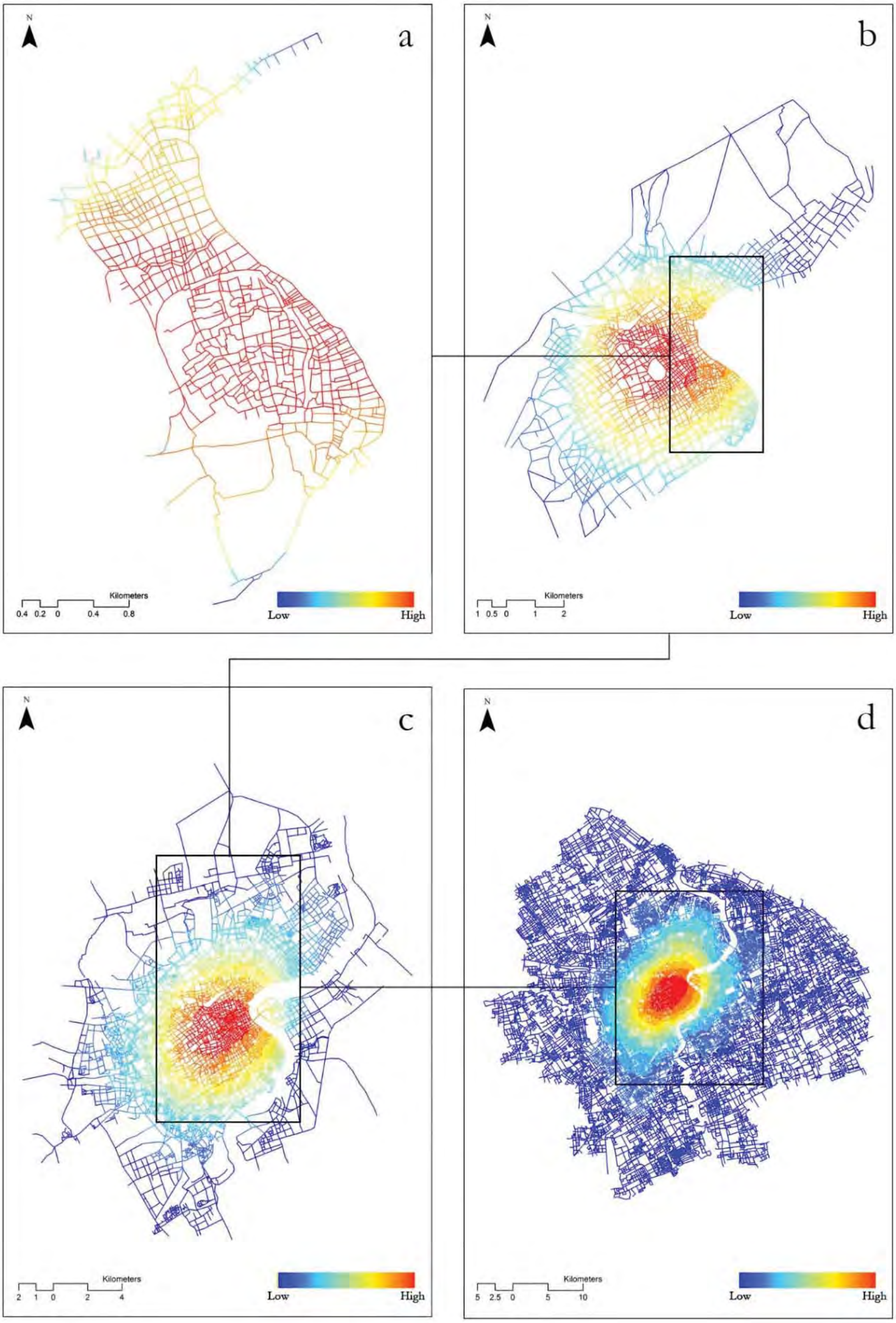

Figure A4-6

Accessible function density maps across periods ((a) 1880s; (b) 1940s; (c) 1980s; (d) 2010s) at 5,000 meters

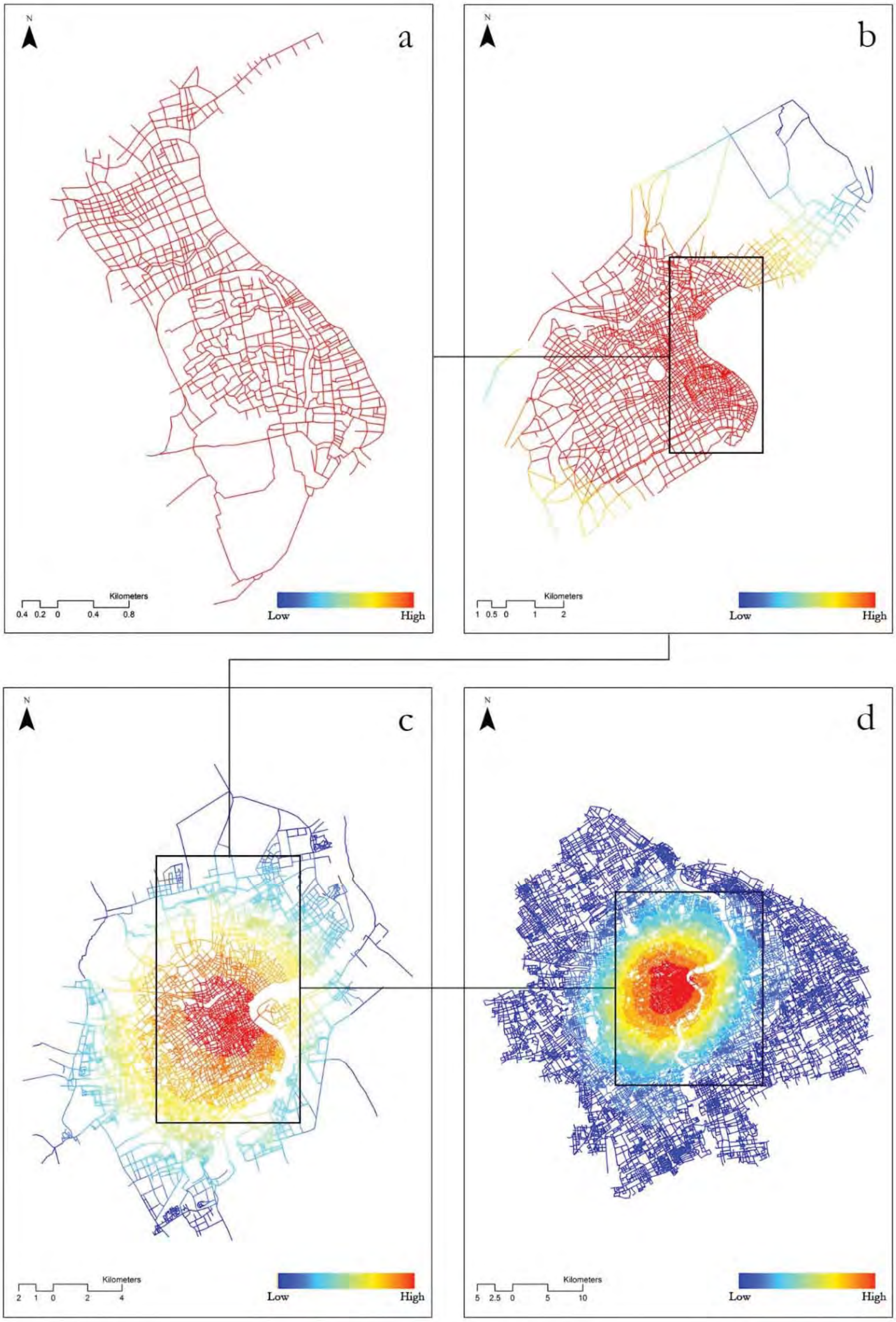

Figure A4-7

Accessible function density maps across periods ((a) 1880s; (b) 1940s; (c) 1980s; (d) 2010s) at 10,000 meters

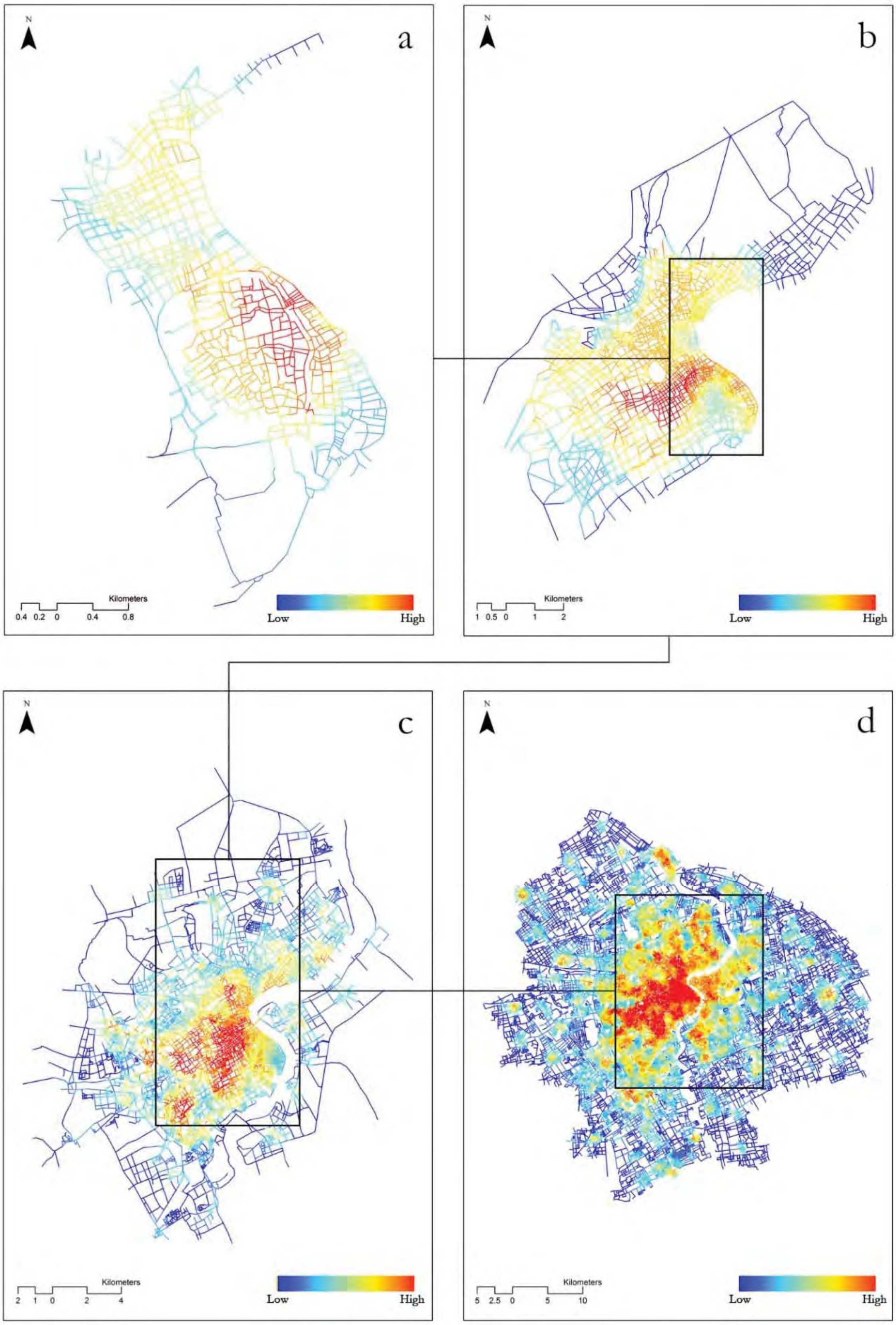

Figure A4-8

Accessible function diversity maps across periods ((a) 1880s; (b) 1940s; (c) 1980s; (d) 2010s) at 1,000 meters

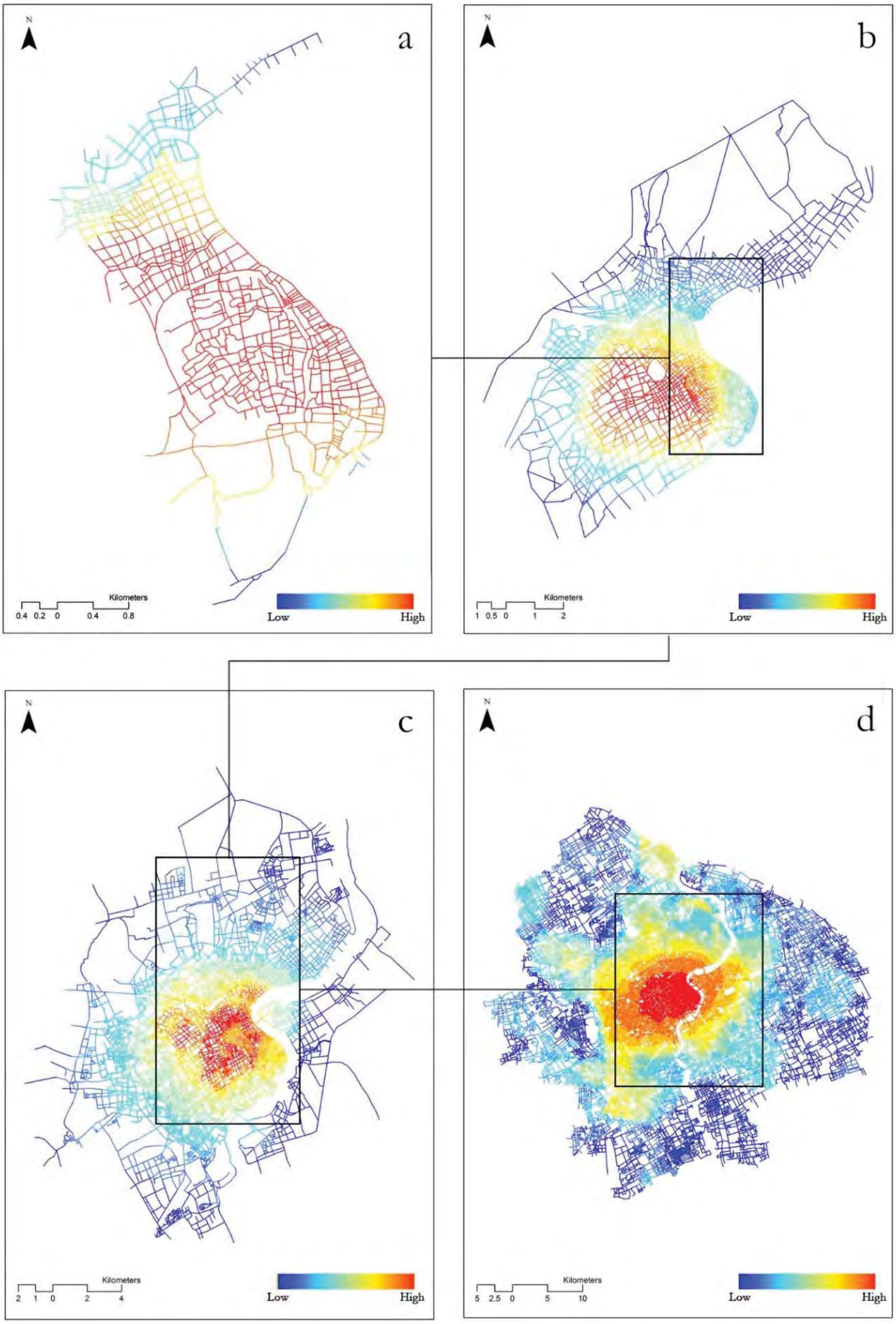

Figure A4-9

Accessible function diversity maps across periods ((a) 1880s; (b) 1940s; (c) 1980s; (d) 2010s) at 5,000 meters

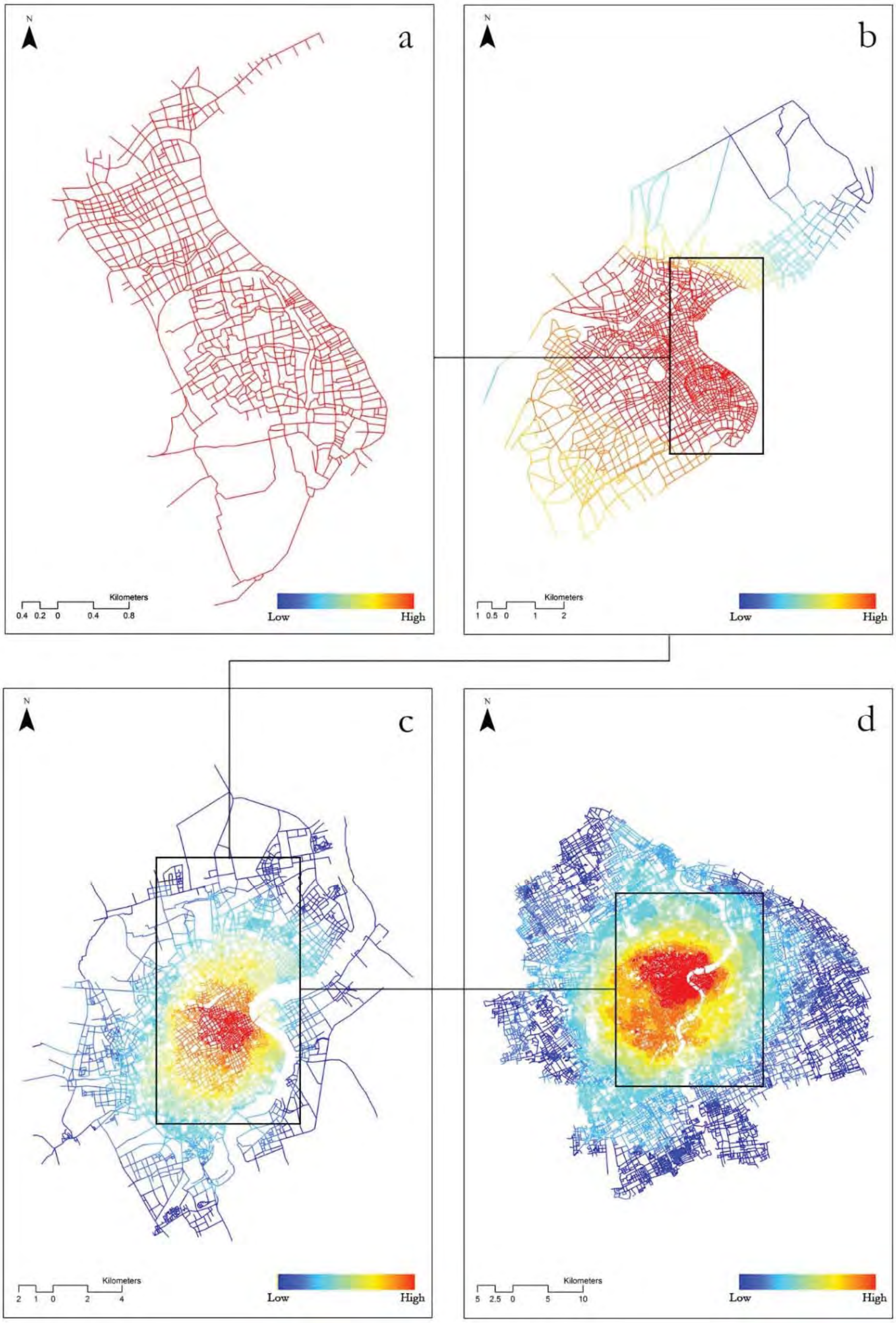

Figure A4-10

Accessible function diversity maps across periods ((a) 1880s; (b) 1940s; (c) 1980s; (d) 2010s) at 10,000 meters

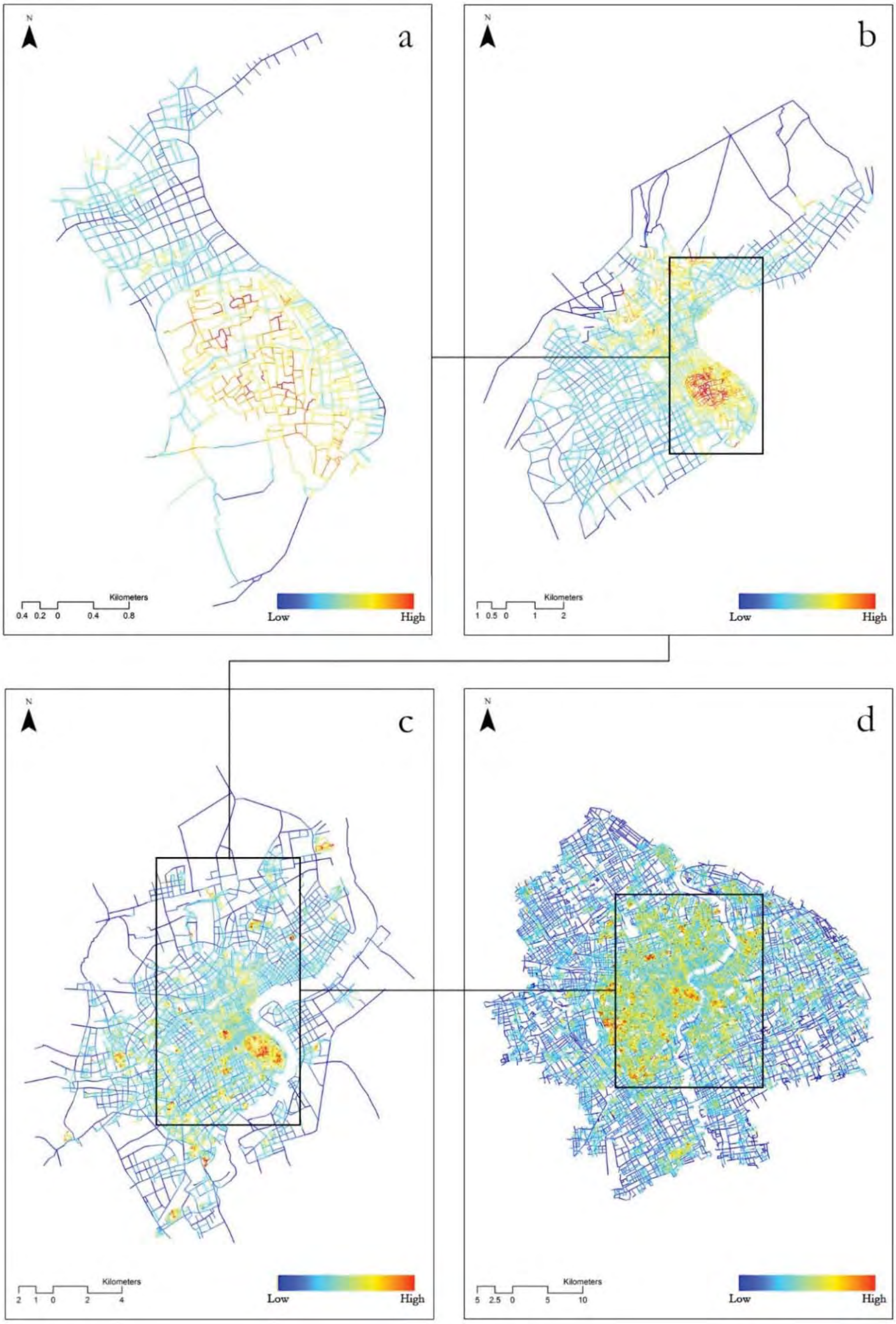

Figure A4-11

Mean angular distance maps across periods ((a) 1880s; (b) 1940s; (c) 1980s; (d) 2010s) at 1,000 meters

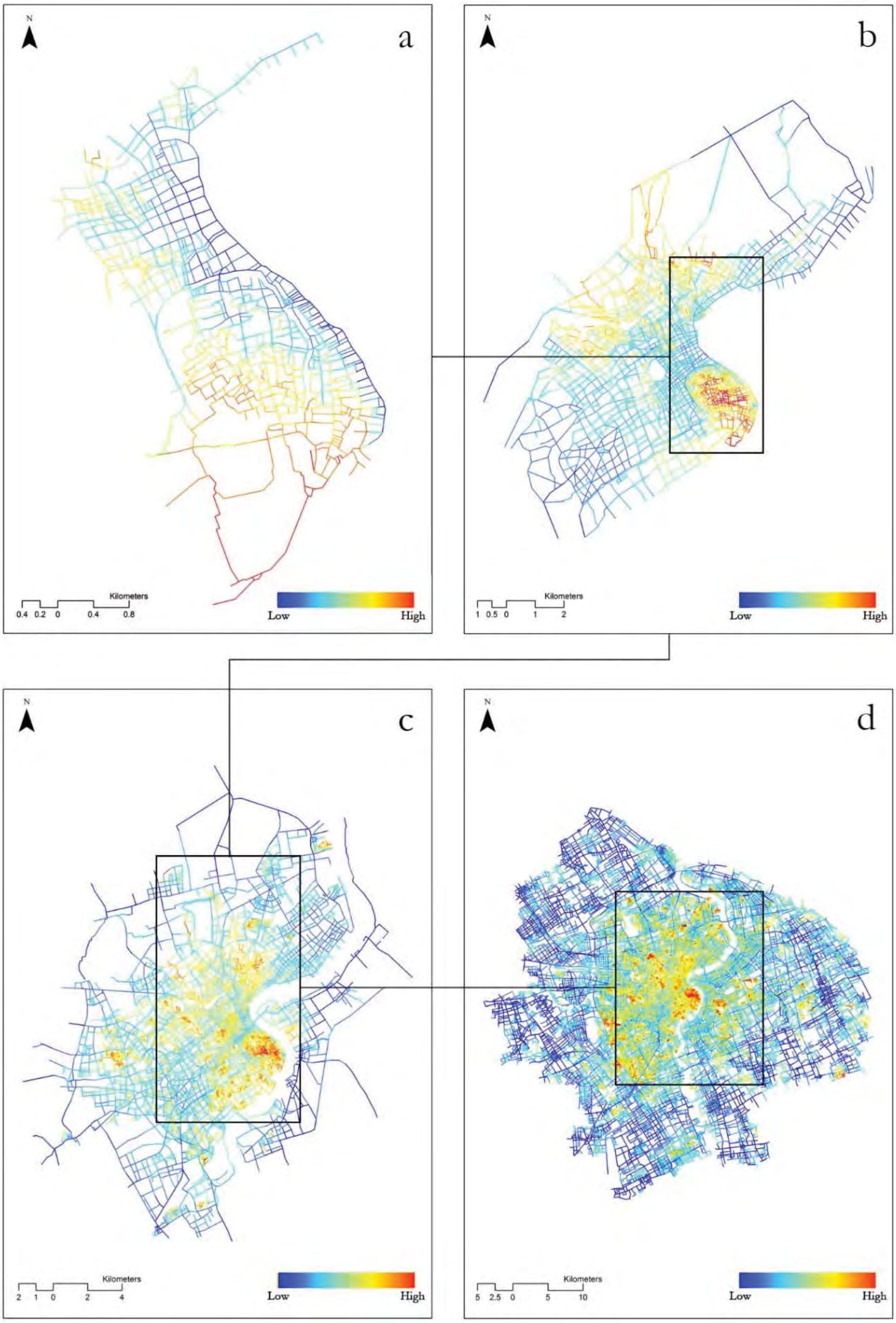

Figure A4-12

Mean angular distance maps across periods ((a) 1880s; (b) 1940s; (c) 1980s; (d) 2010s) at 5,000 meters

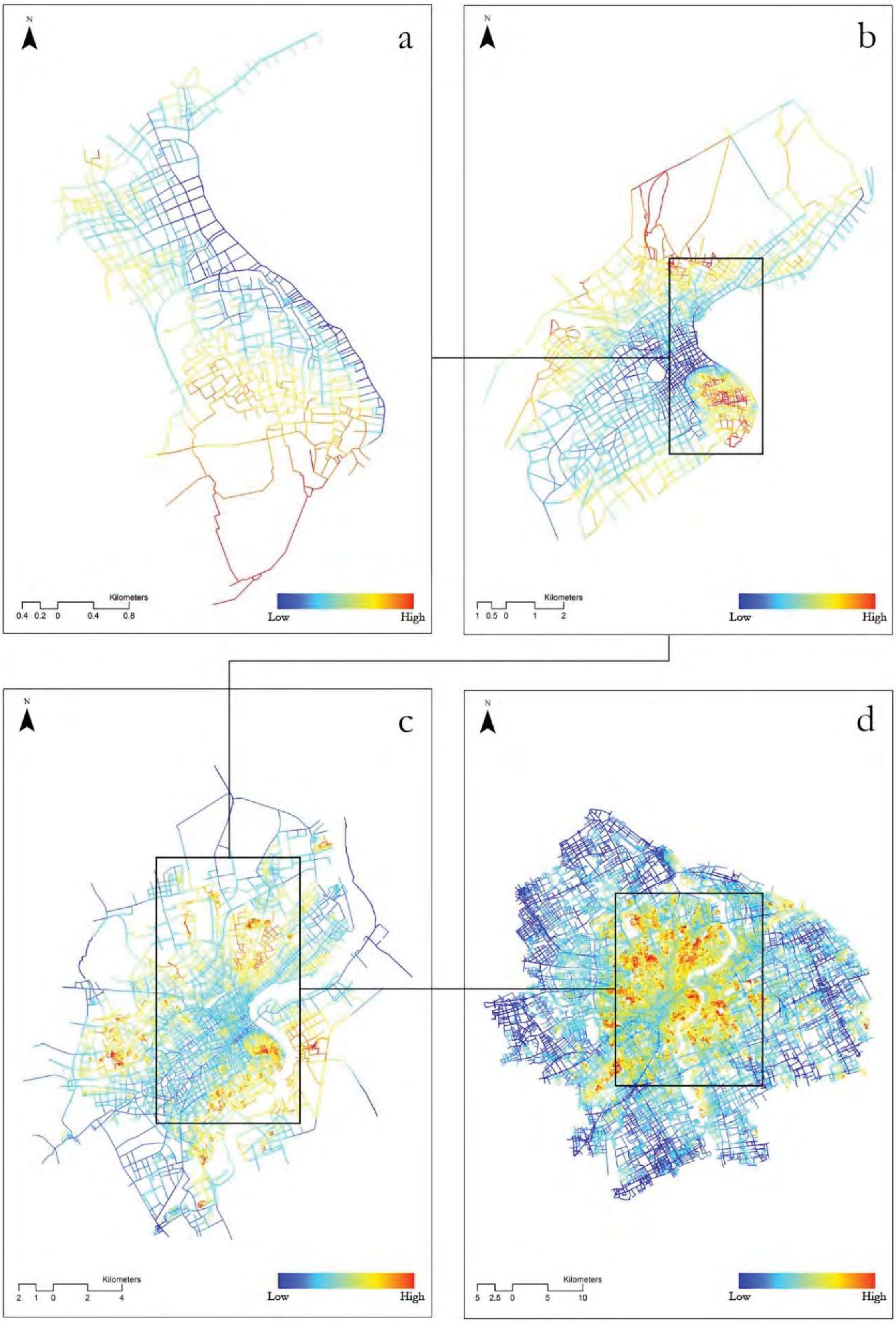

Figure A4-13

Mean angular distance maps across periods ((a) 1880s; (b) 1940s; (c) 1980s; (d) 2010s) at 10,000 meters

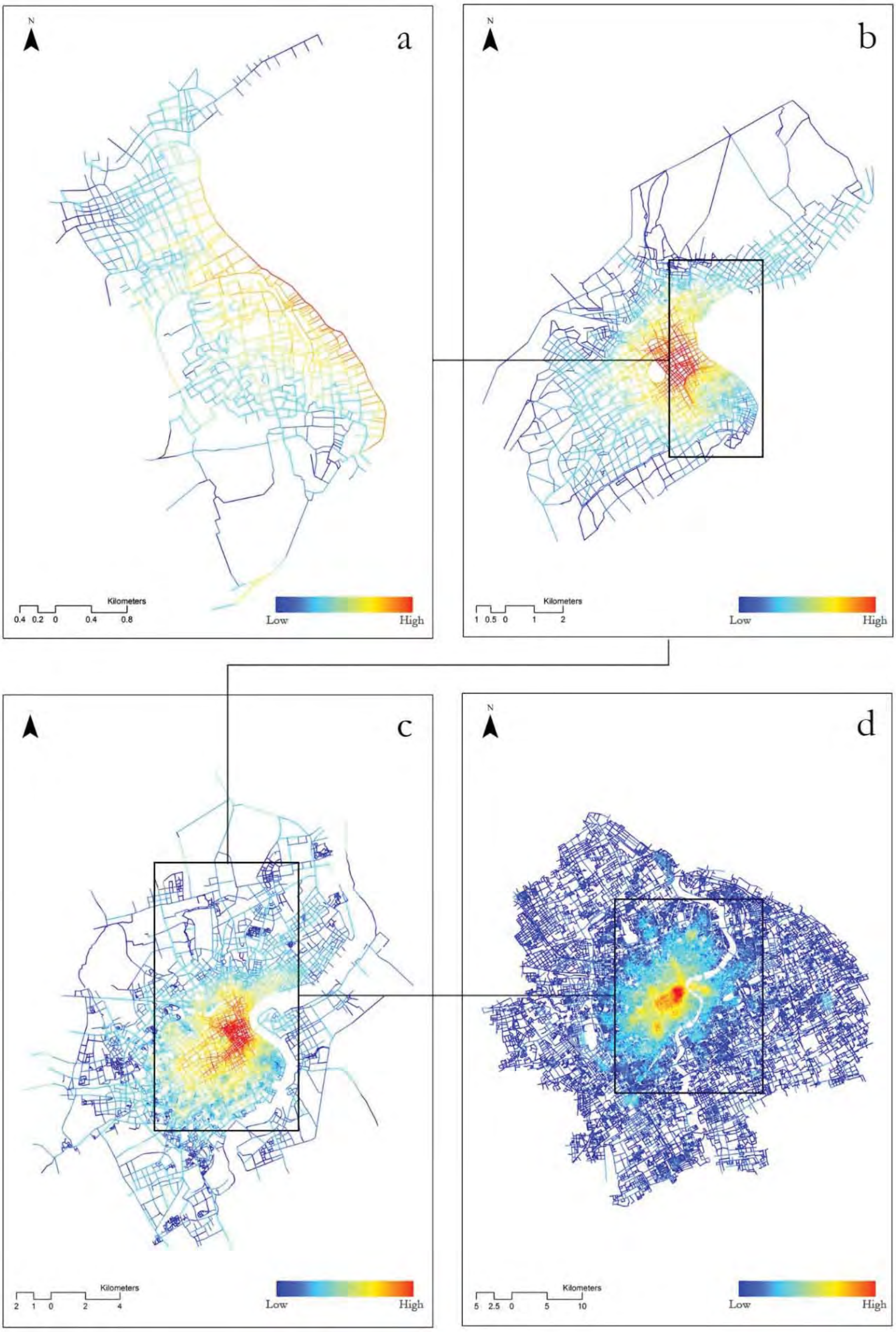

Figure A4-14

Canonical function 1 in the discriminant analysis across periods ((a) 1880s; (b) 1940s; (c) 1980s; (d) 2010s) at 1,000 meters

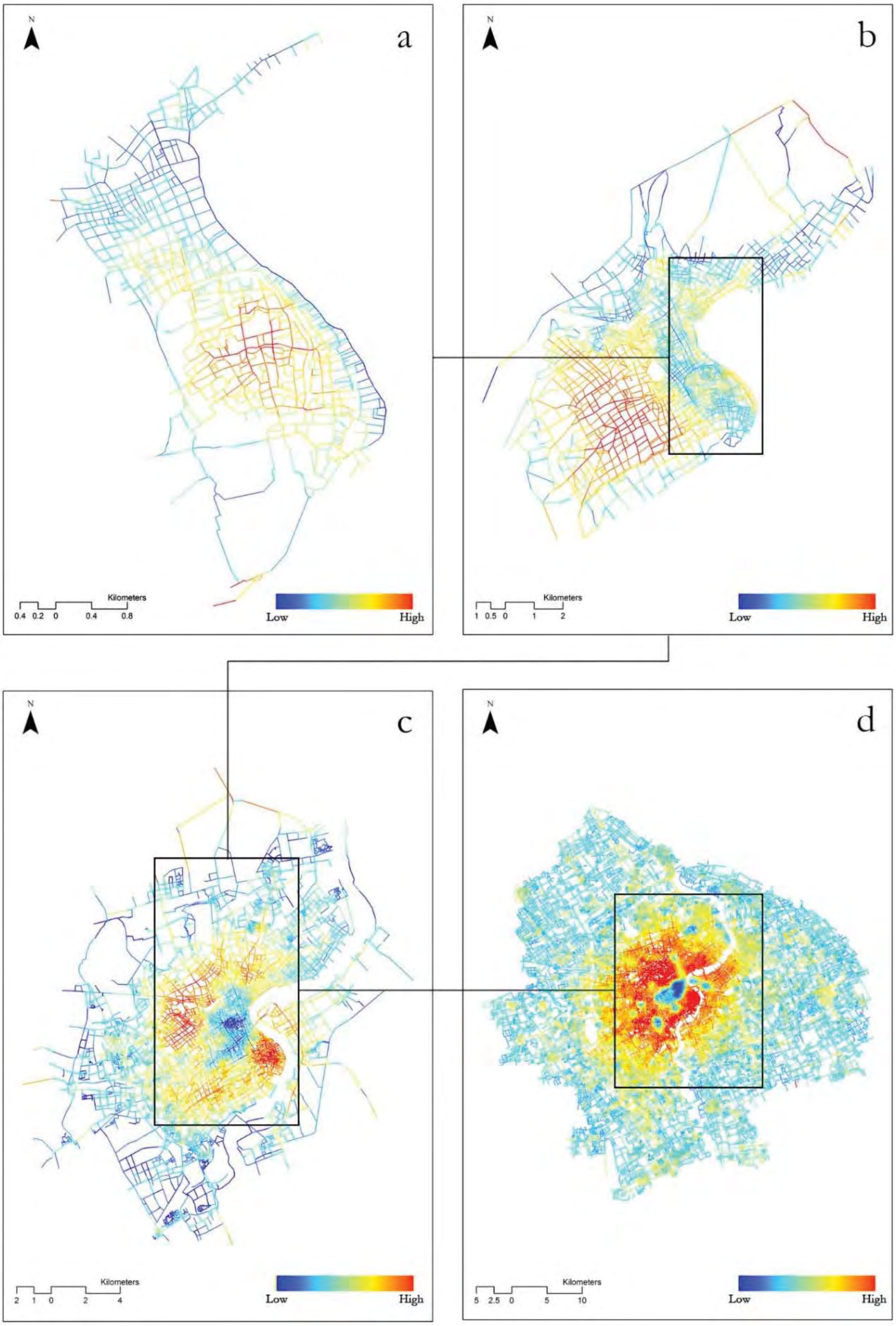

Figure A4-15

Canonical function 2 in the discriminant analysis across periods ((a) 1880s; (b) 1940s; (c) 1980s; (d) 2010s) at 1,000 meters